UNIVERSITY OF ILLINOIS BULLETIN

ISSUED WEEKLY

Vol. XXX June 6, 1933 No. 40

[Entered as second-class matter December 11, 1912, at the post office at Urbana, Illinois, under the Act of August 24, 1912. Acceptance for mailing at the special rate of postage provided for in section 1103, Act of October 3, 1917, authorized July 31, 1918.]

THE FRICTION OF RAILWAY BRAKE SHOES, ITS VARIATION WITH SPEED, SHOE PRESSURE, AND WHEEL MATERIAL

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

THE ASSOCIATION OF MANUFACTURERS
OF CHILLED CAR WHEELS

BY

EDWARD C. SCHMIDT

AND

HERMAN J. SCHRADER

BULLETIN No. 257
ENGINEERING EXPERIMENT STATION

PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

PRICE: ONE DOLLAR

THE Engineering Experiment Station was established by act of the Board of Trustees of the University of Illinois on December 8, 1903. It is the purpose of the Station to conduct investigations and make studies of importance to the engineering, manufacturing, railway, mining, and other industrial interests of the State.

The management of the Engineering Experiment Station is vested in an Executive Staff composed of the Director and his Assistant, the Heads of the several Departments in the College of Engineering, and the Professor of Industrial Chemistry. This Staff is responsible for the establishment of general policies governing the work of the Station, including the approval of material for publication. All members of the teaching staff of the College are encouraged to engage in scientific research, either directly or in coöperation with the Research Corps composed of full-time research assistants, research graduate assistants, and special investigators.

To render the results of its scientific investigations available to the public, the Engineering Experiment Station publishes and distributes a series of bulletins. Occasionally it publishes circulars of timely interest, presenting information of importance, compiled from various sources which may not readily be accessible to the clientele of the Station, and reprints of articles appearing in the technical press written by members of the staff.

The volume and number at the top of the front cover page are merely arbitrary numbers and refer to the general publications of the University. *Either above the title or below the seal* is given the number of the Engineering Experiment Station bulletin, circular, or reprint which should be used in referring to these publications.

For copies of publications or for other information address

THE ENGINEERING EXPERIMENT STATION,
UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 257 JUNE, 1933

THE FRICTION OF RAILWAY BRAKE SHOES, ITS VARIATION WITH SPEED, SHOE PRESSURE, AND WHEEL MATERIAL

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

THE ASSOCIATION OF MANUFACTURERS
OF CHILLED CAR WHEELS

BY

EDWARD C. SCHMIDT
PROFESSOR OF RAILWAY ENGINEERING

AND

HERMAN J. SCHRADER
ASSOCIATE IN RAILWAY MECHANICAL ENGINEERING

ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

6000—6-33—3979

UNIVERSITY
OF ILLINOIS
:: PRESS ::

CONTENTS

LIST OF FIGURES

LIST OF TABLES

THE FRICTION OF RAILWAY BRAKE SHOES, ITS VARIATION WITH SPEED, SHOE PRESSURE, AND WHEEL MATERIAL

I. Introduction

1. *Previous Experiments.*—Beginning with the famous Galton tests* in 1878 and 1879, the friction of railway brake shoes has been the subject of systematic investigation by various agencies. Previous to these tests ideas on the subject had either grown out of railway experience or were deduced from coefficient of friction determinations made under conditions so different from those prevailing in railway braking as to make such deductions unreliable.

In the intervening fifty years a great volume of additional information has been made available through experiments made by the Master Car Builders' Association's Committee on Brake Shoe Tests, by Purdue University and the University of Illinois individually, and also in coöperation with the Association of Manufacturers of Chilled Car Wheels, by the American Brake Shoe and Foundry Company, by the Pennsylvania Railroad, and also through experiments conducted abroad.

These researches have not only established values of the coefficient of shoe friction under various conditions, but they have also made it clear that the coefficient varies with the speed of the rim of the car wheel to which the shoe is applied; that it is modified by the pressure with which the shoe is pressed against the wheel; that under extreme conditions it may vary somewhat with the duration of application of the shoe; and that it is different not only for various shoe materials, but for different wheel materials as well.

Despite the scope and excellence of these investigations there remained some uncertainties with respect to shoe friction and its variations. The Master Car Builders Committee's tests, for example, were undertaken at a time when a great variety of brake shoes was offered to the railways, and the Committee's chief purpose was to establish the values of coefficient of friction and the rate of wear of these shoes in order to lay down specifications for the manufacture and purchase of brake shoes. While in this process the Committee

*Experiments made by Captain Douglas Galton on the London, Brighton and South Coast Railway and on the North Eastern Railway, and reported by him to the Institution of Mechanical Engineers (of Great Britain) in three papers presented at meetings of the Institution held on June 13 and October 24, 1878 and April 24, 1879. In these experiments Captain Galton was greatly aided by Mr. George Westinghouse, especially in the design and construction of suitable testing equipment.

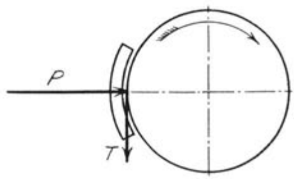
made tests on both steel and chilled wheels, their interest in the influence of wheel material was secondary, and their tests on the two sorts of wheels were seldom made with the same shoes nor at comparable speeds and pressures. The tests, because of these dissimilarities, while they indicated a difference in the friction on steel and chilled wheels, did not establish the magnitude of this difference under identical conditions. The results of earlier experiments give evidence of the decrease of coefficient as speed and pressure increase; but the rates of decrease derived from the various tests are not in good agreement. These discordances are probably to be explained by lack of adequate care in maintaining comparable test conditions, especially as regards the maintenance of equality of fit of the shoe on the wheel tread throughout the whole series of tests.

Such uncertainties as these were the chief reason for undertaking the tests whose results are presented in this bulletin. The precautions taken to ensure and to maintain strictly comparable test conditions are set forth in the succeeding chapters, and are reflected in the concordance among the test results.

2. *Coefficient of Friction.*—In this bulletin the test results are presented and discussed in terms of coefficient of friction, as in all previous experiments. They are also presented in terms of tangential pull of the shoe upon the wheel. It may not be amiss to restate here the meaning of coefficient of friction and its relation to brake pressure and tangential pull.

If, as indicated in the accompanying diagram, a brake shoe be pressed against a revolving wheel with a radial force or "brake shoe pressure" P, the shoe, by its friction on the wheel tread, will tend to grip the wheel and retard its rotation. This retarding force or "tangential pull" of the shoe on the wheel (represented by T in the diagram) is exerted at right angles to the shoe pressure and is always less than this pressure. The sum of such retarding forces coming from each wheel of a car constitutes the total retarding force to which the car is subjected. The ratio that T bears to P is called the coefficient of friction; that is, the coefficient of friction equals the tangential pull divided by the shoe pressure ($T \div P$).

In the usual conditions of railway braking this coefficient or ratio varies from about 0.12 to about 0.35. It is ordinarily expressed as a percentage of the shoe pressure, and for railway brake shoes we may say that the coefficient of friction ranges from 12 per cent to 35 per cent. These values, and all others presented in this bulletin, are developed when the wheel is actually in motion and the shoe is



sliding over the wheel tread. At the moment just before the wheel starts to turn or just after its rotation ceases the coefficient has a much higher value. This is the so-called coefficient of "static friction"—the coefficient when the two contact surfaces are not moving with respect to one another.

As is explained in Chapter II, the force actually measured during the tests is the tangential pull, T. The recorded coefficients of friction have all been derived by calculation—by dividing the measured tangential pull by the known brake shoe pressure. During the first test listed in Table 7, for example, the average tangential pull recorded by the testing machine was 608.9 lb. and the shoe pressure was 2250 lb.; the average coefficient of friction was therefore $608.9 \div 2250 = 0.2706$, or 27.06 per cent.

3. *Purpose and General Program of Tests.*—The purpose of this investigation was to determine, for two kinds of brake shoes, the values of the coefficient of friction over the usual range in shoe pressure and wheel speed,* and on both chilled iron and steel wheels.

Three kinds of tests were made during this research. The first were "stop tests" which simulate the conditions under which a train is brought to rest, and in which the wheel speed gradually decreases until the wheel stops. Nearly all the friction data produced in previous investigations have been derived from this kind of experiment. The results of 845 such stops are here included.

The second kind of test is designated in this bulletin as a "constant speed test." In these the speed of the wheel was held constant at some chosen value and the shoe was alternately applied and released until, in general, ten applications had been made, the duration of each application being 190 revolutions of the wheel. This procedure is the same as that specified by the American Railway Association for tests of brake shoe wear. In the whole research 202 such tests were included, covering more than 2000 shoe applications. Such

*Throughout the bulletin the term speed denotes the speed of a point on the wheel tread, and is expressed in miles per hour. This is, of course, identical with the car speed. A 33-inch wheel has a circumference of 8.64 feet; and in one revolution any point on its rim moves 8.64 feet, while the car travels this same amount.

tests simulate roughly the conditions which prevail in bringing a train down a long grade.

In the third kind of test, which is a modification of the second, the wheel was kept moving at constant speed and the shoe was continuously applied to it for fifteen minutes. Twenty-eight such tests were made.

The two kinds of brake shoes used were the "Diamond S" shoe, used principally on passenger cars, and "Special Chilled" shoes, which are of plain cast iron with chilled ends, and which are representative of many of the shoes used in freight service. Four wheels were used during the tests: Two steel wheels, one new and the other partly worn; and two chilled iron wheels, one new and the other partly worn.

The program and test procedure here briefly summarized are explained at length in the succeeding chapters. Obviously the results obtained under such a program permit conclusions to be drawn with respect to the magnitude of the values of coefficient of friction for each kind of shoe, and with respect to the influence upon the coefficient of

(a) Speed
(b) Shoe pressure
(c) Shoe material
(d) Wheel material
(e) Duration of application of the shoe.

4. *Test Results.*—The results of the tests are discussed in detail in Chapters V, VI, and VII, and they are summarized in Chapter VIII. It is impracticable to summarize them further in any specific manner. It may, however, be of interest to state here the general tenor of the main conclusions.

Like previous investigations, these tests show for both shoes and on all wheels a definite and regular decrease in the coefficient of shoe friction as the speed increases; and they likewise show, in general, a decrease in coefficient as the shoe pressure increases.

In a great majority of both the stop tests and the constant speed tests the Diamond S shoe gave a greater coefficient of friction than the plain shoe.

In the stop tests, with exceptions so infrequent as to be negligible, the coefficient produced by either kind of shoe on chilled wheels was greater than that produced on steel wheels, under identical conditions of speed and pressure. In the constant speed tests this was true without exception.

5. *Acknowledgments.*—This investigation was undertaken as one of the coöperative researches of the Engineering Experiment Station of the University of Illinois, in coöperation with the Association of Manufacturers of Chilled Car Wheels, of Chicago. The University and this Association shared the expense of the tests.

In accordance with the general practice of the Experiment Station in such investigations, the scope of the tests and the general test program were defined by an Advisory Committee on which the Association was represented by MR. G. E. DOKE, President, MR. F. K. VIAL, a Director and Consulting Engineer, and by MR. E. C. EDWARDS, Traveling Engineer of the Griffin Wheel Company; while the University was represented by PROF. EDWARD C. SCHMIDT and MR. HERMAN J. SCHRADER. Toward the end of the investigation, Mr. Doke's place on the committee was taken by MR. H. C. VAN BUSKIRK, Executive Vice-President of the Association.

The conduct of the tests, the calculation and analysis of the data, and the preparation of the report were under the exclusive control of the Railway Engineering Department of the University, which acted for the Experiment Station and which assumes full responsibility for the validity of the tests and the results.

Special acknowledgment is made of the part taken in this work by MR. CLIFFORD E. MORGAN, who was appointed Special Research Assistant for the purposes of this investigation. Under the supervision of Mr. SCHRADER, Mr. MORGAN prepared the shoes and wheels, operated the testing machine and shared in the reduction of the test data. His unflagging zeal and resourcefulness contributed greatly to the accuracy and uniformity of the results. MR. ROBERT H. NEWELL, a graduate student in railway engineering, also shared in the calculation of the test results.

As previously stated, this research has been a part of the work of the Engineering Experiment Station of the University of Illinois, of which DEAN M. S. KETCHUM is the director; and of the Department of Railway Engineering, of which PROF. EDWARD C. SCHMIDT is the head.

II. TESTING EQUIPMENT

6. *Brake Shoe Testing Machine.*—The machine upon which the tests were made is in all essential features of its design the same as the original brake shoe testing machine* made for the Master Car

*This machine is illustrated and described in the Proceedings of the Master Car Builders' Association, Vol. 28, 1894, pages 154-161.

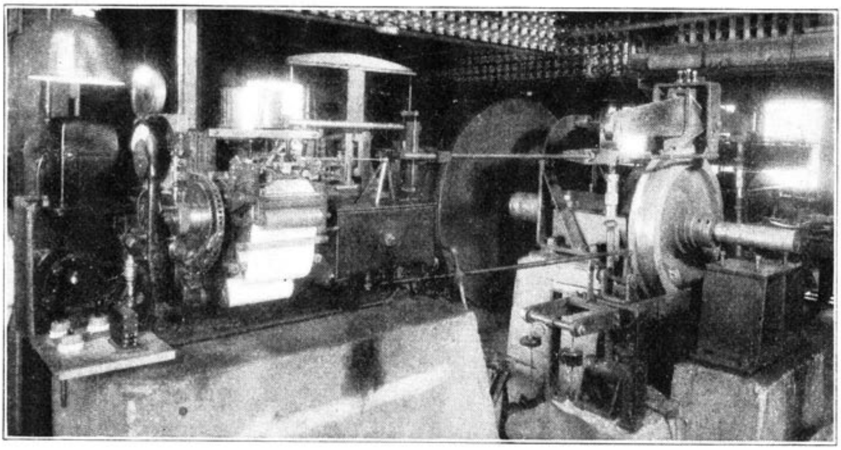


FIG. 1. BRAKE SHOE TESTING MACHINE

Builders' Association, and used by its Committee on Brake Shoe Tests for the work referred to in Chapter I.

The general design of the machine is shown in Fig. 1. It 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 a 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. It follows that the work done by a brake shoe applied to the car wheel of the machine, in bringing the revolving parts to rest, must be the same as the work performed in service on one of the wheels of an eight-wheeled car of this weight, when brought to rest from a like 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 pair of levers by means of which the shoe may be applied to the wheel with any desired pressure up to a maximum of 18 000 pounds. This pressure is produced by weights hung at one end of the lower lever, as shown in Fig. 1. The tangential pull of the shoe which develops when it is thus applied to the rotating wheel is transmitted by a horizontal yoke to the dynamometer shown at the left side of Fig. 1. This dynamometer makes a continuous graphical record of the pull.

In making a stop test from a speed of, say, 40 m.p.h., the rotating element of the machine is brought up to a speed slightly greater than

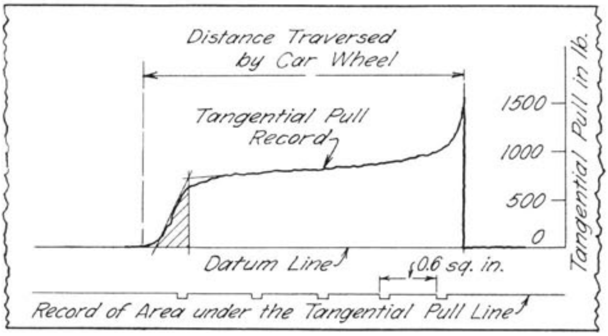


FIG. 2. DYNAMOMETER RECORD OF STOP TEST

40 m.p.h., the clutch is disengaged and the rotating parts are allowed to run free until the wheel speed falls to the desired 40 miles; at this instant the shoe is applied. In a constant speed test the clutch remains engaged and the revolving wheel is constantly driven at the desired speed against the frictional resistance of the applied shoe.

7. *Dynamometer.*—The dynamometer, of the flat-spring type, was designed and built for this machine by the William Sellers Company. The magnified spring deflection is transmitted to a small carriage in which is mounted a pen whose deviation from a base line is proportional to the tangential pull transmitted from the shoe to the dynamometer. This pen draws its pull record on a moving chart whose travel is proportional to the travel of the wheel rim; and the area under the pull curve is consequently proportional to the work done by the brake shoe on the car wheel. An electrically-controlled pen connected to a contacting clock draws a supplementary record of time on the chart. A specially designed area-integrating device, operating another electrically-controlled pen, draws on the chart a record which defines the increments of the area included between the pull curve and its base line. This area record facilitates the determination of the average tangential pull.

Figure 2 is the reproduction of a typical record obtained during a "stop test." It is the record for Test No. 3266, in which, using one of the Special Chilled shoes on the used steel wheel, a stop was made from an initial speed of 20 m.p.h. with a shoe pressure of 3750 pounds.

Figure 3 is a partial reproduction of the record made during the second shoe application in "constant speed test" No. 3208. This test was made with a Diamond S shoe on the used chilled wheel at a shoe pressure of 1500 pounds, the wheel being constantly driven at

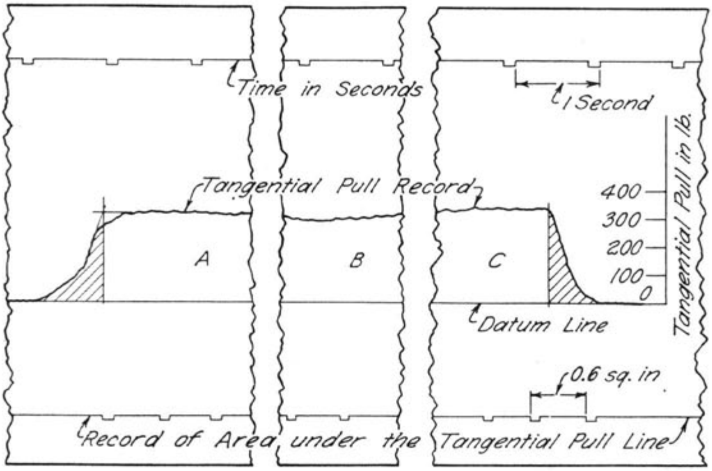


FIG. 3. DYNAMOMETER RECORD OF CONSTANT SPEED TEST

40 m.p.h. In this figure sections A, B and C represent the records obtained during about twenty revolutions of the wheel at the beginning, the middle and the end of the test, respectively; the intermediate portions of the record are eliminated in order to shorten the reproduction. In both figures vertical distances represent the tangential pull of the shoe; and horizontal distances are proportional to the distance traversed by a point on the wheel rim.

In order to obtain a liberal deflection of the pen which records the tangential pull, a light spring was used in the dynamometer during all tests except those stop tests which were made at pressures above 3000 pounds. These required a heavy spring. With the lighter spring in use, one inch of pen deflection corresponds to about 325 pounds pull on the dynamometer; while, with the heavier spring, one inch corresponds to about 1000 pounds. The dynamometer was calibrated at the beginning and at the end of the investigation, and before and after each change in the springs—ten times in all.

III. BRAKE SHOES AND TEST WHEELS

8. *Brake Shoes Used in Tests.*—In anticipation of the tests, 12 "Diamond S" brake shoes and 12 "Special Chilled" shoes were obtained from the American Brake Shoe and Foundry Company. These were all shoes of standard manufacture such as are regularly furnished by this company for railway service. In order, however, to ensure the greatest attainable uniformity of frictional quality all

24 shoes had been cast from the same heat; and they had, moreover, been cast in pairs—one Diamond S and one Special Chilled shoe in the same mold, the ends of both shoes being chilled alike. The bodies of all the shoes are composed therefore of the same kind of cast iron, which had been subjected to the same treatment. The two kinds differ only in that in the Diamond S shoe mild steel plates are embedded within the cast-iron body. These plates are slotted and expanded to form a mesh with diamond-shaped openings; and they are placed in the mold before the shoe is cast. Both types of shoe had reinforced steel backs.

The great majority of passenger train cars on American railroads are equipped with Diamond S shoes; and they are used to a considerable extent on freight cars also. The Special Chilled shoe is used chiefly on freight cars and is fairly typical of the plain chilled cast-iron shoes which preponderate in freight service.

Upon arrival at the laboratory the Diamond S shoes were numbered 1 to 12 and the others, 21 to 32 inclusive. About one-eighth of an inch of material was at once ground from the face of each shoe to remove surface hardness.

Only four shoes of each kind were finally chosen for use in the investigation, the others being set aside to provide for breakage or possible extensions of the test program. Of the eight shoes selected one of each kind was assigned to each of the four wheels tested, fitted to that wheel, and constantly used with it for all tests. As will later appear, the validity of the test procedure depends upon the substantial equality of the frictional properties of the four shoes of each type thus chosen for the investigation. As is explained in detail in the Appendix, the initial choice was made on the basis of preliminary coefficient of friction determinations, and it was subsequently checked by similar determinations made during the investigation. Six shoes of each kind were tested for this purpose and the four most nearly alike in frictional quality were selected for use. The shoes thus chosen and used in the investigation were Diamond S shoes Nos. 2, 3, 6, and 7; and Special Chilled shoes Nos. 26, 28, 30, and 31.

To provide an additional indication of shoe quality and uniformity, these eight shoes, after the removal of the surface material, were tested for hardness before the main tests were begun;* and in order to reveal any possible variation in quality as the shoe material

*Actually all 24 shoes were thus tested for hardness before beginning the tests. For the 12 Diamond S shoes the average Brinell hardness varied from a minimum of 331 to a maximum of 350, with a general average value of 342. Among the 12 Special Chilled shoes the hardness ranged from 320 to 344, with a general average value of 334.

TABLE 1

BRINELL HARDNESS, THICKNESS, AND WEIGHT OF SHOES BEFORE AND AFTER TESTS

Type of Shoe	Shoe No.	Average Brinell Hardness of Shoe						Weight lb.		Average Thickness in.	
		Before Tests			After Tests						
		Chilled End	Body	Entire Shoe	Chilled End	Body	Entire Shoe	Before Tests	After Tests	Before Tests	After Tests
1	2	3	4	5	6	7	8	9	10	11	12
Diamond S.......	2	474	267	350	419	227	304	17.42	14.81	1.242	1.027
	3	477	241	335	374	251	300	17.63	13.10	1.266	0.898
	6	484	250	343	402	233	301	17.94	14.69	1.297	1.031
	7	482	253	345	446	251	329	17.07	12.45	1.219	0.844
Special Chilled....	26	472	246	336	389	243	302	17.62	13.73	1.266	0.953
	28	466	253	338	422	265	328	17.28	11.54	1.219	0.770
	30	476	253	342	409	242	308	17.40	14.08	1.242	1.004
	31	477	234	331	385	227	290	17.40	11.58	1.234	0.777

wore away, hardness tests were again made upon the conclusion of the investigation. All these determinations of hardness were made, at seven points on the contact face of each shoe, by means of a Brinell machine. The results are given in Table 1. The values shown in columns 3 and 6 of this table are the averages of four determinations—two near each end of the shoe in the chilled material. The values in columns 4 and 7 are averages of three determinations made on the longitudinal center line of the shoe face—one at the middle of the length and one 2½ inches each way therefrom. For each shoe all seven hardness determinations are combined to form the average values* for the entire shoe shown in columns 5 and 8.

Each of the eight test shoes was weighed after being made ready for the main tests, and again upon their conclusion. These weights appear in columns 9 and 10 of Table 1.

Table 1 also presents the average thickness of each test shoe, measured before and after the tests on each side of the shoe at points about one and one-half inches from the ends. The averages of these four measurements are given in columns 11 and 12. For all shoes the length of the contact face was about 12.2 inches and its area substantially 40.9 square inches.

A photograph of both kinds of shoes before and after the investigation is reproduced in Fig. 4. The first shoe, shown at the left, is one of the Diamond S shoes after it had been fitted to its wheel, but before it had been used for the tests. The next is a Diamond S

*In finding this average, in order to give due weight to the relative areas of chilled and unchilled surfaces, the end hardness values were first reduced to two averages and these averages were then combined with the three hardness values for the center of the shoe.

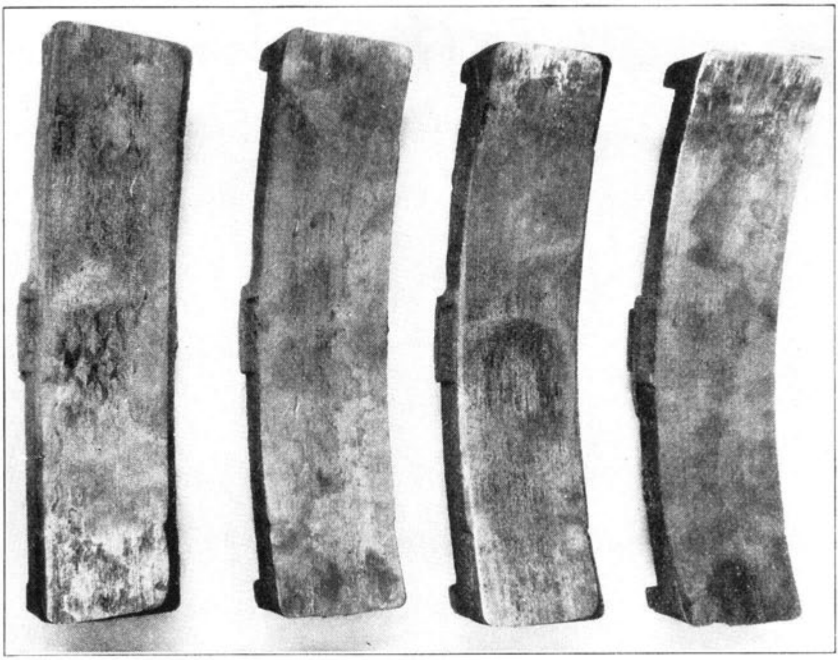


FIG. 4. SHOES BEFORE AND AFTER TESTS

shoe in the condition in which it was left at the conclusion of the tests. The outlines of the diamond-shaped openings in the embedded steel mesh may be distinguished on these two shoes at various points in the photograph. The third and fourth are Special Chilled shoes before and after the tests, respectively. On all four shoes the impression made by the chilling blocks may be noted near the ends; and the tips also show the smoother surfaces produced in the chilled material.

9. *Car Wheels Used in Tests.*—Eight wheels were secured for the tests to provide for the program originally contemplated. The final program, however, required the use of only the four wheels which are described below—two wrought steel wheels and two chilled iron wheels. Of each kind of wheel, one was new and the other had been partially worn in service.

The two wrought steel wheels are designated throughout this report as wheel E and wheel F. Both are multiple-wear rolled steel wheels, and were chosen by a representative of the University from the wheel stock of a western railroad. Wheel E was a new wheel

FIG. 5. NEW CHILLED WHEEL A

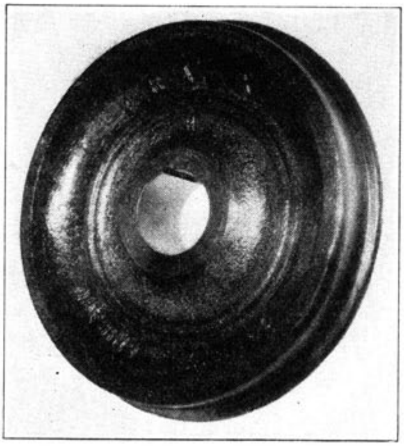


FIG. 6. USED CHILLED WHEEL C

taken at random from a group of about twenty new wheels; it had been made during July, 1930. The other steel wheel, F, had been made during October, 1927, and had been in service on a locomotive tender which weighed 106 000 lb., empty, and 233 000 lb., loaded. It had been removed from service for reasons related solely to the condition of its mate. Both of these wheels were of American Railway Association Standard design, 33 inches in diameter, for use on 6 in. x 11 in. axles; and they had been made under the same specifications. The treads of both wheels were in all respects in good condition, and they were chosen on that basis.

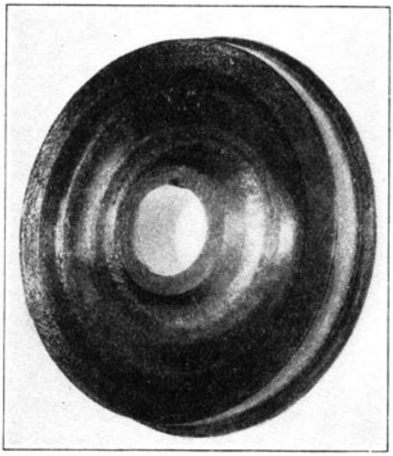


FIG. 7. NEW STEEL WHEEL E

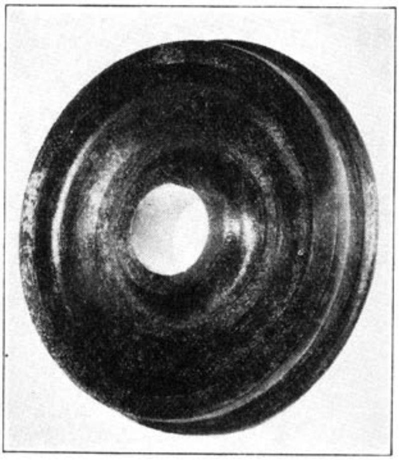


FIG. 8. USED STEEL WHEEL F

The two chilled iron wheels* used in the tests are designated as wheel A and wheel C. They were manufactured by the Griffin Wheel Company at one of its Chicago plants, and were there chosen for the tests by representatives of the Association of Manufacturers of Chilled Car Wheels. Both are American Railway Association Standard 750-pound, 33-inch, single plate wheels. Wheel A was new and had been cast on February 21, 1931. Wheel C had been cast on

*Bulletin No. 129 of the Engineering Experiment Station of the University of Illinois contains, on page 75, a brief history of the chilled car wheel, and information about its manufacture and characteristics.

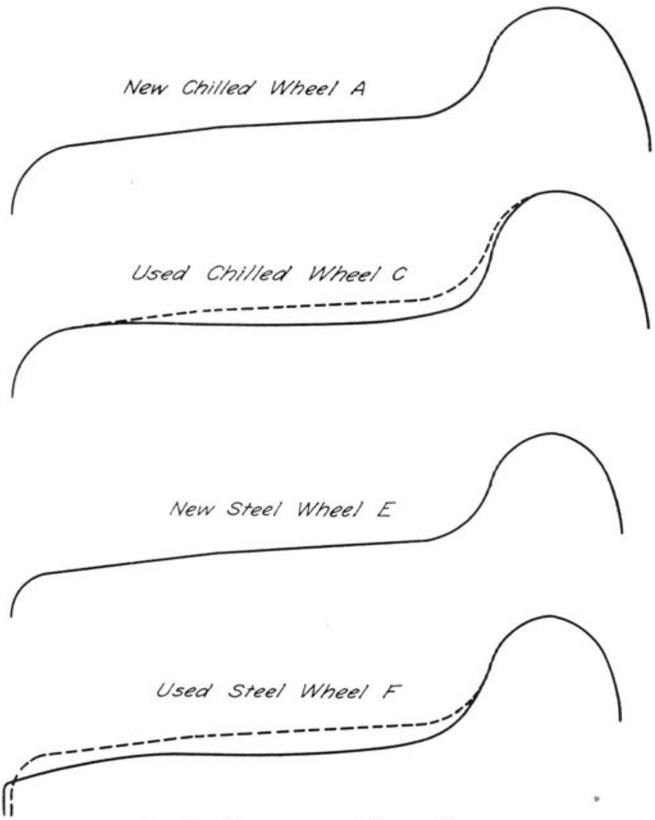


FIG. 9. CONTOURS OF WHEEL TREADS

April 19, 1927, and had been in service; its tread was in good condition—free from "shell-outs," slid flat spots, brake burns, or other defects.

Photographs of the two chilled iron wheels are reproduced in Fig. 5 and Fig. 6; and of the two rolled steel wheels, in Fig. 7 and Fig. 8. The small holes shown in the wheel plates in these figures were drilled at the laboratory merely to facilitate handling the wheels. The dimensions and weights of all wheels are given in Table 2.

After they arrived at the laboratory, plaster casts were taken of the tread contours of all four wheels. The contours thus defined are shown by the full-line outlines drawn in Fig. 9, which show the contours of all the wheels as they were received and tested. The tread contours of both new wheels conformed to the respective contours for new chilled and new steel wheels specified by the A.R.A. The broken line shown for used wheel C in this figure is the A.R.A. stand-

TABLE 2

DESIGNATION, WEIGHT, TAPE SIZE, AND HARDNESS OF TEST WHEELS

Kind	Designation	New or Used	Weight lb.	Tape Size	Circumference ft.	Shore Scleroscope Hardness					
						Before Tests			After Tests		
						Max.	Min.	Av.	Max.	Min.	Av.
1	2	3	4	5	6	7	8	9	10	11	12
Chilled Iron......	A	New	730.4	155	8.62	66	56	61.4	62	55	58.8
	C	Used	723.3	150	8.56	75	68	71.6	64	56	60.3
Steel.............	E	New	773.0	162	8.69	44	31	36.8	43	32	37.3
	F	Used	691.0	138	8.44	53	45	48.8	42	35	39.0

TABLE 3

CHEMICAL COMPOSITION OF TEST WHEELS

Wheel Designation	Total Carbon	Manganese	Phosphorus	Sulphur	Silicon
New Chilled Iron Wheel A........	3.45*	0.58	0.33	0.136	0.57
Used Chilled Iron Wheel C.......	3.40†	0.55	0.30	0.128	0.57
New Steel Wheel E..............	0.73	0.83	0.022	0.038	0.19
Used Steel Wheel F..	0.79	0.72	0.028	0.023	0.20

*Combined Carbon, 0.86. †Combined Carbon, 0.81.

ard contour for new chilled wheels. The broken line imposed upon the actual contour for used steel wheel F is the A.R.A. standard for new steel wheels.

All four wheels were tested for tread hardness before and after the investigation. On both occasions and on each wheel 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 averages of these twenty measurements are presented in columns 9 and 12 of Table 2. The maximum and minimum values among these measurements are also given in the table.

The chemical composition of the four wheels is shown in Table 3. The chemical analyses there given are the heat analyses made at the time the wheels were rolled or cast.

IV. TEST PROGRAM AND PROCEDURE

10. *Purposes of Tests, and General Program.*—As has already been implied, the purpose of the investigation was to determine the coeffi-

cient of friction of Diamond S and Special Chilled brake shoes under such a variety of pressures and speeds, and on such a variety of wheels, as to enable reliable conclusions to be drawn with respect to the influence upon brake friction of shoe composition and structure, shoe pressure, wheel speed, and wheel material; and, furthermore, so to vary the duration of the shoe applications as to simulate, at least roughly, the wide differences of application in service, in order to be able to draw conclusions as to the effect of the duration of the shoe contact upon the coefficient of friction.

To serve these purposes the two kinds of shoes were subjected to three kinds of tests on four different wheels, through a wide range of pressures and wheel speeds. The speeds and pressures, and their combinations, were so chosen as to represent the usual range of those quantities in freight train service. The program of the tests to which the shoes were actually subjected is shown in Tables 4, 5 and 6.

The "Stop Tests," as indicated in Table 4, were run with both kinds of shoes on all four test wheels at pressures ranging between 2250 and 4500 pounds, and at initial speeds varying from 20 to 60 miles per hour.

The "Constant Speed Tests" (Table 5) were also run with both kinds of shoes on all four wheels, at pressures from 500 to 4000 pounds, and at speeds of 20, 30, and 40 miles per hour. The actual combinations of pressure and speed are shown in Table 5.

The "Fifteen-Minute Constant Speed Tests," as shown in Table 6, were run with both kinds of shoes, but on only the used wheels—chilled wheel C and steel wheel F. The pressures used in this series were 1500, 2000, and 2500 pounds, and the speeds, 20, 30, and 40 miles per hour—combined as shown in the table.

The method of conducting each of the three kinds of tests is explained in the following pages.

11. *General Preliminary Test Procedure.*—After calibrating the dynamometer of the testing machine, the wheel to be used was mounted on the machine shaft, and there immediately ground to a true circle. The necessity for this arises from the fact that even a minute eccentricity of mounting or lack of roundness of the wheel causes the brake shoe to rise and fall a corresponding amount as the wheel revolves; and this rise and fall at the shoe is communicated to the weights hung at the end of the lever system by means of which pressure is applied to the shoe. The motion so transmitted is magnified by the levers 24 times, giving the weights enough motion to cause them to jump from the supporting pan. Such motion of the

TABLE 4

PROGRAM OF STOP TESTS

Showing combinations of shoe pressure and wheel speed, at which tests were made with both Diamond S and Special Chilled Shoes on two Chilled Iron Wheels and two Steel Wheels.

Brake Shoe Pressures lb.	Wheel Rim Speeds m.p.h.				
2250	20	30	40	50	60
3000	20	30	40	50	60
3750	20	30	40	50	60
4500	20	30	40	50	60

TABLE 5

PROGRAM OF CONSTANT SPEED TESTS

Showing combinations of shoe pressure and wheel speed, at which tests were made with both Diamond S and Special Chilled Shoes on two Chilled Iron Wheels and two Steel Wheels.

Brake Shoe Pressures lb.	Wheel Rim Speeds m.p.h.		
500	20	30	40
1000	20	30	40
1500	20	30	40
2000	20	30	40
2500	20	30	..
4000	20	..	..

TABLE 6

PROGRAM OF FIFTEEN-MINUTE CONSTANT SPEED TESTS

Showing combinations of shoe pressure and wheel speed, at which tests were made with both Diamond S and Special Chilled Shoes on Used Chilled Iron Wheel C and Used Steel Wheel F.

Brake Shoe Pressures lb.	Wheel Rim Speeds m.p.h.		
1500	..	30	40
2000	20	30	40
2500	20	30	..

weights alternately decreases and increases the shoe pressure, thereby impairing the accuracy and smoothness of the pull record. In thus grinding the wheel, care was taken to maintain its contour and to remove only the minimum of material. In no instance was it necessary to grind off as much as 1/64 of an inch.

The shoe to be used with the test wheel was next ground to an approximate fit on the wheel, by means of a special grinding machine. It was then mounted in the brake shoe head of the machine, applied under pressure to the revolving wheel, and thus worn down to a good fit on the tread—without the use of any abrasive. At intervals during this wearing-in process the shoe was cooled by means of a blower, in order to avoid the warping and cracking which might result from overheating it. Constant care was exercised during the tests to maintain a good shoe fit.

As has been intimated in the Introduction, there is ground for assuming that certain discordances among the results of previous brake shoe tests had arisen from shifting the test shoes from one wheel to another without taking adequate care to maintain equally good shoe fits on all wheels. In order to guard against this difficulty it was decided early in this investigation to assign to each test wheel one shoe of each of the two kinds, and to use those shoes and the wheel together for all tests. This decision was reinforced by the fact that had one shoe been used on all the wheels it doubtless would have worn out before the completion of the tests, and a shoe of equivalent frictional quality would then have had to be chosen by some such procedure as that explained in the following paragraphs.

Obviously, under this procedure, comparisons finally drawn between the results obtained from the two kinds of shoes and from the various wheels will be valid only in so far as the frictional qualities of all four test shoes of each kind are substantially the same. To ensure this equality unusual precautions were taken in the manufacture of the shoes; but chief reliance in securing shoes of like quality was placed in preliminary stop tests in which six shoes of each kind were tested to define their coefficients of friction. By comparison of these preliminary test results, the four shoes of each kind which had coefficients of friction most nearly alike were chosen for the final tests. Among the Diamond S shoes, Nos. 1, 2, 3, 5, 6, and 7 were given this preliminary examination; and shoes Nos. 2, 3, 6, and 7, which proved to be most nearly alike, were chosen for the main tests. Similarly from the six Special Chilled shoes thus examined, Nos. 26, 28, 30, and 31 were selected, and Nos. 25 and 32 were rejected.

The Appendix presents in detail not only the results of these preliminary stop tests, but also the results of other tests made to check the equality of the chosen test shoes during the progress of the work. It is deemed sufficient therefore to say at this point that these stop tests were made at two combinations of speed and pressure; namely, 30 m.p.h. and 2250 lb., and 60 m.p.h. and 3750 lb. Under the first combination the four Diamond S shoes selected for the main tests gave an average coefficient of friction of 25.0 per cent, a minimum of 24.8 per cent, and a maximum of 25.3 per cent. Under this combination, therefore, the lowest coefficient deviates 0.8 per cent from the mean coefficient, while the highest coefficient deviates 1.2

per cent. Under the second combination of speed and pressure the corresponding deviations from the mean value were, respectively, 2.9 and 1.2 per cent. Among the four selected Special Chilled shoes the corresponding deviations from the mean were 1.6 and 1.2 per cent for the first combination of speed and pressure, and 2.0 and 2.0 per cent for the second.

These variations among the coefficients of friction of the chosen test shoes are no greater than those which frequently occur among test values derived from the same shoe under identical test conditions. In other words, these variations in quality among the chosen shoes are no greater than the variations which are inherent in the testing process, and which develop in spite of all precautions—due probably to uncontrollable variations in shoe contact area and to changes in the contact surfaces. If this view be accepted, the plan of assigning to each wheel a shoe chosen as here explained and continuing to use that shoe with that wheel and no other is justified.

Each of the four test wheels, under this plan, had assigned to it one Diamond S shoe and one Special Chilled shoe; the shoes, in numerical order, being assigned to the wheels in alphabetical order. This purely arbitrary mating of wheels and shoes was as follows:

	Diamond S Shoes Nos.	Special Chilled Shoes Nos.
New Chilled Iron Wheel A	2	26
Used Chilled Iron Wheel C	3	28
New Steel Wheel E	6	30
Used Steel Wheel F	7	31

12. *Method of Conducting Stop Tests.*—In this kind of test the shoe, it will be recalled, is applied to the free rotating unit of the testing machine, at some desired initial speed, and brings this unit to rest by its action on the car wheel.

In carrying out such a test, the shoe having been fitted to the wheel and the weights on the lever system adjusted to produce the desired shoe pressure, the test wheel was brought up to a speed a little higher than the desired initial test speed. The clutch between the engine and main shaft of the machine was then disengaged, and the shaft-flywheel-carwheel unit allowed to coast down to the desired test speed. The shoe at that moment was applied to the wheel and, by its friction, destroyed the energy of the revolving parts of the machine, which came to rest after an interval which differed, of course, with different initial speeds and different shoe pressures.

A typical record of the tangential pull made under these circumstances by the recording mechanism of the test machine has already been presented in Fig. 2.

In the early operation of this machine, as well as in the other brake shoe testing machines, the shoe was applied by releasing a latch which supported the lower lever, allowing the weights to at once exert their full effect, and bringing the shoe into sudden contact with the wheel at full pressure. Under this sort of application the shoe frequently chattered on the wheel, failed at first to seat itself properly, and gave a very irregular and variable pull record in the early part of the application, the irregularities occasionally continuing far into the body of the record. To avoid this difficulty in these tests the weights of the machine were supported by the piston of a cylinder containing compressed air which, in applying the shoe, was gradually bled off by an electrically operated valve. By this means the shoe pressure was built up gradually and the shock and irregularities referred to were avoided. The time required thus to build up full shoe pressure varied from about one to about two seconds, depending upon the magnitude of the pressure. In Fig. 2 that part of the record produced while this process was going on is distinguished in the figure by the cross-hatching. This area was ignored in calculating the average tangential pull; and the coefficient of friction values for all stop tests apply therefore to only the remainder of the record—from the time full shoe pressure was attained until the wheel came to rest.

Five such stops constitute what is designated throughout this bulletin as one stop test, the applications being thus repeated in order to secure a more reliable average value. In the tables the value of the coefficient of friction presented for any given set of conditions is consequently the average value obtained from five such shoe applications; and the 169 stop tests included in the report are derived from 845 such "stops" as have just been described.

In the stop tests at initial speeds of 20 and 30 miles per hour, the five stops were made one after the other without any intermediate cooling of the shoe or the wheel. In those from initial speeds of 40 and 50 m.p.h. the shoe and the wheel, between the third and fourth stop, were cooled, by means of an air blast, to about the temperature of the air in the laboratory; and in the tests at 60 m.p.h. shoe and wheel were thus cooled between the second and third stops, and again between the fourth and the fifth. No work was done on either the shoe or the wheel between the individual stops of these tests.

After the first few tests of the series all tests on any given shoe were made without removing the shoe from the brake head of the machine, in order to avoid the possibility of disturbing its seat and fit on the wheel. These stop tests were run, in general, in the order in which they are listed in Table 4—starting with the lowest pressure and the lowest speed, maintaining this pressure and increasing the speed to the end of the speed range, and then proceeding to tests at the next higher pressure.

The chart drum of the recording mechanism is geared from the main shaft of the testing machine to travel at a surface speed proportional to the travel of a point on the tread of the test wheel. Barring slippage of the paper, the drum speed and paper travel are the same. Since the paper travel defines the chart length, which in turn enters into the calculation of the mean pull and the coefficient of friction, its accuracy was checked by a supplementary record of wheel revolutions, taken from a revolution counter which was geared to the test wheel. This counter started automatically when the shoe was applied and stopped when the wheel came to rest.

The testing machine, as has been stated, is equipped with a specially designed integrating device* which makes a mark on the pull chart for each 0.6 square inches of area accumulated under the curve of tangential pull. In both the stop tests and the constant speed tests the mean tangential pull was found by measuring this area and dividing by its length. In general the chart area was measured by means of a Coradi rolling planimeter; but the measurement was checked by comparison with the record produced by the automatic integrator.

13. *Method of Conducting Constant Speed Tests.*—As their name implies, the constant speed tests were made with the test wheel kept running at uniform speed, the engine remaining coupled to the revolving unit of the machine and driving the wheel against the frictional pull of the applied test shoe.

In these tests, the shoe and the car wheel having been prepared and mounted as explained in Section 11, the machine was brought up to the desired speed and the shoe was applied at the chosen pressure. With the wheel speed kept constant by manipulation of the engine throttle, the shoe was held in contact with the wheel throughout 190 wheel revolutions; it was then released, while the wheel was kept running at the same speed for 610 revolutions. The shoe was then immediately reapplied to the wheel for another 190 revolutions; and these alternate applications and releases were continued until

*This integrator is described on page 15 of Bulletin No. 135 of the Engineering Experiment Station of the University of Illinois.

ten such applications had been made. These ten applications, with the intervening release periods, constitute what is designated in the report as one constant speed test. Figure 3 is a reproduction of the two end portions and the middle of the record produced during one of these tests.

The cycle of 190 revolutions with the shoe applied followed by 610 with it released is the same as that prescribed by the American Railway Association for making wear tests of brake shoes on chilled iron wheels. It is intended to simulate the conditions which prevail in braking a train on a long down grade, where the shoes are frequently applied, but have to be periodically released in order to control the speed of the train without depleting the air reserve. In the tests the only cooling effect was that obtained by the action of the surrounding air on the shoe and the revolving wheel during the release periods. The air blast referred to in Section 12 was not used.

The application and release according to this cycle were automatically obtained by means of the air cylinder which lowers and raises the lower lever of the testing machine. The electro-pneumatic valve operating this cylinder was connected to a revolving commutator so proportioned and so geared to the machine shaft as to hold the valve open during 190 revolutions of the test wheel, thus applying the shoe, and then to close the valve for 610 revolutions, lifting the lever and releasing the shoe.

The speed of the wheel was controlled by observing a speedometer and manipulating the engine throttle. In order to provide a means of determining the uniformity of the speed, a time record, which appears in Fig. 3, was drawn on the pull chart by an electrically-operated pen actuated by a contacting chronometer. The speed variations proved to be generally less than one-half mile per hour, either above or below the desired speed.

In calculating the values of coefficient for each of the ten applications, the initial portion of the record—made while the shoe pressure was building up—was ignored, as was likewise the end of the record, produced during the gradual reduction in pressure preceding the final release. These portions are represented in Fig. 3 by the cross-hatched areas.

The area determinations, as in the stop tests, were generally made by means of a rolling planimeter, although in a few cases they were found by measuring the chart heights. They were all checked by comparison with the record made by the integrator. The paper travel was checked by revolution counter readings, as in the stop tests.

The bulletin presents the results of 202 constant speed tests. They entailed the making of more than 2000 such shoe applications as have been here described.

14. *Method of Conducting Fifteen-Minute Constant Speed Tests.*—These tests, run at the end of the investigation, were made to determine the values of the coefficients of friction under long-continued application of the shoes without any opportunity to cool. They were made in the same way as the constant speed tests, except that the shoe was given only one application to the wheel under any combination of pressure and speed, and that the shoe was kept in continuous contact with the wheel for fifteen minutes—no attempt being made to cool either the shoe or the wheel. They were run only on the two used wheels.

A record of pull was made for the entire test period. This record resembles the pull record of the constant speed test shown in Fig. 3, differing chiefly in that it is much longer. Because of its great length the area of the chart was not planimetered to find the mean pull. Instead, the height of the record was measured at intervals of six inches throughout the length of the chart; and these measurements were averaged to find the mean pull and the coefficient of friction. This six-inch interval corresponds to about 45 revolutions of the test wheel. In such respects as maintaining and checking the wheel speed and checking the chart travel the procedure and precautions were like those used for the constant speed tests.

Twenty-eight of these fifteen-minute tests were made—seven applications at various combinations of pressure and speed, with two shoes of each kind, on each of two wheels.

15. *General Treatment of Wheels and Shoes During Progress of Tests.*—Throughout the entire investigation no attempt was made to clean the wheels nor to modify in any way the character of the wheel tread surface produced by the normal shoe action. Some of the shoes, under heavy pressure, warped on account of the heat developed and, when again cool, failed to fit the wheel—touching it only at the ends of the shoe. In extreme cases the space between the center of the shoe and the wheel tread amounted to as much as 1/32 of an inch. Such shoes, before being used again for a regular test, were given several short applications to the moving wheel in order to restore their fit. The temperature of the shoe and the wheel at the beginning of each test was about the same as the general laboratory temperature.

TABLE 7
SUMMARY OF RESULTS OF STOP TESTS

Brake Shoe Pressure lb.	Speed m.p.h.	Diamond S Shoes										Special Chilled Shoes									
		Chilled Wheels					Steel Wheels					Chilled Wheels					Steel Wheels				
		Test No.	Wheel	Average Stopping Distance ft.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Stopping Distance ft.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Stopping Distance ft.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Stopping Distance ft.	Average Tangential Pull lb.	Average Coefficient of Friction per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
2250	20	2843	A	299.1	608.9	27.06	2883	E	444.1	405.0	18.00	2848	A	310.3	570.4	25.35	2888	E	371.9	507.8	22.57
		3155	C	310.7	595.4	26.46	3131	F	299.6	603.5	26.82	3176	C	290.2	650.7	28.92	3142	F	316.5	598.5	26.60
		3167	C	273.1	686.7	30.52	....	..	.....	.....	.....	....	..	.....	.....	.....	....	..	.....	.....	.....
		Av.	A-C	295.5	625.1	27.78	Av.	E-F	371.9	504.2	22.41	Av.	A-C	300.3	610.7	27.14	Av.	E-F	344.2	553.3	24.59
2250	30	2844	A	673.2	549.5	24.42	2884	E	978.5	370.6	16.47	2849	A	712.0	518.6	23.05	2889	E	913.3	415.6	18.47
		3156	C	752.4	513.9	22.84	3132	F	820.4	462.4	20.55	3175	C	696.8	544.5	24.20	3143	F	873.5	450.0	20.00
		3166	C	658.3	610.4	27.13	3141	F	788.3	499.7	22.21	....	..	.....	.....	.....	....	..	.....	.....	.....
		Av.	A-C	689.3	555.8	24.70	Av.	E-F	891.4	425.9	18.93	Av.	A-C	704.4	531.7	23.63	Av.	E-F	893.4	432.9	19.24
2250	40	2845	A	1282.7	482.0	21.42	2885	E	1869.2	323.1	14.36	2850	A	1492.1	407.7	18.12	2890	E	1809.3	345.4	15.35
		3157	C	1561.3	427.7	19.01	3133	F	1620.5	400.1	17.78	3174	C	1641.8	415.1	18.45	3144	F	1692.2	390.2	17.34
		Av.	A-C	1422.0	455.0	20.22	Av.	E-F	1744.9	361.6	16.07	Av.	A-C	1567.0	411.5	18.29	Av.	E-F	1750.8	367.9	16.35
2250	50	2846	A	2083.5	459.2	20.41	2886	E	3035.4	307.8	13.68	2851	A	2655.0	318.8	14.17	2891	E	3160.6	293.4	13.04
		3158	C	2772.6	365.2	16.23	3134	F	2540.4	395.6	17.58	3173	C	2723.8	378.2	16.81	3145	F	2815.6	360.2	16.01
		3165	C	2654.5	390.0	17.33	....	..	......	.....	.....	....	..	......	.....	.....	....	..	......	.....	.....
		Av.	A-C	2398.5	418.5	18.60	Av.	E-F	2787.9	351.7	15.63	Av.	A-C	2689.4	348.5	15.49	Av.	E-F	2988.1	326.9	14.53
2250	60	2847	A	3147.2	431.3	19.17	2887	E	4349.3	295.7	13.14	2852	A	3940.2	312.1	13.87	2892	E	4551.8	294.1	13.07
		3159	C	3960.7	370.4	16.46	3135	F	3758.3	376.9	16.75	3172	C	3943.6	369.9	16.44	3146	F	4143.2	352.6	15.67
		Av.	A-C	3554.0	401.0	17.82	Av.	E-F	4053.8	336.4	14.95	Av.	A-C	3941.9	341.1	15.16	Av.	E-F	4347.5	323.3	14.37
		Av. of 5 Speeds			491.0	21.82	Av. of 5 Speeds			396.0	17.60	Av. of 5 Speeds			448.7	19.94	Av. of 5 Speeds			401.0	17.82
3000	20	2858	A	250.0	736.2	24.54	2907	E	312.0	555.9	18.53	2853	A	295.7	588.3	19.61	2912	E	287.6	658.5	21.95
		3160	C	246.5	790.8	26.36	3136	F	236.3	776.1	25.87	3181	C	239.7	798.3	26.61	3147	F	254.9	741.9	24.73
		3168	C	210.6	921.0	30.70	....	..	.....	.....	.....	....	..	.....	.....	.....	....	..	.....	.....	.....
		Av.	A-C	239.2	796.2	26.54	Av.	E-F	274.2	666.0	22.20	Av.	A-C	267.7	693.3	23.11	Av.	E-F	271.3	700.2	23.34
3000	30	2859	A	514.6	794.7	26.49	2908	E	763.9	488.4	16.28	2854	A	617.2	626.1	20.87	2913	E	714.3	555.3	18.51
		3161	C	568.4	729.6	24.32	3137	F	607.7	656.1	21.87	3180	C	627.4	629.7	20.99	3148	F	707.3	564.6	18.82
		Av.	A-C	541.5	762.3	25.41	Av.	E-F	685.8	572.4	19.08	Av.	A-C	622.3	627.9	20.93	Av.	E-F	710.8	560.1	18.67
3000	40	2860	A	949.9	762.9	25.43	2909	E	1466.0	447.9	14.93	2855	A	1287.8	491.4	16.38	2914	E	1425.2	466.5	15.55
		3162	C	1314.8	522.9	17.43	3138	F	1347.9	495.9	16.53	3179	C	1372.2	490.8	16.36	3149	F	1407.8	475.8	15.86
		Av.	A-C	1132.4	642.9	21.43	Av.	E-F	1407.0	471.9	15.73	Av.	A-C	1330.0	491.1	16.37	Av.	E-F	1416.5	471.3	15.71
3000	50	2861	A	1607.6	669.0	22.30	2910	E	2309.8	433.5	14.45	2856	A	2185.2	426.3	14.21	2915	E	2370.6	409.5	13.65
		3163	C	2156.3	481.8	16.06	3139	F	2131.1	476.1	15.87	3178	C	2283.0	450.6	15.02	3150	F	2319.3	445.2	14.84
		Av.	A-C	1882.0	575.4	19.18	Av.	E-F	2220.5	454.8	15.16	Av.	A-C	2234.1	438.6	14.62	Av.	E-F	2345.0	427.5	14.25
3000	60	2862	A	2561.0	568.5	18.95	2911	E	3412.6	428.4	14.28	2857	A	3227.3	403.5	13.45	2916	E	3371.7	418.2	13.94
		3164	C	3142.4	471.0	15.70	3140	F	3100.0	461.1	15.37	3177	C	3293.9	450.6	15.02	3151	F	3370.9	435.0	14.50
		Av.	A-C	2851.7	519.9	17.33	Av.	E-F	3256.3	444.9	14.83	Av.	A-C	3260.6	427.2	14.24	Av.	E-F	3371.3	426.6	14.22
		Av. of 5 Speeds			659.4	21.98	Av. of 5 Speeds			522.0	17.40	Av. of 5 Speeds			535.5	17.85	Av. of 5 Speeds			517.2	17.24

TABLE 7 (CONCLUDED)

Brake Shoe Pressure lb.	Speed m.p.h.	Diamond S Shoes										Special Chilled Shoes									
		Chilled Wheels					Steel Wheels					Chilled Wheels					Steel Wheels				
		Test No.	Wheel	Average Stopping Distance ft.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Stopping Distance ft.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Stopping Distance ft.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Stopping Distance ft.	Average Tangential Pull lb.	Average Coefficient of Friction per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
3750	20	2863	A	176.7	1068.0	28.48	2922	E	238.1	823.9	21.97	2868	A	225.8	844.1	22.51	2917	E	236.4	836.3	22.30
		3215	C	196.0	984.8	26.26	3281	F	203.4	953.6	25.43	3226	C	208.0	909.8	24.26	3266	F	239.7	789.0	21.04
		3225	C	178.9	1072.5	28.60	....	..	.....	.....	.....	3231	C	204.6	893.6	23.83	....	..	.....	.....	.....
		Av.	A-C	182.1	1048.5	27.96	Av.	E-F	220.8	888.8	23.70	Av.	A-C	216.1	873.0	23.28	Av.	E-F	238.1	812.6	21.67
3750	30	2864	A	387.9	1030.5	27.48	2923	E	555.3	784.5	20.92	2869	A	484.4	835.1	22.27	2918	E	656.1	613.5	16.36
		3216	C	440.8	955.1	25.47	3282	F	594.2	691.1	18.43	3227	C	465.7	859.1	22.91	3267	F	613.6	644.6	17.19
		Av.	A-C	414.4	993.0	26.48	Av.	E-F	574.8	738.0	19.68	Av.	A-C	475.1	847.1	22.59	Av.	E-F	634.9	629.3	16.78
3750	40	2865	A	781.8	904.1	24.11	2924	E	1151.4	585.8	15.62	2870	A	1058.5	655.1	17.47	2919	E	1199.2	576.0	15.36
		3217	C	913.4	739.9	19.73	3283	F	1133.5	629.3	16.78	3228	C	965.6	672.4	17.93	3268	F	1134.3	606.4	16.17
		Av.	A-C	847.6	822.0	21.92	Av.	E-F	1142.5	607.5	16.20	Av.	A-C	1012.1	663.8	17.70	Av.	E-F	1166.8	591.4	15.77
3750	50	2866	A	1318.9	822.4	21.93	2925	E	1895.3	543.8	14.50	2871	A	1898.1	520.5	13.88	2920	E	1911.8	548.6	14.63
		3218	C	1677.8	594.0	15.84	3284	F	1887.2	585.4	15.61	3229	C	1771.9	551.6	14.71	3269	F	1933.6	540.4	14.41
		Av.	A-C	1498.4	708.4	18.89	Av.	E-F	1891.3	564.8	15.06	Av.	A-C	1835.0	536.3	14.30	Av.	E-F	1922.7	544.5	14.52
3750	60	2867	A	2223.1	690.4	18.41	2926	E	2792.1	538.5	14.36	2872	A	2729.1	513.8	13.70	2921	E	2964.2	511.5	13.64
		3219	C	2430.2	592.1	15.79	3285	F	2735.4	587.3	15.66	3230	C	2548.3	547.5	14.60	3270	F	2858.6	510.0	13.60
		Av.	A-C	2326.7	641.3	17.10	Av.	E-F	2763.8	562.9	15.01	Av.	A-C	2638.7	530.6	14.15	Av.	E-F	2911.4	510.8	13.62
		Av. of 5 Speeds			842.6	22.47	Av. of 5 Speeds			672.4	17.93	Av. of 5 Speeds			690.0	18.40	Av. of 5 Speeds			617.6	16.47
4500	20	2878	A	175.0	1047.6	23.28	2898	E	217.3	828.0	18.40	2873	A	202.6	843.8	18.75	2893	E	204.2	910.4	20.23
		....	..	.....	.....	.....	2903	E	.....	896.4	19.92	....	..	.....	.....	.....	....	..	.....	.....	.....
		3220	C	173.8	1102.5	24.50	3276	F	191.6	1020.6	22.68	3232	C	173.8	1067.0	23.71	3271	F	198.3	986.0	21.91
		Av.	A-C	174.4	1075.1	23.89	Av.	E-F	204.5	941.4	20.92	Av.	A-C	188.2	955.4	21.23	Av.	E-F	201.3	948.2	21.07
4500	30	2879	A	381.0	1031.4	22.92	2899	E	474.5	849.2	18.87	2874	A	435.3	895.1	19.89	2894	E	527.5	792.0	17.60
		....	..	.....	.....	.....	2904	E	.....	887.0	19.71	....	..	.....	.....	.....	....	..	.....	.....	.....
		3221	C	404.9	1007.6	22.39	3277	F	515.7	820.4	18.23	3233	C	410.0	960.3	21.34	3272	F	542.7	780.8	17.35
		Av.	A-C	393.0	1019.7	22.66	Av.	E-F	495.1	844.2	18.76	Av.	A-C	422.1	927.9	20.62	Av.	E-F	535.1	786.6	17.48
4500	40	2880	A	691.3	985.1	21.89	2900	E	1008.9	672.3	14.94	2875	A	958.5	688.1	15.29	2895	E	1072.3	644.4	14.32
		3222	C	818.3	839.3	18.65	3278	F	1063.4	663.8	14.75	3234	C	886.0	775.4	17.23	3273	F	1099.7	644.0	14.31
		Av.	A-C	754.8	912.2	20.27	Av.	E-F	1036.2	668.3	14.85	Av.	A-C	922.3	731.7	16.26	Av.	E-F	1086.0	644.4	14.32
4500	50	2881	A	1201.6	898.2	19.96	2901	E	1622.4	631.8	14.04	2876	A	1663.7	581.9	12.93	2896	E	1678.9	634.5	14.10
		3223	C	1405.6	738.0	16.40	3279	F	1605.3	659.3	14.65	3235	C	1540.8	670.1	14.89	3274	F	1742.0	642.6	14.28
		Av.	A-C	1303.6	818.1	18.18	Av.	E-F	1613.9	645.8	14.35	Av.	A-C	1602.3	626.0	13.91	Av.	E-F	1710.5	638.6	14.19
4500	60	2882	A	1949.0	779.0	17.31	2902	E	2437.5	604.8	13.44	2877	A	2408.4	592.2	13.16	2897	E	2604.4	583.7	12.97
		3224	C	2045.0	726.3	16.14	3280	F	2430.7	641.7	14.26	3236	C	2193.9	666.5	14.81	3275	F	2517.7	633.6	14.08
		Av.	A-C	1997.0	752.9	16.73	Av.	E-F	2434.1	623.3	13.85	Av.	A-C	2301.2	629.6	13.99	Av.	E-F	2561.1	608.9	13.53
		Av. of 5 Speeds			915.8	20.35	Av. of 5 Speeds			744.8	16.55	Av. of 5 Speeds			774.0	17.20	Av. of 5 Speeds			725.4	16.12
General Averages		Wheel A		....	....	22.80	Wheel E		....	....	16.12	Wheel A		....	....	17.45	Wheel E		....	....	16.38
		Wheel C		....	....	20.51	Wheel F		....	....	18.62	Wheel C		....	....	19.25	Wheel F		....	....	17.44
		Wheels A-C		....	....	21.65	Wheels E-F		....	....	17.37	Wheels A-C		....	....	18.35	Wheels E-F		....	....	16.91

V. Results of Stop Tests

The results of the first of the three series of tests—the "stop tests"—are presented and discussed in this chapter. In these tests, it will be recalled, the wheel and other rotating parts of the testing machine having first been set in motion and released from the engine, the wheel was allowed to drift down to the desired speed and the brake shoe then applied—gradually bringing the wheel to rest. Five such applications constitute what is here designated as one test. According to the program shown in Table 4 on page 23, these tests were made with both kinds of shoes on all four wheels, each kind being tested on each wheel under four pressures, and, under each pressure, at five speeds.

16. *Tabular Summary of Results.*—All the results of this series of tests are summarized in Table 7, which presents the average values of stopping distance, tangential pull, and coefficient of friction for 169 tests, or 845 "stops." This, because of a few repetitions, is 9 more tests than the number entailed by the program. Such a repetition is illustrated, in the second and third lines of the table, by tests Nos. 3155 and 3167 which were both run with a Diamond S shoe on chilled wheel C under identical combinations of pressure and speed.* These 169 tests comprise

45 tests on the chilled wheels with Diamond S shoes
43 tests on the steel wheels with Diamond S shoes
41 tests on the chilled wheels with Special Chilled shoes
40 tests on the steel wheels with Special Chilled shoes.

The general uniformity among the results of the five stops which constitute a test is illustrated by the following tabulations, which

	First Stop	Second Stop	Third Stop	Fourth Stop	Fifth Stop	Average Coefficient for Test
TEST NO. 3172						
Coefficient of Friction—per cent.	16.80	16.53	16.36	16.36	16.13	16.44
Deviation from the Average Coefficient for the Test—per cent.	+2.19	+0.55	−0.49	−0.49	−1.89	. . . . . .
TEST NO. 3232						
Coefficient of Friction—per cent.	23.69	23.87	23.93	23.16	23.91	23.71
Deviation from the Average Coefficient for the Test—per cent.	−0.08	+0.67	+0.93	−2.32	+0.84	. . . . . .

*In combining the results of these nine pairs of duplicate tests with those of the corresponding test on the other wheel of like kind, their results were averaged before finding the average for the two wheels. For example, the coefficients resulting from the two tests cited are respectively 26.46 and 30.52; and the average coefficient on wheel C is taken as the average of these two values, namely, 28.49. This, when averaged with the coefficient for wheel A (27.06), gives the average 27.78 for the two wheels which is shown in Table 7.

show for two of the stop tests the values of the coefficient of friction produced in the individual stops; and also their percentage deviation from the average value, which is the coefficient for the test itself. Both tests were made with a Special Chilled shoe on the used chilled wheel; test No. 3172, under 2250 pounds shoe pressure at 60 miles per hour, and No. 3232 under 4500 pounds pressure at 20 miles per hour. The uniformity exhibited in these two tests is fairly typical of that for all tests of the series.

The test results are grouped in Table 7 primarily with respect to the four shoe pressures—2250, 3000, 3750, and 4500 pounds. In the two left-hand vertical divisions of the table are presented the results obtained with Diamond S shoes—first on the chilled wheels, and next on the steel wheels. The results obtained with Special Chilled shoes, similarly arranged, appear in the two right-hand vertical divisions. For each of the five speeds at which tests were run under a particular pressure, the values of stopping distance, tangential pull, and coefficient of friction are given for each of the two chilled wheels or each of the two steel wheels; and in the line immediately following appear the average values of these quantities for both wheels of like kind. In the last line for each pressure group the general average values of tangential pull and coefficient are given for both wheels and all five speeds. Three lines of general average values of coefficient of friction appear at the bottom of the table. The first two lines show, for each of the four wheels, the average of all the pertinent values of coefficient in the column above; that is, they show the average, for the individual wheel, of all the coefficients derived with that wheel at all combinations of pressure and speed. The last line gives the corresponding general average coefficient of friction for both chilled wheels or for both steel wheels. In considering Table 7 the wheel designations should be borne in mind. They were as follows:

Wheel A is the new chilled wheel.
Wheel C is the used chilled wheel.
Wheel E is the new steel wheel.
Wheel F is the used steel wheel.

Table 7 presents the results of all but fifteen of the stop tests made during the entire investigation. Eight of these omitted tests were run at speeds or pressures different from those required by the regular program, and the results are not numerous enough to warrant generalizations. Four were run with the shoe specially cooled, or the wheel tread cleaned with sandpaper between individual stops, in order to see if such treatment appreciably affected the resulting

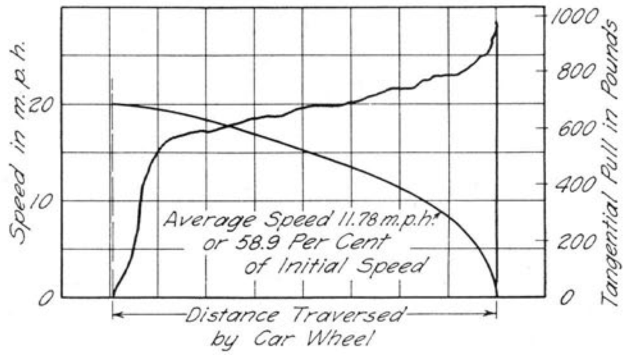


FIG. 10. TANGENTIAL PULL AND SPEED CURVES, DERIVED FROM A STOP TEST AT AN INITIAL SPEED OF TWENTY MILES PER HOUR

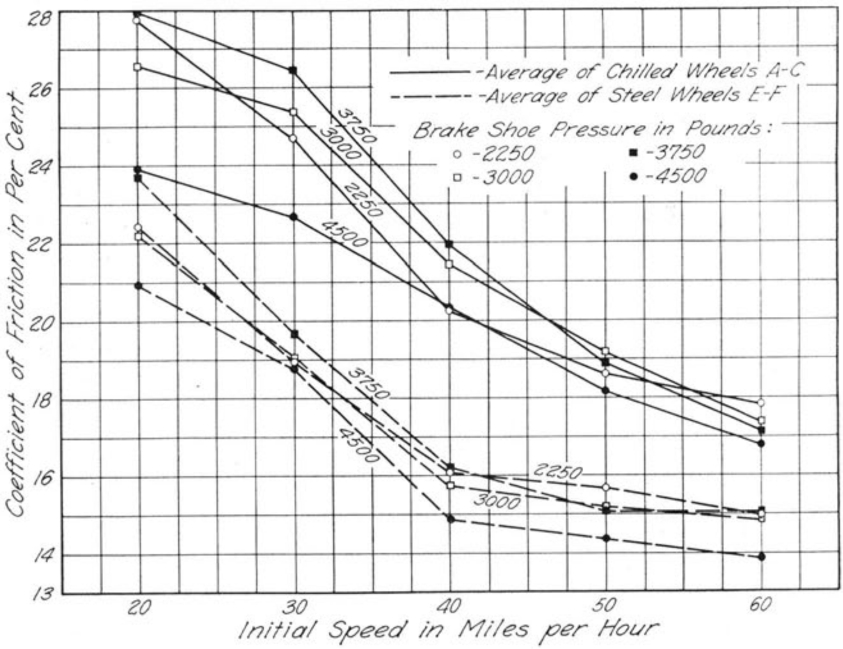


FIG. 11. RELATION BETWEEN COEFFICIENT OF FRICTION AND SPEED, AS DEFINED BY STOP TESTS

For Diamond S Shoes on Both Chilled Wheels and on Both Steel Wheels

coefficient. The results of the remaining three tests are omitted because the wheel tread had become rough.

As has been stated, the "speed" of these stop tests is the initial speed of the wheel at the moment the shoe was applied. This speed,

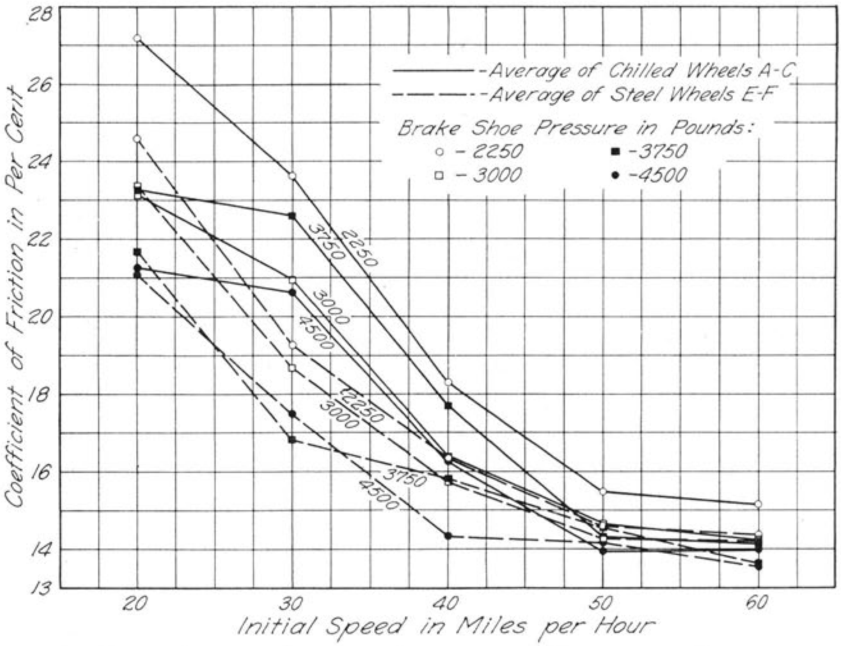


FIG. 12. RELATION BETWEEN COEFFICIENT OF FRICTION AND SPEED, AS DEFINED BY STOP TESTS

For Special Chilled Shoes on Both Chilled Wheels and on Both Steel Wheels

of course, under the shoe action, begins immediately to fall off, as indicated in Fig. 10, which shows, for a test made at a pressure of 2500 lb. and an initial speed of 20 m.p.h., not only the curve of tangential pull, but the speed curve as well. This speed curve has been produced by calculations based upon a record of time intervals drawn upon the test chart; it is thoroughly typical and may be accepted as a general illustration of the variable rate at which the speed decreases during a stop test. In this instance the average speed is 11.78 m.p.h., or 58.9 per cent of the initial speed; and while this percentage will vary with the test conditions, it is always considerably greater than half the initial speed. These well-known facts are here cited in order to make it clear that no direct comparison may be drawn between the value of coefficient of friction determined by means of a stop test and that derived from what is called in this bulletin a "constant speed test," in which the wheel speed was kept the same from the beginning of the application until the end.

17. *Influence of Speed on Coefficient of Friction.*—The way in which the coefficient of friction falls off as the wheel speed is increased

TABLE 8

RELATION BETWEEN COEFFICIENT OF FRICTION AND SPEED AS DEFINED BY STOP TESTS

For both kinds of shoes on both chilled and steel wheels

Kind of Shoes	Kind of Wheels	Initial Wheel Speed m.p.h.	Coefficient of Friction—per cent				
			At Various Shoe Pressures				Average for All Four Shoe Pressures
			2250 lb.	3000 lb.	3750 lb.	4500 lb.	
1	2	3	4	5	6	7	8
Diamond S Shoes	Chilled Wheels A and C	20	27.78	26.54	27.96	23.89	26.54
		30	24.70	25.41	26.48	22.66	24.81
		40	20.22	21.43	21.92	20.27	20.96
		50	18.60	19.18	18.89	18.18	18.71
		60	17.82	17.33	17.10	16.73	17.25
	Steel Wheels E and F	20	22.41	22.20	23.70	20.92	22.31
		30	18.93	19.08	19.68	18.76	19.11
		40	16.07	15.73	16.20	14.85	15.71
		50	15.63	15.16	15.06	14.35	15.05
		60	14.95	14.83	15.01	13.85	14.66
Special Chilled Shoes	Chilled Wheels A and C	20	27.14	23.11	23.28	21.23	23.69
		30	23.63	20.93	22.59	20.62	21.94
		40	18.29	16.37	17.70	16.26	17.16
		50	15.49	14.62	14.30	13.91	14.58
		60	15.16	14.24	14.15	13.99	14.39
	Steel Wheels E and F	20	24.59	23.34	21.67	21.07	22.67
		30	19.24	18.67	16.78	17.48	18.04
		40	16.35	15.71	15.77	14.32	15.54
		50	14.53	14.25	14.52	14.19	14.37
		60	14.37	14.22	13.62	13.53	13.94

is illustrated in Figs. 11 and 12, in which each line shows the decrease for a particular kind of shoe at a particular pressure. The former shows this decrease for Diamond S shoes on both chilled and steel wheels; and the latter, the decrease for Special Chilled shoes on both kinds of wheels. The values plotted in these two figures to define the lines there drawn are the average coefficients for wheels A and C or wheels E and F given in columns 7, 12, 17, and 22 of Table 7. For convenience of further analysis these values are repeated in columns 4, 5, 6, and 7 of Table 8.

The four lines of the upper group in Fig. 11 show the values of the coefficients obtained with Diamond S shoes on the two chilled wheels—one line for each of the four test pressures. With the exception of that applying to 2250 pounds pressure, these lines are approximately alike in slope; or, more strictly speaking, the percentage decrease in coefficient from one speed to the next is nearly the same at all four pressures. This similarity in the rate of decrease is even more marked in the lower group in Fig. 11, applying to Diamond S shoes on steel wheels, and also in both groups in Fig. 12,

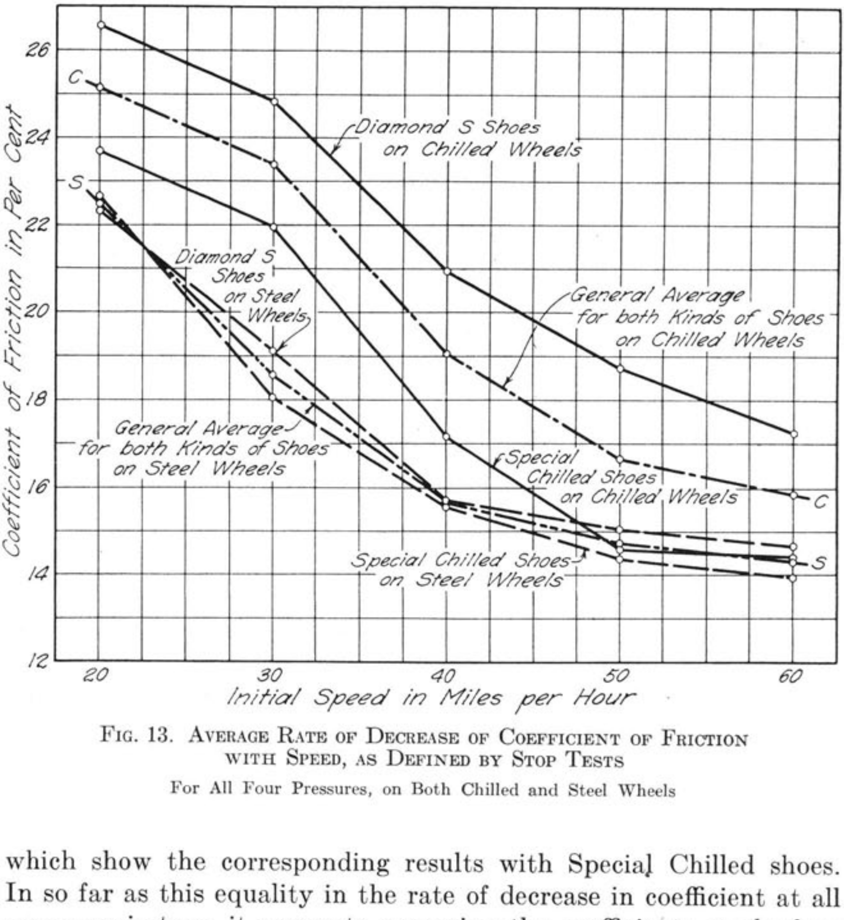


FIG. 13. AVERAGE RATE OF DECREASE OF COEFFICIENT OF FRICTION WITH SPEED, AS DEFINED BY STOP TESTS

For All Four Pressures, on Both Chilled and Steel Wheels

which show the corresponding results with Special Chilled shoes. In so far as this equality in the rate of decrease in coefficient at all pressures is true, it warrants averaging the coefficients at the four pressures in order to define the general influence of speed—in other words, substituting for each group of four lines in Figs. 11 and 12 a single line based on the average values of the coefficient for the four test pressures. The purpose of this discussion—to generalize the influence of speed upon coefficient of friction—will be adequately served by such substitution; and we shall deal therefore with the general average coefficients at all four pressures, instead of with the rates of decrease at individual pressures shown in Figs. 11 and 12, by the process explained in the following paragraphs.

If we average the fundamental test results shown in columns 4 to 7 of Table 8, we obtain the general average values of the coefficient of friction at all four pressures shown in column 8. For example, the value 26.54, in the first line of column 8, is the average of the

TABLE 9

AVERAGE RATE OF DECREASE OF COEFFICIENT OF FRICTION WITH SPEED AS DEFINED BY STOP TESTS

For all four pressures, on chilled and steel wheels.

Kind of Wheels	Initial Wheel Speed m.p.h.	Average Coefficient of Friction for All Four Shoe Pressures			Rate of Decrease of Coefficient with Speed, Expressed in Percentage of Coefficient at 20 Miles per Hour		
		With Diamond S Shoes	With Special Chilled Shoes	Average for Both Kinds of Shoes	With Diamond S Shoes	With Special Chilled Shoes	Average for Both Kinds of Shoes
1	2	3	4	5	6	7	8
Chilled Wheels A and C	20	26.54	23.69	25.12	100	100	100
	30	24.81	21.94	23.38	93	93	93
	40	20.96	17.16	19.06	79	72	76
	50	18.71	14.58	16.65	71	62	66
	60	17.25	14.39	15.82	65	61	63
Steel Wheels E and F	20	22.31	22.67	22.49	100	100	100
	30	19.11	18.04	18.58	86	80	83
	40	15.71	15.54	15.63	70	69	70
	50	15.05	14.37	14.71	67	63	65
	60	14.66	13.94	14.30	66	62	64

four preceding values in this line, and is the general average coefficient obtained with Diamond S shoes on the two chilled wheels. It is therefore the average of the four values plotted in Fig. 11 for the upper group of lines at 20 m.p.h. The four succeeding values in column 8 are the general average coefficients at 30, 40, 50, and 60 m.p.h. These five values of coefficient, with their respective speed values, are plotted in Fig. 13 to define there the upper full line, which represents for Diamond S shoes on chilled wheels the average relation between coefficient and speed for all four shoe pressures; and this line, for the purposes of this discussion, takes the place of the four lines constituting the upper group in Fig. 11. The upper group in Fig. 12 is similarly replaced in Fig. 13 by the second full line there drawn, which is defined by plotting the average values of the coefficient for Special Chilled shoes on chilled wheels given in column 8 of Table 8. In like manner the facts shown in the lower groups of lines in Figs. 11 and 12 are summarized and generalized in Fig. 13 by the two broken lines, which represent the general average relation between coefficient and speed for both kinds of shoes on steel wheels.

Figure 13, thus derived, is accepted as the basis for the attempt to draw general conclusions with respect to the influence of speed upon coefficient of friction. Ignoring for the moment the lines CC and SS, Fig. 13 makes it clear that the rate of decrease in the coefficient with speed is, on the chilled wheels, nearly the same for both Diamond S and Special Chilled shoes. This fact is disclosed not only by the similarity in slope of the two full lines applying to chilled wheels, but can be more specifically shown by establishing the actual ratios between the successive coefficients. For this purpose Table 9 has been prepared. In the upper half of this table, in columns 3 and 4, appear the general average values of coefficient of friction which define the two full lines in Fig. 13—here transposed from column 8 of Table 8. These values for Diamond S shoes on chilled wheels (column 3) are 26.54, 24.81, 20.96, 18.71, and 17.25, at the respective speeds. Taking the coefficient at 20 m.p.h. as the basis of comparison (100 per cent) the coefficients at 30, 40, 50, and 60 m.p.h. are respectively 93, 79, 71, and 65 per cent of the coefficient at 20 m.p.h., as shown in column 6 of Table 9. The corresponding relative values of the coefficients for Special Chilled shoes on chilled wheels, given in column 7, are 100, 93, 72, 62, and 61 per cent. These percentages are so nearly alike as to warrant, for the present purpose, the conclusion that when using either Diamond S or Special Chilled shoes on chilled wheels the rate of decrease in coefficient of friction with increase in speed is almost the same; in other words, that we may establish for chilled wheels the general approximate rate of decrease by averaging the coefficients for both kinds of shoes. This is done in column 5 of Table 9, where the average coefficients of friction for both kinds of shoes on the chilled wheels, at all four pressures, are shown to be 25.12, 23.38, 19.06, 16.65, and 15.82 per cent, for the five successive test speeds respectively. These five coefficient values, with their appropriate speeds, define the line CC of Fig. 13, which is accepted as representing the general average rate of decrease in the coefficient of friction with increase in speed for all the stop tests made on chilled wheels, with both kinds of shoes and at all four shoe pressures. The percentage relations among the coefficients which define this line are shown in the last column of Table 9; they are 100, 93, 76, 66, and 63 per cent for speeds of 20, 30, 40, 50, and 60 miles per hour, respectively. The influence of speed upon the coefficient of friction on chilled wheels is approximately defined by these percentages.

By an exactly analogous treatment of the values of the coefficients for both kinds of shoes on steel wheels, which define the two broken lines in Fig. 13, we derive the general averages represented by the line SS, and the corresponding ratios shown in the lower part of column 8 of Table 9, namely, 100, 83, 70, 65, and 64 per cent; which are accepted as defining the influence of speed upon the coefficient of friction of both kinds of shoes upon steel wheels. It is to be noted that on steel wheels, throughout the speed range, the rate of decrease

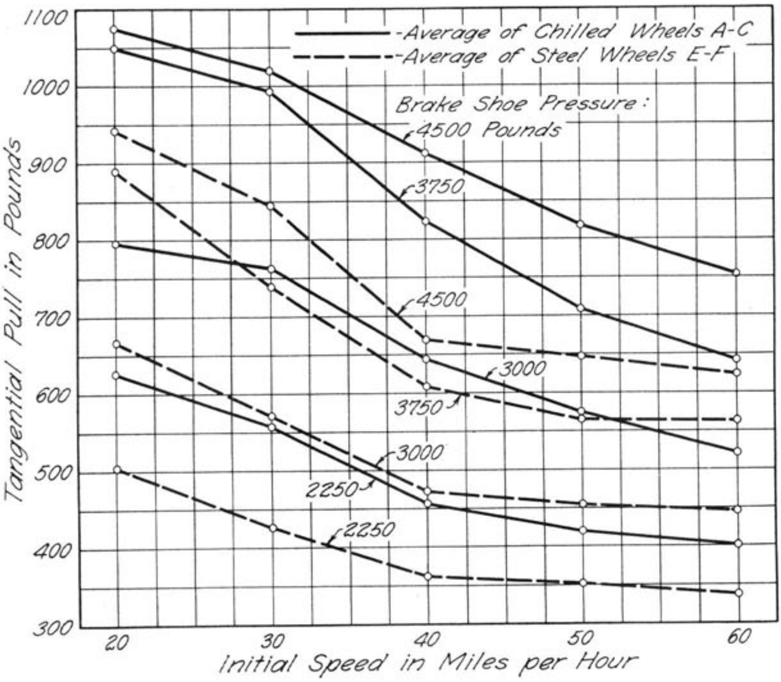


Fig. 14. Relation Between Tangential Pull and Speed, as Defined by Stop Tests

For Diamond S Shoes on Both Chilled Wheels and on Both Steel Wheels

in coefficient is somewhat more uniform, and the performance of the two kinds of shoes more nearly the same than on chilled wheels.

Bearing in mind the fact that the percentage values given in the last column of Table 9 are derived from a substantially equal number of tests made with each kind of shoe on each of two wheels of a kind, under strictly comparable test conditions, it is probable that they define the influence of speed upon coefficient of friction more exactly than it has hitherto been defined by experiments applicable to modern train conditions, notwithstanding the averaging processes which have been resorted to in arriving at these percentages. Such errors as reside in these ratios are probably less than the variations in frictional performance among individual shoes or individual wheels in a train; and if for a particular train equipped with either kind of shoe and, for example, steel wheels, we know the braking force at one speed, we may with considerable confidence undertake to predict that force at another speed by applying the ratios given in Table 9—provided the shoe pressures do not greatly exceed 4500 pounds.

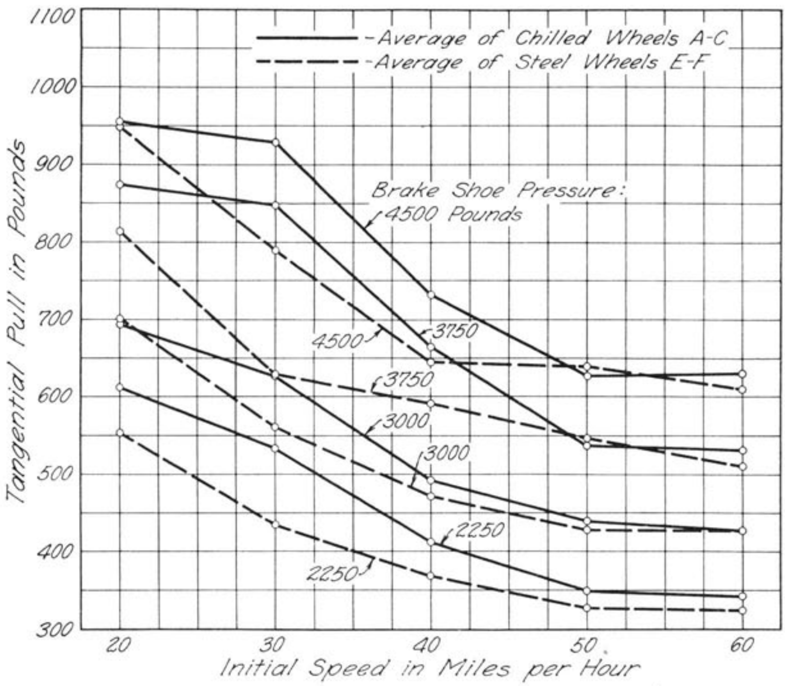


FIG. 15. RELATION BETWEEN TANGENTIAL PULL AND SPEED, AS DEFINED BY STOP TESTS

For Special Chilled Shoes on Both Chilled Wheels and on Both Steel Wheels

18. *Relation Between Tangential Pull and Speed.*—It will be recalled that in all the tests the fundamental measurement made by the testing machine is the retarding force or tangential pull of the brake shoe upon the wheel; and that all values of coefficient of friction are calculated therefrom by dividing this pull by the shoe pressure. The values of tangential pull for the stop tests are presented in columns 6, 11, 16, and 21 of Table 7. These are the mean values of a slightly variable force, as illustrated in Fig. 2 and as explained on page 26. The table shows, in addition to the pull on individual wheels, the average values for both wheels of a kind; and these averages, with their accompanying speed values, are plotted in Figs. 14 and 15; the former showing the results obtained with Diamond S shoes on both chilled and steel wheels, and the latter, those obtained with Special Chilled shoes on both kinds of wheels.

Because of the direct relationship between tangential pull and coefficient of friction, Figs. 14 and 15 convey the same information as that presented by Figs. 11 and 12, and either pair might be easily

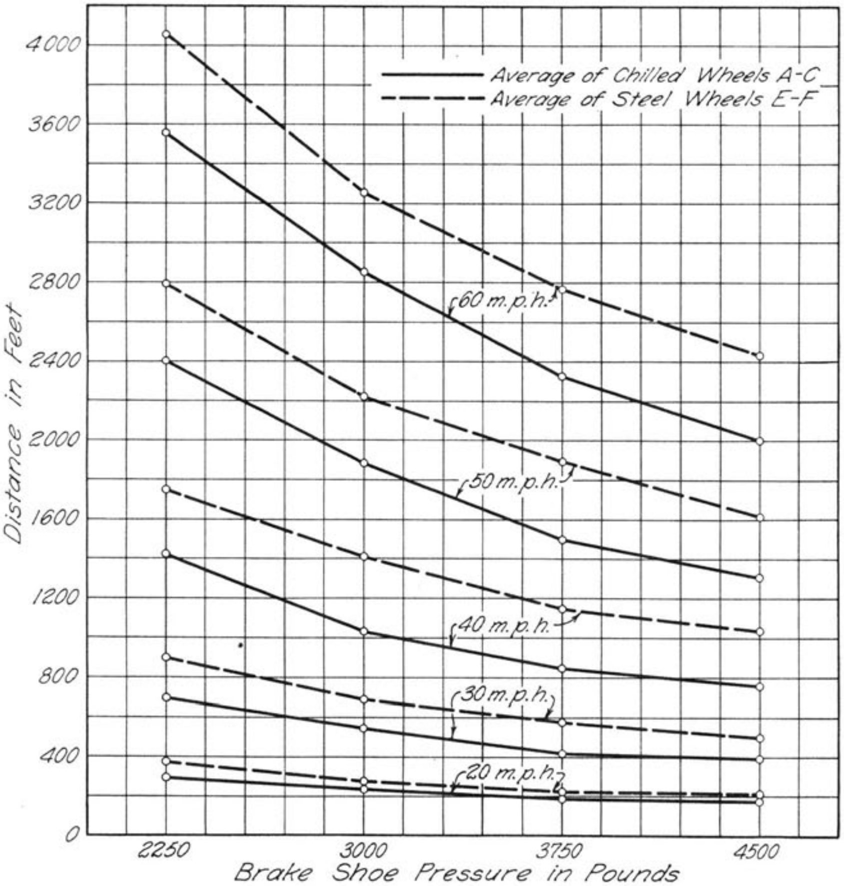


FIG. 16. RELATION BETWEEN STOPPING DISTANCE AND BRAKE SHOE PRESSURE, AS DEFINED BY STOP TESTS

For Diamond S Shoes on Both Chilled Wheels and on Both Steel Wheels

derived from the other. For those practically concerned with the problems of braking and train operation, however, the concept of tangential pull is more directly related to their daily experience, and is one with which they are more accustomed to deal than that of coefficient of friction; and it seems on this account desirable to present the results in terms of this quantity.

Figures 14 and 15 need little comment. Every line there drawn shows a decline in the value of tangential pull as the speed increases; which, of course, is inevitable in view of the fact that the coefficient of friction decreases with speed. The pull exerted, for example, by Diamond S shoes when applied to chilled wheels with a pressure of

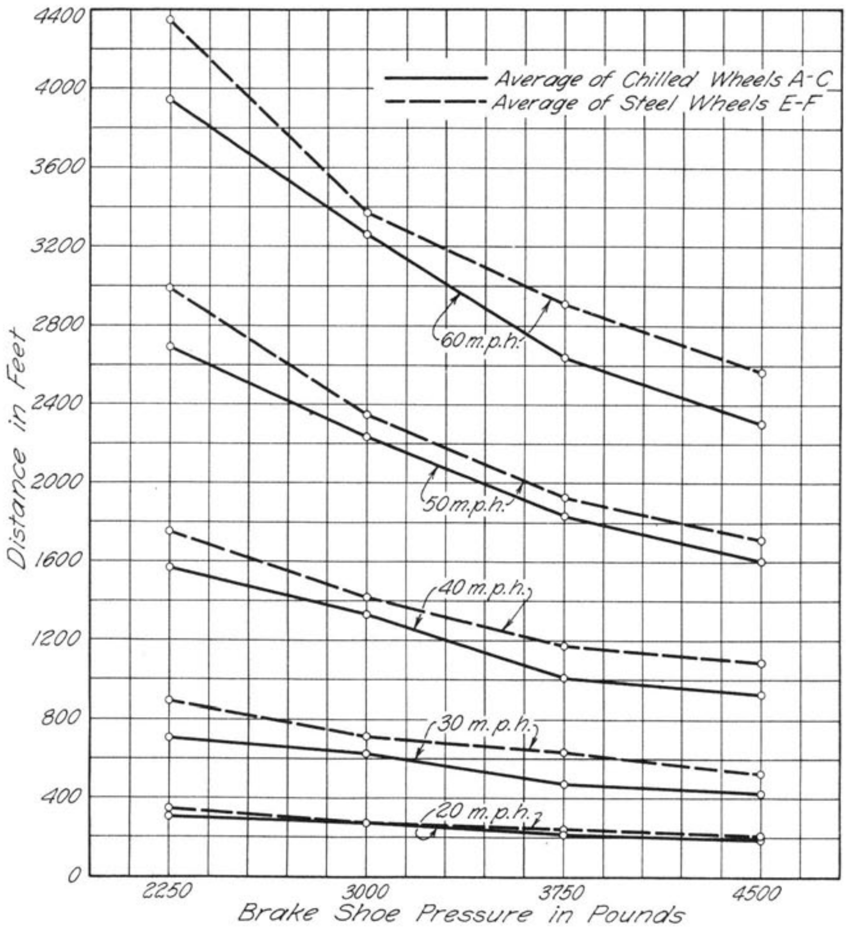


FIG. 17. RELATION BETWEEN STOPPING DISTANCE AND BRAKE SHOE PRESSURE, AS DEFINED BY STOP TESTS

For Special Chilled Shoes on Both Chilled Wheels and on Both Steel Wheels

4500 pounds at an initial speed of 20 miles per hour, is 1075 pounds (Fig. 14); whereas with the same pressure at 60 miles per hour the pull is only 753 pounds.

Another fact deserves brief comment in this connection, namely, that on account of the usual decline in coefficient of friction with increasing shoe pressure, an increase in pressure under like conditions of speed does not always proportionally increase the tangential pull. Figure 15 shows, for example, for Special Chilled shoes on steel wheels at 2250 pounds shoe pressure and 30 miles per hour, a tangential pull

Table 10

Rate of Decrease in Stopping Distance with Increase in Shoe Pressure

For both kinds of shoes on both kinds of wheels.

Kind of Shoes	Kind of Wheels	Initial Wheel Speed m.p.h.	Stopping Distances at Four Shoe Pressures ft.				Relation Between Stopping Distances at Various Pressures, Expressed as Percentages of Distance at 2250 lb. Pressure			
			2250 lb. Pressure	3000 lb. Pressure	3750 lb. Pressure	4500 lb. Pressure	2250 lb. Pressure	3000 lb. Pressure	3750 lb. Pressure	4500 lb. Pressure
1	2	3	4	5	6	7	8	9	10	11
Diamond S Shoes	On Chilled Wheels	20	296	239	182	174	100	80.8	61.5	58.8
		30	689	542	414	393	100	78.7	60.1	57.1
		40	1422	1132	848	755	100	79.6	59.6	53.1
		50	2399	1882	1498	1304	100	78.4	62.4	54.4
		60	3554	2852	2327	1997	100	80.2	65.4	56.2
							Averages	79.5	61.8	55.9
	On Steel Wheels	20	372	274	221	205	100	73.6	59.4	55.1
		30	891	686	575	495	100	77.0	64.6	55.6
		40	1745	1407	1143	1036	100	80.6	65.5	59.3
		50	2788	2221	1891	1614	100	79.7	67.8	57.9
		60	4054	3256	2764	2434	100	80.3	68.2	60.0
							Averages	78.2	65.1	57.6
Special Chilled Shoes	On Chilled Wheels	20	300	268	216	188	100	89.3	72.0	62.7
		30	704	622	475	422	100	88.4	67.5	59.9
		40	1567	1330	1012	922	100	85.0	64.6	58.9
		50	2689	2234	1835	1602	100	83.1	68.2	59.6
		60	3942	3261	2639	2301	100	82.7	66.9	58.4
							Averages	85.7	67.8	59.9
	On Steel Wheels	20	344	271	238	201	100	78.8	69.2	58.4
		30	893	711	635	535	100	79.6	71.1	59.9
		40	1751	1417	1167	1086	100	80.9	66.7	62.0
		50	2988	2345	1923	1711	100	78.5	64.4	57.3
		60	4348	3371	2911	2561	100	77.5	66.9	58.9
							Averages	79.1	67.7	59.3

of 433 pounds. At twice this pressure, 4500 lb., and the same speed, the pull is 787 pounds—not twice, but only 1.82 times as much as at the lower pressure.

19. *Relation Between Stopping Distance and Brake Shoe Pressure.*—The test data include a record of the number of revolutions of the wheel from the moment the shoe was applied until the wheel stopped. From this record has been calculated, for each test, the distance travelled by any point on the wheel tread during the period of the stop; which is analagous to the stopping distance of a train in practical braking problems. These stopping distances are recorded in columns 5, 10, 15, and 20 of Table 7, where values are given for individual wheels and average values for both wheels of a kind. These averages, with the corresponding brake shoe pressures, are plotted in Figs. 16 and 17 to establish the lines which are there drawn to show the relations between stopping distance and shoe pressure. Figure 16 shows the results obtained with Diamond S shoes, and Fig. 17, those obtained with Special Chilled shoes.

The customary and obvious decrease in stopping distance as the shoe pressure is increased is illustrated in both of these figures. Since the energy impressed upon the wheel is always the same provided the initial speed be the same, and since this energy is destroyed during a stop by the tangential pull of the shoe on the wheel, we might expect that stopping distances at any given speed would be exactly inversely proportional to the shoe pressure; and they would be so if the coefficient of friction remained exactly the same. The coefficient, however, changes with pressure—generally decreasing; and on this account the expected proportionality is not exact. This is disclosed by examination of Table 10, which is here introduced to show the actual rates of decrease in stopping distance as the shoe pressure increases.

The stopping distances shown in columns 4 to 7 of Table 10 are transposed from Table 7 and rearranged, the decimals being dropped. The relative values of the successive stopping distances at any given speed are presented in columns 8 to 11, where they are expressed as percentages of the distance at the lowest pressure, 2250 lb., which is taken as the basis of comparison, or 100 per cent. If there were no variation of coefficient of friction with shoe pressure, and the stopping distances were consequently in the inverse ratio of the pressures, the percentages in columns 9, 10, and 11 would be respectively 75, 60, and 50 per cent. The differences between these and the actual percentages shown in the table are an indirect measure of the variation of coefficient with pressure.

It is to be noted that the rates of decrease in stopping distance within any of the four groups of the table do not vary widely from speed to speed; that is, the rates of decrease at 60 miles per hour, for example, are not very different from those at 20 miles. Hasty consideration of the rapidly changing slope of the lines in Figs. 16 and 17 in passing from one speed to another might lead to an opposite and incorrect conclusion.

20. *Variations of Coefficient of Friction with Shoe Pressure.*—In Table 7, for each combination of shoe and wheel, the values of coefficient of friction are presented for each speed in each of the four pressure groups—first the values for the individual wheels, then an average value for each pair of wheels, and finally, at the end of each pressure group, a general average value for all five speeds of that group. These values of the coefficient of friction can be arranged with respect to shoe pressure in order to study its influence upon the coefficient. To do so graphically would result in a diagram comprising 20 lines, many of them superimposed, which would be more con-

TABLE 11
RATES OF VARIATION OF COEFFICIENT OF FRICTION WITH SHOE PRESSURE IN STOP TESTS

Kind of Wheels	Kind of Shoes	Initial Wheel Speed m.p.h.	Relative Magnitudes of Coefficients of Friction at Four Shoe Pressures, Expressed, for Each Speed, as Percentages of Coefficient at 2250 lb. Shoe Pressures and at That Speed			
			2250 lb. Pressure	3000 lb. Pressure	3750 lb. Pressure	4500 lb. Pressure
1	2	3	4	5	6	7
On Chilled Wheels	Diamond S Shoes	20	100	95.5	100.6	86.0
		30	100	102.8	107.2	91.7
		40	100	106.0	108.4	100.2
		50	100	103.1	101.5	97.8
		60	100	97.3	96.0	93.9
	Av. for 5 Speeds		100	100.7	103.0	93.3
	Special Chilled Shoes	20	100	85.2	85.8	78.2
		30	100	88.6	95.6	87.2
		40	100	89.4	96.8	88.8
		50	100	94.4	92.3	89.8
		60	100	94.0	93.4	92.3
	Av. for 5 Speeds		100	89.5	92.3	86.2
On Steel Wheels	Diamond S Shoes	20	100	99.1	105.7	93.3
		30	100	100.8	104.0	99.1
		40	100	98.0	100.8	92.4
		50	100	96.9	96.3	91.8
		60	100	99.2	100.4	92.6
	Av. for 5 Speeds		100	98.9	101.9	94.0
	Special Chilled Shoes	20	100	94.9	88.1	85.6
		30	100	96.9	87.2	90.8
		40	100	96.1	96.4	87.6
		50	100	98.0	99.9	97.6
		60	100	99.0	94.8	94.2
	Av. for 5 Speeds		100	96.8	92.4	90.5

fusing than helpful. Such confusion can be avoided, however, by arranging the data in tabular form, and Table 11 is presented for this purpose.

Table 11 is based upon the average coefficients shown in Table 7 for both wheels of a kind—for the two chilled wheels, A and C, or the two steel wheels, E and F. Since in studying the influence of pressure we are concerned, not with the actual coefficients at various pressures, but with their relative magnitudes, Table 11 (in columns 4 to 7) presents these magnitudes expressed as percentages of the coefficient at the lowest test pressure—2250 lb. The first line of the table, for example, relates to the performance of Diamond S shoes on chilled wheels at 20 miles per hour; and the coefficients (from column 7 of Table 7) for these conditions are 27.78, 26.54, 27.96, and 23.89 for shoe pressures of 2250, 3000, 3750, and 4500 pounds, respectively. Using the coefficient at 2250 lb. as the basis of comparison (100 per cent), the coefficients at 3000, 3750, and 4500 pounds pressure are respectively 95.5, 100.6, and 86.0 per cent of the coefficient at the lowest pressure. The other percentages in the table show the relative

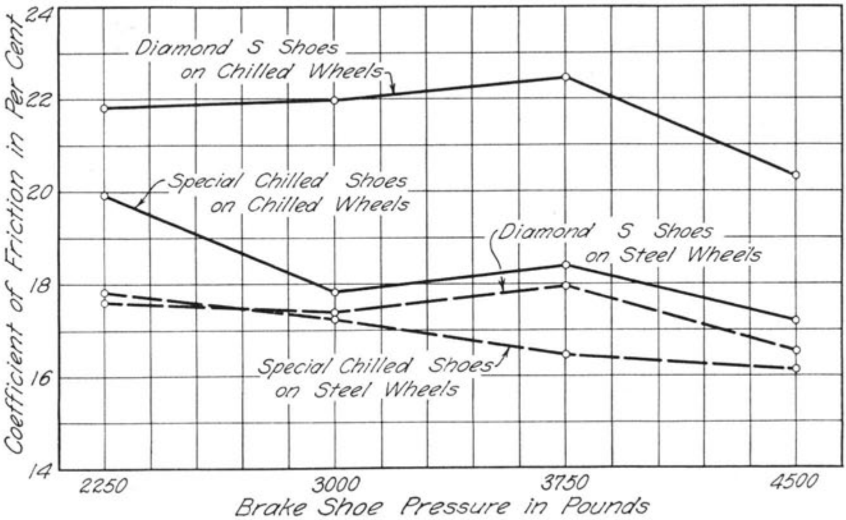


FIG. 18. AVERAGE RATE OF VARIATION OF COEFFICIENT OF FRICTION WITH BRAKE SHOE PRESSURE, AS DEFINED BY STOP TESTS

For All Five Speeds, on Both Chilled and Steel Wheels

magnitudes of the coefficients at other speeds and for other combinations of shoe and wheel. Examination of Table 11 discloses the following facts.

Ignoring temporarily the four lines of general average percentages, and first considering the results for Diamond S shoes, it is to be noted that neither on chilled nor on steel wheels do these shoes show a regular decrease in coefficient of friction as the shoe pressure is increased; indeed, at the two intermediate pressures there is frequently an increase instead of a decrease. On the chilled wheels this tendency shows itself at both 3000 and 3750 pounds pressure; while on the steel wheels the rise in coefficient is chiefly observable in passing from 3000 to 3750 pounds. At the highest pressure, however, there is with Diamond S shoes a decided drop in coefficient on both kinds of wheels.

The drop in coefficient with increase in pressure is more clearly exhibited by the performance of the Special Chilled shoes. With these shoes on chilled wheels the tendency to rise in passing from 3000 to 3750 pounds shows itself only in the first three speeds; otherwise there is a regular decline in the coefficient. On the steel wheels the performance of Special Chilled shoes shows a nearly uninterrupted decline with pressure increase—the only exceptions of consequence occur at 50 m.p.h., where there is a slight rise in passing to 3750 pounds pressure, and at 30 m.p.h., in passing to 4500 pounds.

At the end of each pressure group in Table 7 is given the general average value of the coefficient of friction for all five speeds of the group. These averages are plotted in Fig. 18 to define the four lines there drawn to show the general relations between coefficient and shoe pressure; and the "averages for 5 speeds" shown in Table 11 give the percentage relationships between these average values of the coefficient. These percentages and the lines in Fig. 18 serve only to emphasize the relations between coefficient and pressure which have been pointed out in the preceding paragraphs; thus generalized, however, they are more easily followed. In concluding this section, it ought to be added that the somewhat more unvarying decline of coefficient with pressure disclosed by previous experiments occurs at pressures beyond the maximum pressure used in these tests.

21. *Difference in Performance of Diamond S and Special Chilled Shoes.*—All the 169 stop tests fall into 80 pairs of tests, in each of which the conditions as regards wheel, shoe pressure and speed are identical, the only difference being that one test of the pair was made with a Diamond S shoe, while the other was made with a Special Chilled shoe. In 68 of these 80 pairs the coefficient of friction produced by Diamond S shoes was greater than that produced by Special Chilled shoes. When we deal with the average values of the coefficient on both wheels of like kind, the values fall into 40 comparable pairs, of which all but five show a greater coefficient with Diamond S shoes. These five exceptions all occur in tests on steel wheels. There is nothing unexpected in this relationship between the two kinds of shoes; previous tests of modern brake shoes in this laboratory and elsewhere have repeatedly shown the superiority of Diamond S shoes over various types of plain cast iron shoes.

Table 12 exhibits more specifically the differences above referred to. It presents, for the various combinations of pressure and speed, the average coefficients of friction on two wheels of like kind obtained with each kind of brake shoe; first for the tests on chilled wheels, in columns 3 and 4, and then for the tests on steel wheels, in columns 6 and 7. The percentages* by which the various coefficients produced by Diamond S shoes exceed those produced by Special Chilled shoes are shown in columns 5 and 8.

---

*The values in columns 5 and 8 are not the mere numerical differences between the coefficients (which are themselves expressed as percentages); but percentages representing the ratio of this difference to the smaller of the two comparable coefficients.

TABLE 12

DIFFERENCES BETWEEN COEFFICIENTS OF FRICTION PRODUCED IN STOP TESTS BY DIAMOND S SHOES AND BY SPECIAL CHILLED SHOES

Shoe Pressure lb.	Initial Wheel Speed m.p.h.	On Chilled Wheels A and C: Average Coefficient on Both Wheels per cent: With Diamond S Shoes	With Special Chilled Shoes	Excess of Coefficient for Diamond S Shoes, over that for Special Chilled Shoes per cent	On Steel Wheels E and F: Average Coefficient on Both Wheels per cent: With Diamond S Shoes	With Special Chilled Shoes	Excess of Coefficient for Diamond S Shoes, over that for Special Chilled Shoes per cent
1	2	3	4	5	6	7	8
2250	20	27.78	27.14	2.4	22.41	24.59	9.7*
	30	24.70	23.63	4.5	18.93	19.24	1.6*
	40	20.22	18.29	10.6	16.07	16.35	1.7*
	50	18.60	15.49	20.1	15.63	14.53	7.6
	60	17.82	15.16	17.6	14.95	14.37	4.0
Av. for 5 Speeds		21.82	19.94	9.4	17.60	17.82	1.3*
3000	20	26.54	23.11	14.8	22.20	23.34	5.1*
	30	25.41	20.93	21.4	19.08	18.67	2.2
	40	21.43	16.37	30.9	15.73	15.71	0.1
	50	19.18	14.62	31.2	15.16	14.25	6.4
	60	17.33	14.24	21.7	14.83	14.22	4.3
Av. for 5 Speeds		21.98	17.85	23.1	17.40	17.24	0.9
3750	20	27.96	23.28	20.1	23.70	21.67	9.4
	30	26.48	22.59	17.2	19.68	16.78	17.3
	40	21.92	17.70	23.8	16.20	15.77	2.7
	50	18.89	14.30	32.1	15.06	14.52	3.7
	60	17.10	14.15	20.8	15.01	13.62	10.2
Av. for 5 Speeds		22.47	18.40	22.1	17.93	16.47	8.9
4500	20	23.89	21.23	12.5	20.92	21.07	0.7*
	30	22.66	20.62	9.9	18.76	17.48	7.3
	40	20.27	16.26	24.7	14.85	14.32	3.7
	50	18.18	13.91	30.7	14.35	14.19	1.1
	60	16.73	13.99	19.6	13.85	13.53	2.4
Av. for 5 Speeds		20.35	17.20	18.3	16.55	16.12	2.7

*The asterisks in column 8 indicate those instances in which the coefficient for the Special Chilled Shoe is greater than that for the Diamond S Shoe; and the value shown is the percentage excess of the former over the latter.

The table shows that in some instances the excess of the coefficient for Diamond S shoes is more than thirty per cent. There is no apparent regularity in the variations in this excess. They appear to bear no very definite relation to either pressure or speed; although most of the highest excesses occur, in the various pressure groups, at speeds of either 40 or 50 miles per hour.

The most noteworthy fact disclosed by Table 12 is that the superiority of Diamond S shoes is much more marked on chilled wheels than on steel wheels. As previously remarked, the five instances in which Special Chilled shoes produced the larger coefficient all occur in tests on steel wheels; and in all but one of the remaining tests on steel wheels the excess in the coefficient for Diamond S shoes is markedly less than on chilled wheels, at corresponding pressures and speeds.

TABLE 13

DIFFERENCES IN PERFORMANCE OF BRAKE SHOES ON NEW AND USED WHEELS AND ON CHILLED AND STEEL WHEELS IN STOP TESTS

Based on general average values of the coefficients of friction at all speeds and all pressures

Kind of Shoes	Coefficients of Friction—per cent General Average Values at All Speeds and Pressures				Percentage Excess of One Coefficient over the Other, in Comparable Pairs of Values in Columns 2 to 5			
	Chilled Wheels		Steel Wheels		Chilled Wheels		Steel Wheels	
	New Wheel A	Used Wheel C	New Wheel E	Used Wheel F	New Wheel A	Used Wheel C	New Wheel E	Used Wheel F
1	2	3	4	5	6	7	8	9
Diamond S	22.80	20.51	16.12	18.62	11.2	....	....	15.5
Special Chilled	17.45	19.25	16.38	17.44	....	10.3	....	6.5
Both Kinds of Shoes	20.13	19.88	16.25	18.03	1.3	....	....	11.0
General Average Results for Both New and Used Wheels								
Diamond S	21.65		17.37		24.7		....	
Special Chilled	18.35		16.91		8.5		....	
Both Kinds of Shoes	20.00		17.14		16.7		....	

22. *Difference in Brake Shoe Performance on New Wheels and Used Wheels.*—New and used wheels of each kind were used in the tests, not only because their combined results would better represent service conditions, but because, if there were any marked difference in performance on new and used wheels, the results might be expected to disclose it.

In Table 7, which gives all the results of the stop tests, there are for each of the four combinations of shoes and wheels 20 pairs of tests in which the only difference in conditions is that one test was made with a new wheel and the other with a used wheel. Considering the tests made with Special Chilled shoes on steel wheels, we find that in 15 of the 20 pairs of tests the coefficient of friction was greater on used wheel F than on new wheel E; whereas in the remaining 5 pairs of tests the relation is reversed and the coefficient was greater on the new wheel. In the three other combinations of shoe and wheel there are likewise occasional reversals of the general tendency. The general trend is therefore better disclosed by comparing the general average values of the coefficient at all speeds and pressures than by comparing the results of the numerous separate pairs of tests. These general averages are given at the bottom of Table 7. To facilitate the comparison and discussion they are repeated and rearranged in columns 2 to 5 of the upper part of Table 13.* The general average coefficients produced at all speeds and pressures by Diamond S shoes on new chilled wheel A and on used chilled wheel C are, respectively, 22.80 and 20.51, as shown in columns 2 and 3 in the first line of Table 13. The coefficient on new wheel A is consequently 11.2 per cent greater than that on used wheel C; and this percentage excess is therefore entered under wheel A in column 6. The remaining percentages shown in columns 6 to 9 are similarly derived, and their positions there have a similar significance.

With Diamond S shoes on chilled wheels, as has just been pointed out, the greater coefficient occurs on the new wheel; on the steel wheels, however, this relation is reversed, and the coefficient is 15.5 per cent greater on the used wheel. With Special Chilled shoes there is no such reversal; these shoes produce the larger coefficient on the used wheel with both chilled and steel wheels, the excesses being respectively 10.3 and 6.5 per cent. In three out of four combinations of shoe and wheel, therefore, the greater coefficient is obtained on used wheels. There is nothing in the hardness relations among the four test wheels to account for the variation of the performance of Diamond S shoes on chilled wheels from the general trend; nor has it been feasible otherwise to account for it.

23. *Difference in Brake Shoe Performance on Chilled Wheels and Steel Wheels.*—The tests disclose a notable difference between the results produced on the two kinds of wheels. Both the coefficient of friction and the tangential pull are much greater on the chilled wheels than on the steel wheels under identical conditions of shoe pressure and speed; and this is true for both kinds of shoes. Dealing with average values of coefficient and pull on both new and used wheels of like kind, among 40 pairs of comparable values there are only three pairs in which this relationship is reversed. These exceptions, which are again referred to in this section, all occur in tests with Special Chilled shoes. The magnitude of this excess on chilled wheels is far greater than the slight incidental variations in frictional quality among the test shoes; and the superiority of performance on chilled wheels must be ascribed to differences in the frictional quality of the material constituting the treads of the two kinds of wheels.

From the practical point of view of those responsible for brake design and train operation, this superiority of coefficient and pull obtained on chilled wheels is probably the most important information developed by these tests. While, as was intimated in the Intro-

*The lower part of Table 13 is irrelevant to this purpose. It is used in the discussion in Section 23.

duction, the general facts have been known, the magnitude of the difference has been inadequately appreciated; and only rarely has any attempt been made so to apply these facts in service that each car of a train, whether equipped with chilled or steel wheels, would contribute its proper share to the total braking force required. Except in a few instances, brake leverage has continued to be determined without reference to the important difference in tangential pull which is produced under like shoe pressures on the two kinds of wheels. It is to be hoped that the evidence here again presented will arouse renewed interest in this fact, and lead to some effort to capitalize it in practical train operation.

The general magnitude of the excess of the coefficient of friction on chilled wheels is best exhibited by a comparison of the gross average values of the coefficient on both wheels of like kind at all speeds and pressures. These averages are shown in the lower part of Table 13. With Diamond S shoes the general average coefficient on chilled wheels is 21.65; whereas on steel wheels the coefficient is 17.37—an excess of 24.7 per cent for the chilled wheels. With Special Chilled shoes the average coefficients are 18.35 and 16.91 on chilled and steel wheels, respectively—an excess of 8.5 per cent on chilled wheels. Combining the results obtained with both kinds of shoes, the average on chilled wheels is 20.00 and on steel wheels, 17.14—a difference of 16.7 per cent. In other words, the general average coefficient of friction produced in the 86 stop tests made on the two chilled wheels with both kinds of shoes and under all combinations of shoe pressure and speed, is 16.7 per cent greater than the corresponding average coefficient produced in the 83 tests made on the two steel wheels. The almost invariable occurrence of this excess and its great magnitude, under conditions which differ solely in the kind of wheels used, leave no question as to its reality, nor any ground for doubt that it arises from qualities inherent in the chilled wheel tread.

The general average values cited above have been used with full realization of the objections which may lie against such a gross averaging process if used for making specific predictions. They are not here used for such a purpose, but merely to emphasize the magnitude of the difference in performance on the two kinds of wheels. Specific comparisons and discussion are based on Table 14, and are given in the following paragraphs.

The values of both tangential pull and coefficient of friction are shown, for each of the combinations of speed and shoe pressure, in Table 14. For tests made with Diamond S shoes the values for these quantities are given in columns 3 and 4 or 5 and 6. These values

TABLE 14

EXCESS OF COEFFICIENT OF FRICTION AND TANGENTIAL PULL OBTAINED ON CHILLED WHEELS OVER THOSE OBTAINED ON STEEL WHEELS IN STOP TESTS

Shoe Pressure lb.	Initial Wheel Speed m.p.h.	With Diamond S Shoes: Tangential Pull. Average on Both Wheels of Like Kind lb. On Chilled Wheels A and C	With Diamond S Shoes: Tangential Pull. Average on Both Wheels of Like Kind lb. On Steel Wheels E and F	With Diamond S Shoes: Coefficient of Friction. Average on Both Wheels of Like Kind per cent On Chilled Wheels A and C	With Diamond S Shoes: Coefficient of Friction. Average on Both Wheels of Like Kind per cent On Steel Wheels E and F	With Diamond S Shoes: Excess of Coefficient of Friction (or Tangential Pull) on Chilled Wheels over that on Steel Wheels per cent	With Special Chilled Shoes: Tangential Pull. Average on Both Wheels of Like Kind lb. On Chilled Wheels A and C	With Special Chilled Shoes: Tangential Pull. Average on Both Wheels of Like Kind lb. On Steel Wheels E and F	With Special Chilled Shoes: Coefficient of Friction. Average on Both Wheels of Like Kind per cent On Chilled Wheels A and C	With Special Chilled Shoes: Coefficient of Friction. Average on Both Wheels of Like Kind per cent On Steel Wheels E and F	With Special Chilled Shoes: Excess of Coefficient of Friction (or Tangential Pull) on Chilled Wheels over that on Steel Wheels per cent
1	2	3	4	5	6	7	8	9	10	11	12
2250	20	625	504	27.78	22.41	24.0	611	553	27.14	24.59	10.4
	30	556	426	24.70	18.93	30.5	532	433	23.63	19.24	22.8
	40	455	362	20.22	16.07	25.8	412	368	18.29	16.35	11.9
	50	419	352	18.60	15.63	19.0	349	327	15.49	14.53	6.6
	60	401	336	17.82	14.95	19.2	341	323	15.16	14.37	5.5
Av. for 5 Speeds		...	...	21.82	17.60	24.0	...	...	19.94	17.82	11.9
3000	20	796	666	26.54	22.20	19.6	693	700	23.11	23.34	1.0*
	30	762	572	25.41	19.08	33.2	628	560	20.93	18.67	12.1
	40	643	472	21.43	15.73	36.2	491	471	16.37	15.71	4.2
	50	575	455	19.18	15.16	26.5	439	428	14.62	14.25	2.6
	60	520	445	17.33	14.83	16.9	427	426	14.24	14.22	0.1
Av. for 5 Speeds		...	...	21.98	17.40	26.3	...	...	17.85	17.24	3.5
3750	20	1049	889	27.96	23.70	18.0	873	813	23.28	21.67	7.4
	30	993	738	26.48	19.68	34.6	847	629	22.59	16.78	34.6
	40	822	608	21.92	16.20	35.3	664	591	17.70	15.77	12.2
	50	708	565	18.89	15.06	25.4	536	545	14.30	14.52	1.5*
	60	641	563	17.10	15.01	13.9	531	511	14.15	13.62	3.9
Av. for 5 Speeds		...	...	22.47	17.93	25.3	...	...	18.40	16.47	11.7
4500	20	1075	941	23.89	20.92	14.2	955	948	21.23	21.07	0.8
	30	1020	844	22.66	18.76	20.8	928	787	20.62	17.48	18.0
	40	912	668	20.27	14.85	36.5	732	644	16.26	14.32	13.6
	50	818	646	18.18	14.35	26.7	626	639	13.91	14.19	2.0*
	60	753	623	16.73	13.85	20.8	630	609	13.99	13.53	3.4
Av. for 5 Speeds		...	...	20.35	16.55	23.0	...	...	17.20	16.12	6.7

*The asterisks in column 12 indicate the three instances in which the coefficient is greater on the steel wheels than on the chilled wheels; and the values shown are the percentage excess on the steel wheels.

are the averages of the results obtained, at the indicated speed and pressure, on the new and used chilled wheels, or on the new and used steel wheels. For tests made with Special Chilled shoes the corresponding average values of pull and coefficient are shown in the right-hand half of Table 14—in columns 8 and 9 or 10 and 11. These averages are transcribed directly from Table 7; the values of pull, however, are presented to the nearest full unit only, the decimals shown in Table 7 having been eliminated. Adjacent values in columns 5 and 6 or in columns 10 and 11, since they apply to identical conditions of pressure and speed, may be directly compared to find the difference in performance on the two kinds of wheels. The comparisons drawn in the next four paragraphs are between values of the coefficient of friction. Discussion of the differences in tangential pull appears later.

The first two values in columns 5 and 6 are the average coefficients obtained with Diamond S shoes at 2250 pounds and 20 miles per hour. They are 27.78 on chilled wheels and 22.41 on steel wheels. The excess of the coefficient on chilled wheels is in this instance 24.0 per cent, which is entered in column 7; and the remaining figures in this column present, for Diamond S shoes, the excess of the coefficient on chilled wheels at all other pressures and speeds. For tests with Special Chilled shoes the corresponding percentage excess values appear in column 12. It is to be first observed that with Special Chilled shoes there are three exceptions to the general superiority of the coefficient on chilled wheels. These instances are denoted by the asterisks in column 12; and in all three pairs of tests thus marked the coefficient is greater on steel wheels. The excess varies from 1.0 to 2.0 per cent, and the average excess is only 1.5 per cent. Among the forty pairs of comparable values in the table, these three pairs offer the only exceptions to the general excess of the coefficient on chilled wheels. Because they are so few and so small in amount these exceptions are ignored in the further discussion of the general tendencies disclosed by Table 14.

Recurring to the results with Diamond S shoes, it is to be noted that the percentage excess of the coefficient on chilled wheels varies rather regularly with speed in each pressure group; the excess rises in passing from 20 m.p.h., reaches its maximum at either 30 or 40 m.p.h., and then decreases as we pass to the two higher speeds. The rate of this variation differs somewhat in the four pressure groups; but the general trend is very definitely observable in each group. It may be further noted that the general average excess is very nearly the same in each group, the values being 24.0, 26.3, 25.3, and 23.0 per cent at the four successive shoe pressures.

Among the results obtained with Special Chilled shoes there is observable (see column 12) the same general tendency for the excess of the coefficient on chilled wheels to rise to a maximum and then to decline as the speed increases. With these shoes, however, the maximum excess occurs at 30 m.p.h.; and both its rate of rise and its rate of decline are sharper than with Diamond S shoes. With Special Chilled shoes there is less uniformity among the general average values of the excess in the four pressure groups, which are respectively 11.9, 3.5, 11.7, and 6.7 per cent. Dealing again with the gross overall averages of the excess, which, it will be recalled, are 24.7 per cent with Diamond S shoes and 8.5 per cent with Special Chilled shoes, it may be remarked, in conclusion, that the superiority of performance on chilled wheels is with Special Chilled shoes only about one-third of that obtained with Diamond S shoes.

These coefficient of friction relationships on the two kinds of wheels are exhibited in Figs. 11 and 12. Although these figures were not prepared for this purpose, they disclose the relations between the coefficients presented in columns 5 and 6 and 10 and 11 of Table 14. Figure 13 shows the general average values of the coefficient on chilled and on steel wheels for both kinds of shoes at all four pressures; and, consequently, it also exhibits the general superiority of performance on chilled wheels.

From the fact that the coefficient of friction is obtained by merely dividing the tangential pull by the shoe pressure, it is obvious that the ratios between comparable values of the pull are the same as the ratios between the corresponding coefficients.* It follows, of course, that the percentage excess values of the coefficient in columns 7 and 12 of Table 14 apply equally well to comparisons of the tangential pull; and that whatever has been said about the coefficient of friction relations and excesses on chilled and steel wheels is true also of the tangential pull relations on the two kinds of wheels.

The superiority of shoe performance on the chilled wheels is more striking when the excess is expressed in terms of pull than when it is expressed as the excess of one coefficient over the other. For the practical railroad man it is probably more impressive to be told, for example, that with Diamond S shoes the tangential pull produced at 2250 pounds pressure and 20 miles per hour is 625 pounds on the chilled wheels, and only 504 pounds on the steel wheels (121 pounds less), than to be told that on chilled wheels the coefficient of friction is 24 per cent greater than on steel wheels, although he is receiving the same information in either case.

The excess of the tangential pull on chilled wheels exhibited in Table 14 is also shown graphically in Figs. 14 and 15. The tangential pull values plotted in these figures are the same as those given in columns 3 and 4 or 8 and 9 in Table 14.

VI. Results of Constant Speed Tests

This chapter presents in detail the results of the "constant speed" tests—the second of the three series of tests included in the investigation. The method of making these tests has been described in

*This is strictly true only when the ratios are based upon the exact values of tangential pull given in Table 7.

TABLE 15

SUMMARY OF RESULTS OF CONSTANT SPEED TESTS

Brake Shoe Pressure lb.	Speed m.p.h.	Diamond S Shoes, Chilled Wheels: Test No.	Wheel	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Diamond S Shoes, Steel Wheels: Test No.	Wheel	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Special Chilled Shoes, Chilled Wheels: Test No.	Wheel	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Special Chilled Shoes, Steel Wheels: Test No.	Wheel	Average Tangential Pull lb.	Average Coefficient of Friction per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
500	20	3081	A	182.8	36.56	3038	E	169.4	33.88	3058	A	174.3	34.86	3025	E	158.5	31.70
		....	..	.....	.....	....	..	.....	.....	3078	A	174.5	34.90	3034	E	170.1	34.02
		3203	C	179.7	35.94	3116	F	175.4	35.08	3184	C	177.8	35.56	3099	F	146.5	29.30
		Av.	A-C	181.3	36.25	Av.	E-F	172.4	34.48	Av.	A-C	176.1	35.22	Av.	E-F	155.4	31.08
500	30	3082	A	175.1	35.02	3039	E	139.5	27.90	3059	A	153.3	30.66	3026	E	119.6	23.92
		3204	C	160.9	32.18	3117	F	142.1	28.42	3183	C	130.5	26.10	3100	F	107.6	21.52
		Av.	A-C	168.0	33.60	Av.	E-F	140.8	28.16	Av.	A-C	141.9	28.38	Av.	E-F	113.6	22.72
500	40	3083	A	161.1	32.22	3040	E	122.5	24.50	3060	A	120.9	24.18	3027	E	103.3	20.66
		3205	C	146.4	29.28	3118	F	120.5	24.10	3182	C	119.0	23.80	3101	F	100.9	20.18
		Av.	A-C	153.8	30.75	Av.	E-F	121.5	24.30	Av.	A-C	120.0	23.99	Av.	E-F	102.1	20.42
		Av. of Three Speeds			33.53	Av. of Three Speeds			28.98	Av. of Three Speeds			29.20	Av. of Three Speeds			24.74
1000	20	2932	A	336.0	33.60	2986	E	242.7	24.27	2927	A	306.7	30.67	3024	E	246.5	24 65
		3080	A	338.8	33.88	3010	E	225.5	22.55	3061	A	252.9	25.29	....	....	.....	.....
		....	....	.....	.....	3041	E	227.1	22.71	3067	A	329.3	32.93	....	....	.....	.....
		3202	C	326.4	32.64	3119	F	241.4	24.14	3185	C	257.4	25.74	3095	F	221.9	22.19
		....	....	.....	.....	....	....	.....	.....	3196	C	304.5	30.45	3105	F	229.6	22.96
		Av.	A-C	331.9	33.19	Av.	E-F	236.6	23.66	Av.	A-C	288.7	28.87	Av.	E-F	236.1	23.61
1000	30	2933	A	304.5	30.45	2985	E	204.2	20.42	2928	A	240.5	24.05	3023	E	193.1	19.31
		3084	A	309.8	30.98	2999	E	189.4	18.94	3062	A	206.4	20.64	....	....	.....	.....
		....	....	.....	.....	3042	E	204.0	20.40	3077	A	220.2	22.02	....	....	.....	.....
		3201	C	255.1	25.51	3120	F	199.9	19.99	3186	C	233.7	23.37	3103	F	187.4	18.74
		Av.	A-C	281.1	28.11	Av.	E-F	199.6	19.96	Av.	A-C	228.0	22.80	Av.	E-F	190.3	19.03
1000	40	2934	A	283.6	28.36	2984	E	170.4	17.04	2930	A	205.7	20.57	2998	E	185.3	18.53
		3085	A	274.9	27.49	3011	E	167.5	16.75	3063	A	192.2	19.22	3022	E	182.9	18.29
		....	....	.....	.....	3043	E	194.5	19.45	....	....	.....	.....	....	....	.....	.....
		3200	C	242.1	24.21	3121	F	191.3	19.13	3187	C	194.6	19.46	3104	F	180.6	18.06
		Av.	A-C	260.7	26.07	Av.	E-F	184.4	18.44	Av.	A-C	196.8	19.68	Av.	E-F	182.4	18.24
		Av. of Three Speeds			29.12	Av. of Three Speeds			20.69	Av. of Three Speeds			23.78	Av. of Three Speeds			20.29
1500	20	2942	A	455.9	30.39	2981	E	311.4	20.76	2945	A	350.9	23.39	2978	E	310.2	20.68
		2948	A	514.8	34.32	3009	E	328.1	21.87	3064	A	347.0	23.13	3021	E	336.5	22.43
		3086	A	469.1	31.27	3044	E	323.0	21.53	3076	A	379.7	25.27	....	....	.....	.....
		3206	C	440.9	29.39	3122	F	338.1	22.54	3190	C	380.3	25.35	3106	F	285.5	19.03
		....	....	.....	.....	....	....	.....	.....	....	....	.....	.....	3112	F	319.1	21.27
		Av.	A-C	460.4	30.69	Av.	E-F	329.4	21.96	Av.	A-C	369.6	24.64	Av.	E-F	312.8	20.85
1500	30	2943	A	439.2	29.28	2982	E	257.1	17.14	2946	A	274.7	18.31	2979	E	275.6	18.37
		3087	A	403.5	26.90	3000	E	257.9	17.19	3065	A	287.3	19.15	3019	E	273.5	18.23
		....	....	.....	.....	3015	E	299.3	19.95	....	....	.....	.....	....	....	.....	.....
		....	....	.....	.....	3045	E	296.0	19.73	....	....	.....	.....	....	....	.....	.....
		3207	C	373.1	24.87	3123	F	261.8	17.45	3189	C	288.8	19.25	3107	F	247.6	16.51
		....	....	.....	.....	....	....	.....	.....	3197	C	299.4	19.96	....	....	.....	.....
		Av.	A-C	397.2	26.48	Av.	E-F	269.7	17.98	Av.	A-C	287.6	19.17	Av.	E-F	261.2	17.41

TABLE 15 (CONCLUDED)

		Diamond S Shoes								Special Chilled Shoes							
		Chilled Wheels				Steel Wheels				Chilled Wheels				Steel Wheels			
Brake Shoe Pressure lb.	Speed m.p.h.	Test No.	Wheel	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Wheel	Average Tangential Pull lb.	Average Coefficient of Friction per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1500	40	2944	A	389.1	25.94	2983	E	227.6	15.17	3066	A	262.5	17.50	2980	E	254.3	16.95
		3088	A	379.4	25.29	3001	E	263.4	17.56	....	....	.....	.....	3005	E	225.2	15.01
		....	....	.....	.....	3046	E	275.9	18.39	....	....	.....	.....	3020	E	257.3	17.15
		3208	C	333.6	22.24	3124	F	248.1	16.54	3188	C	260.1	17.34	3108	F	236.0	15.73
		Av.	A-C	359.0	23.93	Av.	E-F	251.9	16.79	Av.	A-C	261.3	17.42	Av.	E-F	240.8	16.05
		Av. of Three Speeds			27.03	Av. of Three Speeds			18.91	Av. of Three Speeds			20.41	Av. of Three Speeds			18.10
2000	20	2950	A	590.8	29.54	2974	E	416.4	20.82	2953	A	469.8	23.49	2977	E	419.0	20.95
		2963	A	590.8	29.54	3008	E	379.8	18.99	2966	A	513.0	25.65	3028	E	426.8	21.34
		3089	A	599.0	29.95	3013	E	435.2	21.76	3068	A	454.0	22.70	....	....	.....	.....
		....	....	.....	.....	3047	E	424.8	21.24	3075	A	428.6	21.43	....	....	.....	.....
		....	....	.....	.....	....	....	.....	.....	3079	A	420.2	21.01	....	....	.....	.....
		3211	C	545.4	27.27	3125	F	415.6	20.78	3191	C	447.2	22.36	3109	F	385.2	19.26
		....	....	.....	.....	....	....	.....	.....	3198	C	447.2	22.36	....	....	.....	.....
		Av.	A-C	569.4	28.47	Av.	E-F	414.8	20.74	Av.	A-C	452.2	22.61	Av.	E-F	404.0	20.20
2000	30	2951	A	511.4	25.57	2973	E	367.2	18.36	2954	A	375.4	18.77	2976	E	354.0	17.70
		2962	A	471.6	23.58	3002	E	342.4	17.12	2965	A	373.6	18.68	3029	E	356.0	17.80
		3090	A	498.2	24.91	3048	E	363.0	18.15	3069	A	378.4	18.92	....	....	.....	.....
		3210	C	439.4	21.97	3126	F	329.8	16.49	3192	C	384.4	19.22	3110	F	319.4	15.97
		Av.	A-C	466.6	23.33	Av.	E-F	343.6	17.18	Av.	A-C	380.2	19.01	Av.	E-F	337.2	16.86
2000	40	2952	A	475.8	23.79	2972	E	344.2	17.21	2955	A	340.0	17.00	2975	E	326.0	16.30
		3091	A	459.4	22.97	3003	E	329.2	16.46	2964	A	358.8	17.94	3004	E	319.2	15.96
		....	....	.....	.....	3014	E	335.6	16.78	3070	A	347.4	17.37	3030	E	331.8	16.59
		....	....	.....	.....	3049	E	341.6	17.08	....	....	.....	.....	....	....	.....	.....
		3209	C	406.6	20.33	3127	F	306.8	15.34	3193	C	339.4	16.97	3111	F	292.4	14.62
		Av.	A-C	437.2	21.86	Av.	E-F	322.2	16.11	Av.	A-C	344.0	17.20	Av.	E-F	309.0	15.45
		Av. of Three Speeds			24.55	Av. of Three Speeds			18.01	Av. of Three Speeds			19.61	Av. of Three Speeds			17.50
2500	20	2958	A	744.8	29.79	2971	E	542.8	21.71	2956	A	576.0	23.04	2969	E	527.5	21.10
		2967	A	727.5	29.10	3007	E	495.3	19.81	3071	A	573.5	22.94	3033	E	524.0	20.96
		3092	A	704.0	28.16	3012	E	510.5	20.42	....	....	.....	.....	....	....	.....	.....
		....	....	.....	.....	3050	E	490.5	19.62	....	....	.....	.....	....	....	.....	.....
		3213	C	607.5	24.30	3128	F	502.0	20.08	3195	C	563.0	22.52	3113	F	449.5	17.98
		Av.	A-C	666.5	26.66	Av.	E-F	506.0	20.24	Av.	A-C	569.0	22.76	Av.	E-F	487.8	19.51
2500	30	2959	A	609.5	24.38	2970	E	428.3	17.13	2957	A	474.3	18.97	2968	E	425.5	17.02
		3093	A	588.5	23.54	3006	E	421.3	16.85	3072	A	443.3	17.73	3031	E	430.0	17.20
		....	....	.....	.....	3051	E	433.0	17.32	3074	A	457.0	18.28	....	....	.....	.....
		3212	C	490.0	19.60	3129	F	406.5	16.26	3194	C	435.8	17.43	3114	F	381.0	15.24
		Av.	A-C	544.5	21.78	Av.	E-F	417.0	16.68	Av.	A-C	447.0	17.88	Av.	E-F	404.5	16.18
		Av. of Two Speeds			24.22	Av. of Two Speeds			18.46	Av. of Two Speeds			20.32	Av. of Two Speeds			17.85
4000	20	2961	A	936.8	23.42	2996	E	650.4	16.26	2960	A	831.2	20.78	2997	E	721.2	18.03
		3094	A	988.8	24.72	3052	E	733.2	18.33	3073	A	804.0	20.10	3032	E	757.6	18.94
		3214	C	826.8	20.67	3130	F	702.0	17.55	3199	C	722.0	18.05	3115	F	656.4	16.41
		Av.	A-C	894.8	22.37	Av.	E-F	696.8	17.42	Av.	A-C	770.0	19.25	Av.	E-F	698.0	17.45
General Averages		Wheel A......		....	29.11	Wheel E......		....	20.95	Wheel A......		....	22.83	Wheel E......		....	20.52
		Wheel C......		....	26.03	Wheel F......		....	20.93	Wheel C......		....	22.35	Wheel F......		....	18.82
		Wheels A-C...		....	27.57	Wheels E-F...		....	20.94	Wheels A-C...		....	22.59	Wheels E-F...		....	19.67

Section 13, on page 27. It will be recalled that each test comprises ten successive applications of the brake shoe, separated by cooling periods, the wheel being kept constantly in motion at the predetermined speed. The shoe pressures and speeds for the series are shown in Table 5. Tests were made under six pressures, ranging from 500 to 4000 pounds and, with all but the two highest pressures, at speeds of 20, 30, and 40 miles per hour. The pressure range and the number of pressures used are greater therefore than in the stop tests; but the range and variety of speeds are smaller.

24. *Tabular Summary of Results.*—All the results of this series are summarized in Table 15, which presents the values of tangential pull and coefficient of friction for 202 tests. The number of tests made with each of the various combinations of shoe and wheel is as follows:

With Diamond S Shoes				With Special Chilled Shoes			
On Chilled Wheels		On Steel Wheels		On Chilled Wheels		On Steel Wheels	
A (new)	C (used)	E (new)	F (used)	A (new)	C (used)	E (new)	F (used)
31	15	42	15	36	18	28	17
46		57		54		45	
103				99			

There were therefore 100 tests on the two chilled wheels and 102 on the steel wheels. With each kind of wheels, roughly twice as many tests were made on the new wheel as on the used wheel. In determining the average values of pull or coefficient for both wheels of like kind, the mean values on the new and on the used wheel, where there had been more than one test under identical conditions of pressure and speed, were first separately found; and the two mean values were then combined to find the average for the two wheels.

The degree of uniformity among the results of the ten applications which together constitute a constant speed test is illustrated in the following tabulation. This gives for each of two tests the value of the coefficient produced in each of the ten applications, and also the percentage deviation of this value from the average for all ten applications, which is the coefficient for the test itself.

In Test No. 3085		In Test No. 3093	
Coefficient of Friction for Each of the Ten Applications per cent	Deviation of Each Coefficient from the Average for All Ten per cent	Coefficient of Friction for Each of the Ten Applications per cent	Deviation of Each Coefficient from the Average for All Ten per cent
27.6	+0.40	24.00	+1.95
28.4	+3.31	23.20	−1.44
29.2	+6.22	23.40	−0.59
27.4	−0.33	23.28	−1.10
28.8	+4.77	23.80	+1.10
27.6	+0.40	23.80	+1.10
26.2	−4.69	22.96	−2.46
27.5	+0.04	24.48	+3.99
26.6	−3.24	23.16	−1.61
25.6	−6.88	23.32	−0.93
Aver. 27.49		Aver. 23.54	

These two tests are fairly typical of the whole series. Both were made with a Diamond S shoe on new chilled wheel A; test No. 3085, under 1000 pounds shoe pressure at 40 miles per hour, and test No. 3093 under 2500 pounds pressure at 30 miles per hour.

In the arrangement of the results in Table 15 the primary division is between tests made with the two kinds of shoes—the left half of the table relating to Diamond S shoes, and the right half to Special Chilled shoes. In each of these main divisions the results are first presented for the tests on chilled wheels, and then for those on steel wheels. In these four vertical divisions, each of which relates to a particular combination of shoe and wheel, the results are grouped with respect to the six shoe pressures—500, 1000, 1500, 2000, 2500, and 4000 pounds; and within each pressure group they are arranged in the order of the speeds. It should be observed that, while at each of the four lower pressures tests were made at 20, 30, and 40 miles per hour, at 2500 pounds only two speeds were used (20 and 30 m.p.h.); and that the tests under 4000 pounds pressure were run at 20 miles per hour only. For each shoe-wheel-pressure-speed combination the values of tangential pull and coefficient of friction are given—first for the new wheel, next for the used wheel; and these are followed by the average values for both wheels. At the end of each pressure group appears the average value of the coefficient for all speeds of that group. At the bottom of the table appear finally the general average values of the coefficient of friction produced on each wheel at all the various combinations of pressure and speed, followed by its overall average value on both wheels of like kind.

In addition to the 202 tests here included, 27 constant speed tests were made under the conditions defined by the program, but rejected

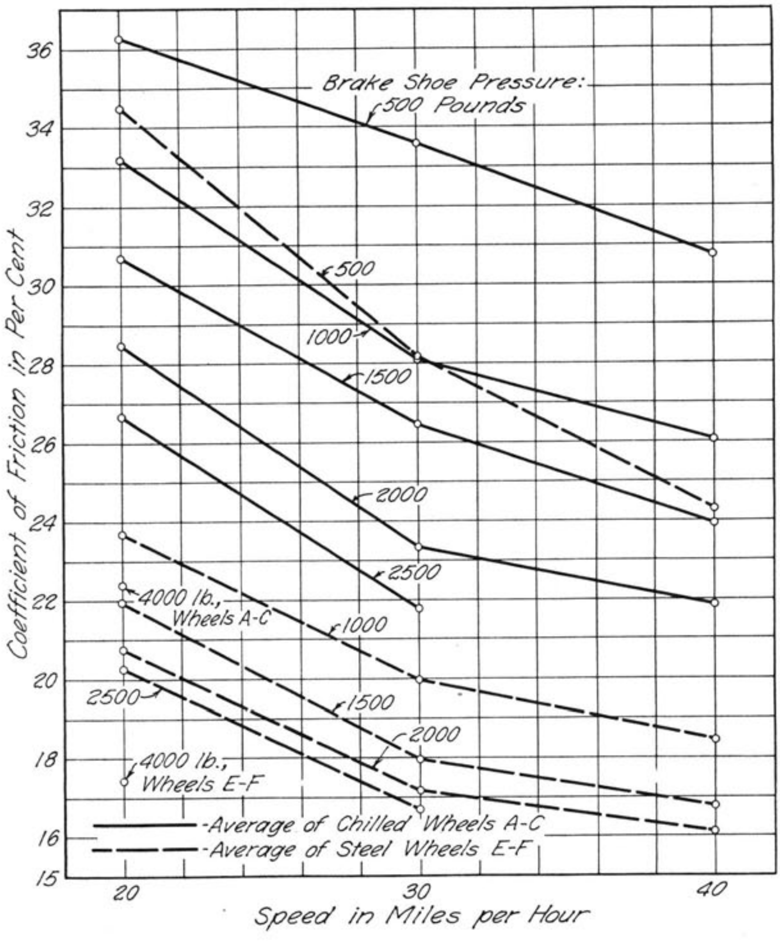


FIG. 19. RELATION BETWEEN COEFFICIENT OF FRICTION AND SPEED, AS DEFINED BY CONSTANT SPEED TESTS

For Diamond S Shoes on Both Chilled Wheels and on Both Steel Wheels

immediately upon their completion because of imperfections in either procedure or test conditions—such as wheel eccentricity or poor shoe fit. The results of 35 other tests are also omitted. These were made under various combinations of speed and pressure other than those of the program, chiefly in order to arrive at decisions with respect to the program limits. While they served that purpose, they are not numerous enough to support additional generalizations.

Since the program for the constant speed tests includes the same variables as that for the stop tests, the results of these tests are

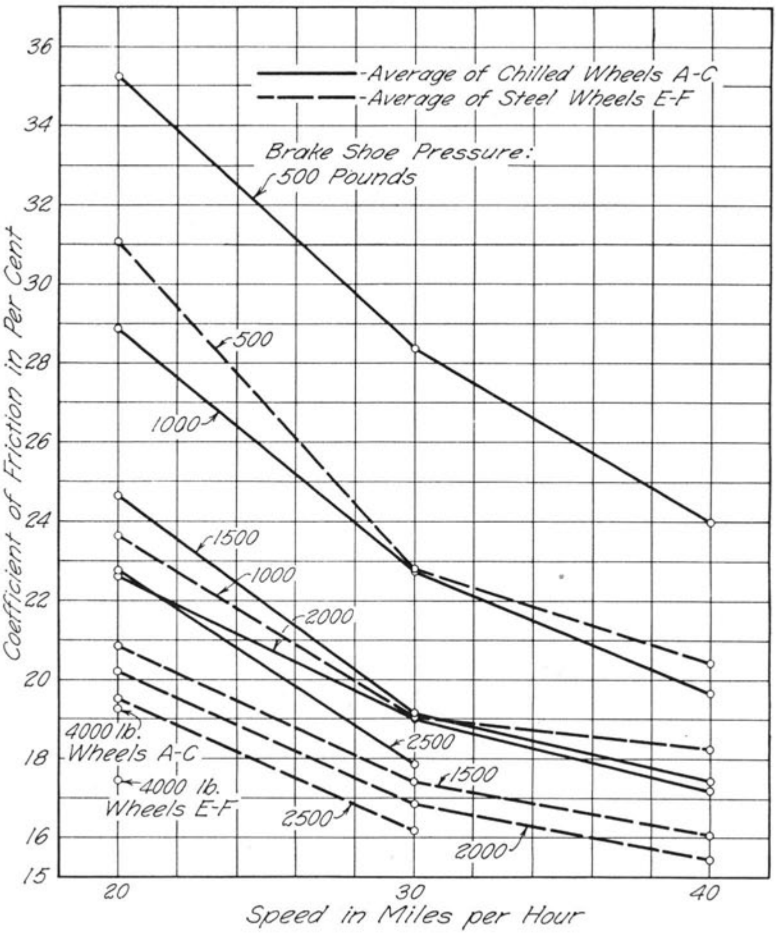


FIG. 20. RELATION BETWEEN COEFFICIENT OF FRICTION AND SPEED, AS DEFINED BY CONSTANT SPEED TESTS

For Special Chilled Shoes on Both Chilled Wheels and on Both Steel Wheels

discussed below on the same bases as were the stop test results in Chapter V. The variations in coefficient of friction and tangential pull with speed and with pressure are first discussed; the difference in the frictional quality of the two kinds of shoes is next presented; and finally the discussion exhibits the difference in performance on new and used wheels, and also on chilled and steel wheels.

Although in the discussion comparisons are occasionally drawn between general tendencies in the two series of tests, it should be emphasized that direct comparisons between the results of individual

TABLE 16

RELATION BETWEEN COEFFICIENT OF FRICTION AND SPEED AS DEFINED BY CONSTANT SPEED TESTS

For both kinds of shoes on both chilled and steel wheels

Kind of Shoes	Kind of Wheels	Wheel Speed m.p.h.	Coefficient of Friction—per cent						
			At Various Shoe Pressures						Average for First Four Shoe Pressures
			500 lb.	1000 lb.	1500 lb.	2000 lb.	2500 lb.	4000 lb.	
1	2	3	4	5	6	7	8	9	10
Diamond S Shoes	Chilled Wheels A and C	20	36.25	33.19	30.69	28.47	26.66	22.37	32.15
		30	33.60	28.11	26.48	23.33	21.78	.....	27.88
		40	30.75	26.07	23.93	21.86	.....	.....	25.65
	Steel Wheels E and F	20	34.48	23.66	21.96	20.74	20.24	17.42	25.21
		30	28.16	19.96	17.98	17.18	16.68	.....	20.82
		40	24.30	18.44	16.79	16.11	.....	.....	18.91
Special Chilled Shoes	Chilled Wheels A and C	20	35.22	28.87	24.64	22.61	22.76	19.25	27.84
		30	28.38	22.80	19.17	19.01	17.88	.....	22.34
		40	23.99	19.68	17.42	17.20	.....	.....	19.57
	Steel Wheels E and F	20	31.08	23.61	20.85	20.20	19.51	17.45	23.94
		30	22.72	19.03	17.41	16.86	16.18	.....	19.01
		40	20.42	18.24	16.05	15.45	.....	.....	17.54

tests or of groups of tests ought not be made, even though they apply to apparently similar conditions; because, not only do the shoe pressures differ in the two series, but (as previously explained) the speeds also have different meanings, even when nominally alike.

25. *Influence of Speed on Coefficient of Friction.*—The basic test results used in discussing the influence of speed on the coefficient of friction are the average values of the coefficient on the two chilled wheels, A and C, and on the two steel wheels, E and F, which are given in Table 15 for the various combinations of shoe and wheel.

These values, with their appropriate speeds, are plotted in Figs. 19 and 20 to define there the lines which show the relations between coefficient and speed. They are also tabulated in columns 4 to 9 of Table 16; and they provide the basis for the general average values of the coefficient and their ratios, which are given in Table 17. This table, in its turn, provides the coordinates for the lines of Fig. 21, which show the relations between speed and the general average coefficients at the first four pressures. Figures 19, 20, and 21 and Tables 16 and 17 are, in their derivation, their meaning, and their function in this discussion, respectively analogous to Figs. 11, 12, and 13 and Tables 8 and 9, which were used in Section 17 in the discussion of the influence of speed on coefficient of friction in the stop tests. The general arguments for that discussion, and the explanation of

TABLE 17

AVERAGE RATE OF DECREASE OF COEFFICIENT OF FRICTION WITH SPEED AS DEFINED BY CONSTANT SPEED TESTS

For four shoe pressures, on chilled and steel wheels

Kind of Wheels	Wheel Speed m.p.h.	Average Coefficient of Friction for Shoe Pressures of 500, 1000, 1500, and 2000 lb.			Rate of Decrease of Coefficient with Speed, Expressed in Percentage of Coefficient at 20 Miles per Hour		
		With Diamond S Shoes	With Special Chilled Shoes	Average for Both Kinds of Shoes	With Diamond S Shoes	With Special Chilled Shoes	Average for Both Kinds of Shoes
1	2	3	4	5	6	7	8
Chilled Wheels A and C	20	32.15	27.84	30.00	100	100	100
	30	27.88	22.34	25.11	87	80	84
	40	25.65	19.57	22.61	80	70	75
Steel Wheels E and F	20	25.21	23.94	24.58	100	100	100
	30	20.82	19.01	19.92	83	79	81
	40	18.91	17.45	18.18	75	73	74

the derivation of these figures and tables and of their relations to one another were there so elaborately set forth that it seems unnecessary here to repeat them in as great detail. The argument for dealing finally with general average coefficients for all shoe pressures applies with even greater force in these tests, because the rates of decline of the coefficient with speed are here more nearly alike at all pressures than in the stop tests.

Figures 19 and 20 represent the basic test results for all combinations of shoe and wheel, the former relating to tests with Diamond S shoes and the latter to tests with Special Chilled shoes. The uppermost line in Fig. 19 represents the results obtained with Diamond S shoes, tested on chilled wheels under 500 pounds shoe pressure, at speeds of 20, 30, and 40 miles per hour; and its slope is a measure of the rate at which, under this pressure, the coefficient of friction declines with increase in speed. The three points defining this line are located by plotting the first three coefficient values shown in column 4 of Table 16, with the appropriate speeds. All other lines in these two figures have a similar significance and are similarly derived by plotting the values of the coefficient given in columns 4 to 9 of Table 16. They fall into four groups—one for each combination of shoe and wheel.

Consideration, within each group, of the lines in Figs. 19 and 20 shows that, despite the approximate parallelism, there is generally a gradual decrease in slope as we go toward the bottom of the figure; and this suggests the inference that the rate of decline in the coefficient with increase in speed is about the same at all pressures. Specific calculation of these rates of decline shows that, with few exceptions, they are actually nearly alike at all pressures. Our purpose in this discussion is to find a general statement for this rate of decrease for the tests made with each combination of shoe and wheel; and, if feasible, a similar generalization for the entire series. The uniformity in the rate of decrease at the various pressures just referred to justifies us, in pursuit of this purpose, in averaging the coefficient values at all pressures, and in dealing thereafter with these averages. These average values of the coefficient are given in column 10 of Table 16 where, for example, the first value, 32.15, is the average of the four coefficients applying to the first four pressures; namely, 36.25, 33.19, 30.69, and 28.47.* The discussion from this point on rests upon the values given in this column.

These average coefficients fall into four groups, each relating to a particular combination of shoe and wheel; and for convenience of comparison and discussion they are transposed to Table 17, where in columns 3 and 4 they are rearranged to correspond with the four wheel-shoe combinations. For Diamond S shoes on chilled wheels these values are 32.15, 27.88, and 25.65 for speeds of 20, 30, and 40 miles per hour, respectively; and for this combination of wheel and shoe they show the general relation between coefficient and speed. The rate of decline of the coefficient as the speed increases through this speed range may be defined by establishing the ratios between these values. Using the coefficient at 20 miles per hour as the basis of comparison, the coefficient at 30 miles is 87 per cent thereof, and that at 40 miles is 80 per cent. These percentages are shown in column 6 of Table 17. For the three other combinations of wheel and shoe the rates of decline in the coefficient with speed are represented by the three other groups of percentages shown in columns 6 and 7; and these two columns may be accepted as defining for the constant speed tests the influence of speed on the coefficient of friction.

The ratios for chilled wheels shown in columns 6 and 7 are nearly enough alike to warrant merging the coefficients for Diamond S and Special Chilled shoes if we desire a generalization for both kinds of shoes on chilled wheels. If we do this we find the general average coefficients to be 30.00, 25.11, and 22.61, as given in column 5; and

*The discussion is limited throughout to the first four pressures, because for the tests at 40 m.p.h. only these four pressures were used. If in finding the average for Diamond S shoes on chilled wheels at 20 m.p.h. given in column 10 of Table 16 we should include the two coefficient values relating to pressures of 2500 and 4000 lb. (columns 8 and 9), they would so lower the general average (32.15) as to make it non-comparable with the average at 40 m.p.h. There is a decrease of the coefficient with pressure as well as with speed, and if this pressure influence were allowed to exert itself more often at one speed than at another, the comparison among the values of column 10 would not show the influence of speed alone, as is desired.

the ratios between these averages are given in column 8. With the two kinds of shoes on steel wheels the similarity in rate of decline of the coefficients as exhibited in columns 6 and 7 is considerably greater than on chilled wheels, and there is, therefore, even better warrant for combining them. Thus combined, they give the average coefficient values shown in the lower part of column 5, and the ratios shown in column 8.

Inspection of column 8 shows that the relative magnitudes of the coefficients of friction obtained with both kinds of shoes on chilled wheels at speeds of 20, 30, and 40 miles per hour are, respectively, 100, 84, and 75 per cent; and that with both kinds of shoes on steel wheels the relative magnitudes are 100, 81, and 74 per cent. Once again these ratios are so nearly alike that, going one step further in generalizing the test results, we may combine the coefficients for both kinds of shoes on both kinds of wheels; that is, we may average for each speed the two coefficient values for that speed given in column 5. This process gives, as the general average values of the coefficient of friction for both kinds of shoes on both kinds of wheels, 27.29, 22.52, and 20.40, which relate respectively to speeds of 20, 30, and 40 miles per hour. The corresponding ratios* which approximately define the rate of decline of the coefficient of friction with speed for the entire constant speed test series are 100, 83† and 75† per cent.

The conclusions with respect to the influence of speed upon the coefficient of friction in the constant speed tests may be summarized thus. For each of the four combinations of shoe and wheel the rate at which the coefficient of friction decreases with increase of speed is defined with considerable accuracy by the four groups of ratios represented by the percentages given in columns 6 and 7 of Table 17. If our purposes are served by greater generalization and less accuracy, we may accept the following percentages as defining the rate of decline of the coefficient with increase in speed:

	Relative Magnitudes of the Coefficients of Friction		
	at 20 m.p.h.	at 30 m.p.h.	at 40 m.p.h.
With both kinds of shoes on chilled wheels	100	84	75
With both kinds of shoes on steel wheels	100	81	74
With both kinds of shoes on both kinds of wheels	100	83	75

*Neither these ratios nor the coefficient values from which they are derived are given in Table 17.
†These values, like all the other ratio percentages, are given to the nearest unit. Their exact values are 82.5 and 74.7.

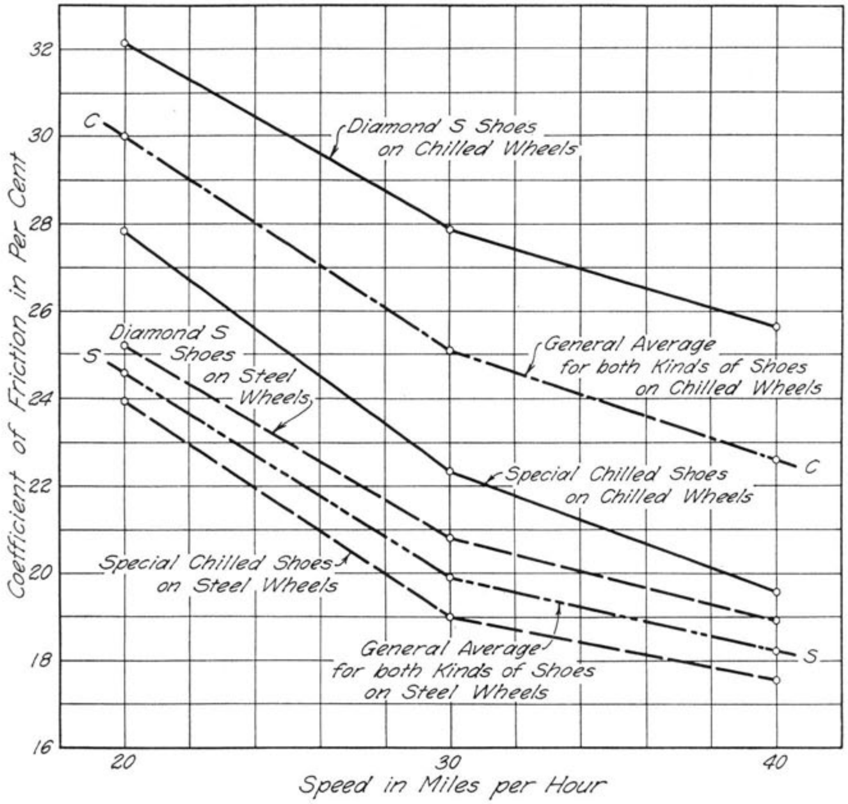


FIG. 21. AVERAGE RATE OF DECREASE OF COEFFICIENT OF FRICTION WITH SPEED, AS DEFINED BY CONSTANT SPEED TESTS

For Pressures of 500, 1000, 1500, and 2000 Pounds, on Both Chilled and Steel Wheels

The general average rates of decline in the coefficient with speed are represented in Fig. 21. The two full lines show the relation between coefficient and speed for each kind of shoe on chilled wheels; they are defined by plotting the values given in columns 3 and 4 of Table 17. The average relation for both kinds of shoes on chilled wheels is represented by the line CC, which is defined by the values in column 5. The two broken lines and the line SS show the corresponding general relations between coefficient and speed for the tests on steel wheels, and they are similarly derived.

26. *Relation Between Tangential Pull and Speed.*—The average values of tangential pull obtained on both wheels of like kind, which are given in columns 5, 9, 13, and 17 of Table 15, are plotted with

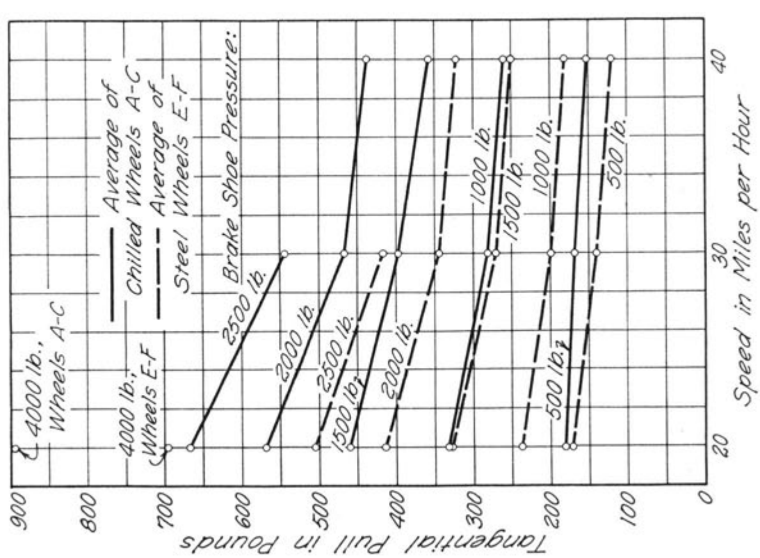


Fig. 22. Relation Between Tangential Pull and Speed, as Defined by Constant Speed Tests

For Diamond S Shoes on Both Chilled Wheels and on Both Steel Wheels

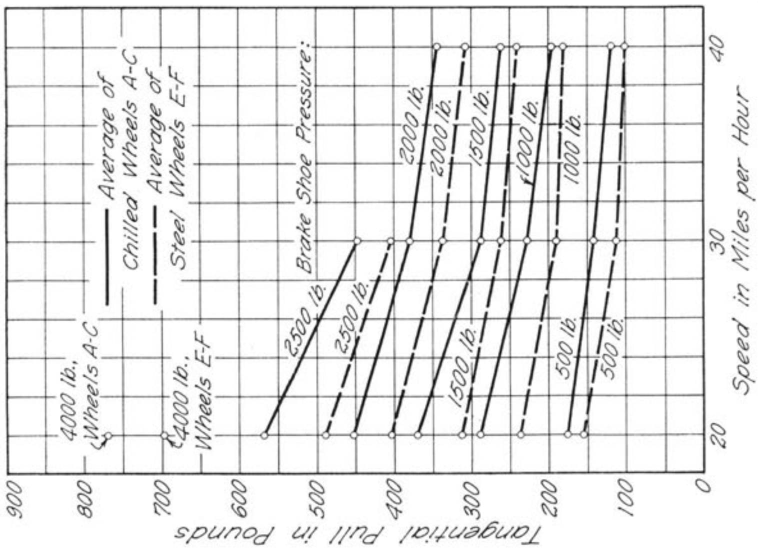


Fig. 23. Relation Between Tangential Pull and Speed, as Defined by Constant Speed Tests

For Special Chilled Shoes on Both Chilled Wheels and on Both Steel Wheels their appropriate speed values to define the lines in Figs. 22 and 23. These lines show, for the various speeds, the relation between tangential pull and speed; those in Fig. 22 for Diamond S shoes when tested on both chilled and steel wheels, and those in Fig. 23 for Special Chilled shoes.

These two figures need no comment, except to point out that among the tests at the successive pressures they exhibit somewhat greater regularity and uniformity in the decrease in tangential pull with speed than are exhibited by Figs. 14 and 15, applying to the stop tests.

27. *Variations of Coefficient of Friction with Shoe Pressure.*—As in the other analyses, we shall again use, in discussing the influence of shoe pressure on the coefficient of friction, the average values of the coefficient on both wheels of like kind. These averages are given, in each of the four divisions of Table 15, for each combination of pressure and speed. Assembling for each combination of shoe and wheel the average coefficient values obtained under the various pressures at any particular speed, we may establish for that speed the influence of pressure. Thus arranged the coefficients exhibit an almost invariable decrease as the pressure decreases. We may define the rate of this decrease by establishing for each coefficient the ratio it bears to the coefficient at the lowest pressure—500 pounds. These ratios have been calculated for successive values of the coefficient at all three speeds for each of the four wheel-shoe combinations; and they are presented in Table 18, where they are expressed as percentages. In this table are given also the corresponding ratios based upon average values of the coefficient for all three speeds at each pressure; these appear in the last line in each group of the table, and they define the general rate of decline of the coefficient for the group. In its purpose and derivation Table 18 is similar to Table 11, which presents the corresponding ratios for the stop tests. If the brief explanation here given of the derivation of Table 18 is not sufficiently clear, it may perhaps become so by reference to the more elaborate explanation of Table 11, given in Section 20.

Table 18 exhibits, as stated, an almost invariable and marked decline in the coefficient of friction as the pressure increases.* The aggregate decrease in passing from 500 to 4000 pounds varies from about forty to about fifty per cent; that is, the coefficient decreases almost by half in passing through that range in pressure.

*There is only one exception. This occurs in the tests at 20 m.p.h. with Special Chilled shoes on chilled wheels, in passing from 2000 lb. pressure to 2500 lb.; here the coefficient increases slightly—from 22.61 to 22.76.

TABLE 18

RATE OF VARIATION OF COEFFICIENT OF FRICTION WITH SHOE PRESSURE IN CONSTANT SPEED TESTS

Kind of Wheels	Kind of Shoes	Wheel Speed m.p.h.	Relative Magnitudes of the Coefficients of Friction at Six Shoe Pressures, Expressed, for Each Speed, as Percentages of Coefficient at 500 lb. Shoe Pressure and at That Speed					
			500 lb. Pressure	1000 lb. Pressure	1500 lb. Pressure	2000 lb. Pressure	2500 lb. Pressure	4000 lb. Pressure
1	2	3	4	5	6	7	8	9
On Chilled Wheels	Diamond S Shoes	20	100	91.6	84.7	78.5	73.5	61.7
		30	100	83.7	78.8	69.4	64.8	....
		40	100	84.8	77.8	71.1	....	....
	Av. for 3 Speeds		100	86.8	80.6	73.2	....	....
	Special Chilled Shoes	20	100	82.0	70.0	64.2	64.6	54.7
		30	100	80.3	67.5	67.0	63.0	....
		40	100	82.0	72.6	71.7	....	....
	Av. for 3 Speeds		100	81.4	69.9	67.2	....	....
On Steel Wheels	Diamond S Shoes	20	100	68.6	63.7	60.2	58.7	50.5
		30	100	70.9	63.8	61.0	59.2	....
		40	100	75.9	69.1	66.3	....	....
	Av. for 3 Speeds		100	71.4	65.3	62.1	....	....
	Special Chilled Shoes	20	100	76.0	67.1	65.0	62.8	56.1
		30	100	83.8	76.6	74.2	71.2	....
		40	100	89.3	78.6	75.7	....	....
	Av. for 3 Speeds		100	82.0	73.2	70.7	....	....

If in any of the four groups we compare the rates of decline in the coefficient at the three speeds, it is to be observed that, with very few exceptions, the decrease from one pressure to the next is approximately the same at the three speeds.

Within each group the general rate of decrease in the coefficient is defined by the last line of ratios, designated as the "average for 3 speeds." For reasons analogous to those stated in the footnote on page 64, in Section 25, these ratios are presented for the four lowest pressures only. They are derived from the average values of the coefficient for all three speeds given in Table 15; and these average coefficients are plotted, for each combination of shoe and wheel in Fig. 24. This figure exhibits, more clearly than the ratios in the table, the general relations between coefficient of friction and pressure. Figure 24 shows that, excepting the tests with Diamond S shoes on steel wheels, there is marked uniformity in the rate of decline of the coefficient with increasing pressure.

Comparison of Figs. 24 and 18 shows that the decline in coefficient with increase in pressure is much greater and more definite in the constant speed tests than in the stop tests; but in this connection it should be remembered that the pressure range of the former lies below that of the latter.

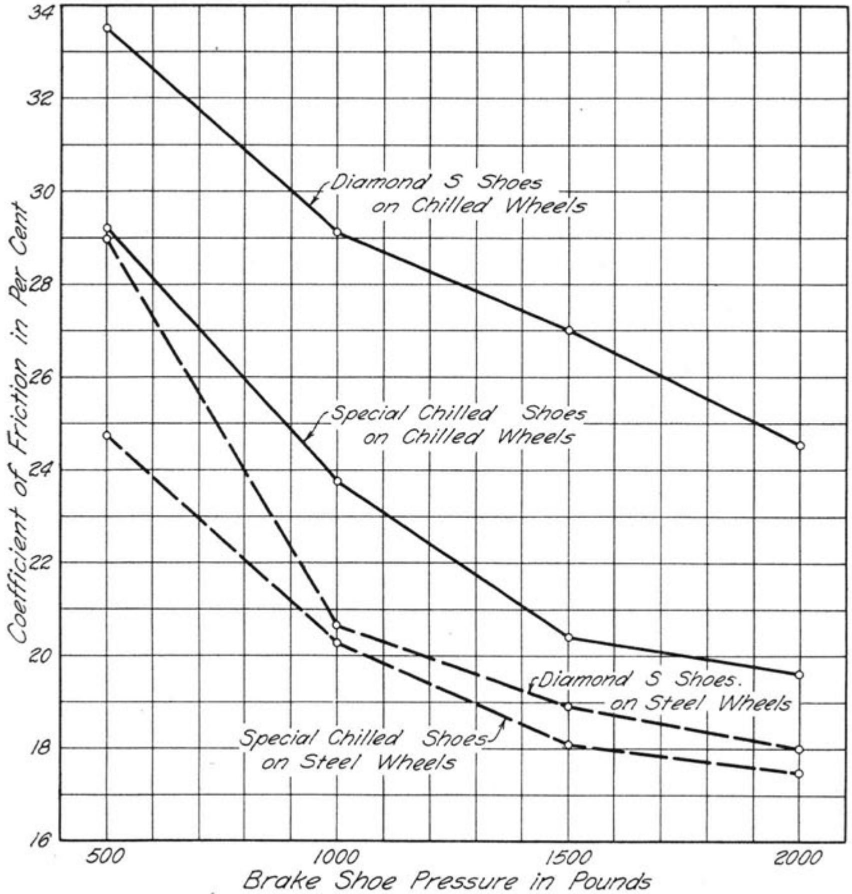


FIG. 24. AVERAGE RATE OF VARIATION OF COEFFICIENT OF FRICTION WITH BRAKE SHOE PRESSURE, AS DEFINED BY CONSTANT SPEED TESTS

For All Three Speeds, on Both Chilled and Steel Wheels

28. *Difference in Performance of Diamond S and Special Chilled Shoes.*—If we average all the coefficient values of the constant speed tests made on both chilled wheels, and also those made on both steel wheels under like conditions of pressure and speed, they fall into 30 pairs; and in each pair the conditions as regards kind of wheel, shoe pressure, and speed are identical, the only difference being that one coefficient for the pair was produced by Diamond S shoes and the other by Special Chilled shoes. These pairs of values consequently provide a basis for determining the difference in performance of the two kinds of shoes. These values of the coefficient of friction are

TABLE 19

DIFFERENCES BETWEEN COEFFICIENTS OF FRICTION PRODUCED IN CONSTANT SPEED TESTS BY DIAMOND S SHOES AND BY SPECIAL CHILLED SHOES

Shoe Pressure lb.	Wheel Speed m.p.h.	On Chilled Wheels A and C			On Steel Wheels E and F		
		Average Coefficient on Both Wheels per cent		Excess of Coefficient for Diamond S Shoes over that for Special Chilled Shoes per cent	Average Coefficient on Both Wheels per cent		Excess of Cofficeient for Diamond S Shoes over that for Special Chilled Shoes per cent
		With Diamond S Shoes	With Special Chilled Shoes		With Diamond S Shoes	With Special Chilled Shoes	
1	2	3	4	5	6	7	8
500	20	36.25	35.22	2.9	34.48	31.08	10.9
	30	33.60	28.38	18.4	28.16	22.72	23.9
	40	30.75	23.99	28.2	24.30	20.42	19.0
Av. for 3 Speeds		33.53	29.20	14.8	28.98	24.74	17.1
1000	20	33.19	28.87	15.0	23.66	23.61	0.2
	30	28.11	22.80	23.3	19.96	19.03	4.9
	40	26.07	19.68	32.5	18.44	18.24	1.1
Av. for 3 Speeds		29.12	23.78	22.5	20.69	20.29	2.0
1500	20	30.69	24.64	24.6	21.96	20.85	5.3
	30	26.48	19.17	38.1	17.98	17.41	3.3
	40	23.93	17.42	37.4	16.79	16.05	4.6
Av. for 3 Speeds		27.03	20.41	32.4	18.91	18.10	4.5
2000	20	28.47	22.61	25.9	20.74	20.20	2.7
	30	23.33	19.01	22.7	17.18	16.86	1.9
	40	21.86	17.20	27.1	16.11	15.45	4.3
Av. for 3 Speeds		24.55	19.61	25.2	18.01	17.50	2.9
2500	20	26.66	22.76	17.1	20.24	19.51	3.7
	30	21.78	17.88	21.8	16.68	16.18	3.1
Av. for 2 Speeds		24.22	20.32	19.2	18.46	17.85	3.4
4000	20	22.37	19.25	16.2	17.42	17.45	0.2*

*In this one instance the greater coefficient is produced by Special Chilled Shoes.

presented in Table 19; those obtained on chilled wheels are given in columns 3 and 4, and those obtained on steel wheels in columns 6 and 7. Adjacent values in either pair of columns are comparable, and their difference is a measure of the difference in performance of the two kinds of shoes.

In all but one* of these pairs the greater coefficient was produced by Diamond S shoes. The excess has been calculated for each pair of values, and is given in column 5 or column 8, where it is expressed as a percentage of the smaller coefficient. The maximum value of this excess is 38.1 per cent. Among the coefficients obtained on chilled wheels the excess (with two exceptions) increases as the speed increases; but among those obtained on steel wheels there is no such regularity in its variation. Except at a shoe pressure of 500 pounds,

*This is the pair pertaining to tests on steel wheels, under 4000 lb. pressure and at 20 m.p.h.

the excess of the coefficients produced by Diamond S shoes is very much greater on chilled wheels than on steel wheels.

29. *Difference in Brake Shoe Performance on New Wheels and Used Wheels.*—The values of the coefficient of friction given in Table 15 may be reduced to 60 pairs in each of which the test conditions are alike, except that one coefficient of the pair was obtained on a new wheel and the other on a used wheel. In 47 of these pairs the coefficient is greater on the new wheels; whereas in the 13 remaining pairs it is greater on the used wheels. Eight of these thirteen exceptions to the prevailing tendency occur in tests made with Diamond S shoes on steel wheels; and the five others occur in tests with Special Chilled shoes on chilled wheels. Among the sixty pairs of tests the excess of one coefficient over the other varies considerably in amount.

The general magnitude of the difference is better disclosed by dealing with the general average values of the coefficient at all speeds and pressures. These general averages are given at the bottom of Table 15 for each of the four combinations of shoe and wheel; and for convenience of comparison they are repeated in columns 2 to 5 in the upper part of Table 20. Comparing these values, it is to be observed that the coefficient produced on the new wheels is greater than that produced on the used wheels in all four combinations of shoe and wheel. The percentage excess varies from a minimum of 0.1 of one per cent with Diamond S shoes on steel wheels to a maximum of 11.8 per cent with Diamond S shoes on chilled wheels. Considering both kinds of shoes together, the general excess on chilled wheels is 7.4 per cent, and on steel wheels, 4.3 per cent. These percentages are shown in the upper part of Table 20, in columns 6 and 8.

30. *Difference in Brake Shoe Performance on Chilled Wheels and Steel Wheels.*—In the discussion, in Section 23, of the difference in the performance of brake shoes on the two kinds of wheels as exhibited in the stop tests, certain observations were made as to the practical importance of this difference and the desirability of giving it adequate recognition in practice. These observations need not be repeated here, although they are equally relevant in this discussion; for if the recognition of this difference is important in the stopping of trains, it is certainly not less important in the problems which arise in checking their speed on long grades by intermittent shoe applications, such as were simulated in the constant speed tests.

The results of the constant speed tests exhibit the same superiority in the coefficient of friction and the tangential pull for chilled wheels

TABLE 20

DIFFERENCES IN PERFORMANCE OF BRAKE SHOES ON NEW AND USED WHEELS AND ON CHILLED AND STEEL WHEELS IN CONSTANT SPEED TESTS

Based on general average values of the coefficients of friction at all speeds and all pressures

Kind of Shoes	Coefficients of Friction—per cent General Average Values at All Speeds and Pressures				Percentage Excess of One Coefficient over the Other, in Comparable Pairs of Values in Columns 2 to 5			
	Chilled Wheels		Steel Wheels		Chilled Wheels		Steel Wheels	
	New Wheel A	Used Wheel C	New Wheel E	Used Wheel F	New Wheel A	Used Wheel C	New Wheel E	Used Wheel F
1	2	3	4	5	6	7	8	9
Diamond S	29.11	26.03	20.95	20.93	11.8	...	0.1	...
Special Chilled	22.83	22.35	20.52	18.82	2.1	...	9.0	...
Both Kinds of Shoes	25.97	24.19	20.74	19.88	7.4	...	4.3	...
	General Average Results for Both New and Used Wheels							
Diamond S	27.57		20.94		31.7		....	
Special Chilled	22.59		19.67		14.8		....	
Both Kinds of Shoes	25.08		20.31		23.5		....	

as was exhibited by the results of the stop tests; indeed the magnitude of the excess for chilled wheels is considerably greater in the constant speed tests. If we compare the values of coefficient or pull given in Table 15, using either the average values obtained on the new chilled wheel and the new steel wheel, or those obtained on the used wheels of each kind, we find that, without any exceptions, the coefficient and the pull produced on chilled wheels are greater than those produced on steel wheels under identical conditions of pressure and speed—whether we deal with the results produced by Diamond S shoes or those produced by Special Chilled shoes. Here again the magnitude of the excess and its invariable occurrence leave no question as to its reality nor any ground for doubt that it arises from qualities inherent in the chilled wheel.

Before proceeding to a more detailed examination of these differences under the individual combinations of pressure and speed, it will be of interest to exhibit their general average magnitudes by comparing the average values of the coefficient of friction at all pressures and speeds on both chilled wheels with the values on both steel wheels. The discussion from here on is presented in terms of coefficient alone, comment on the differences in tangential pull being with-held until the end of the section. The general average values of the coefficient just referred to are given in the last line of Table 15, and they are repeated and rearranged in the lower part of Table 20. For all tests with Diamond S shoes the average coefficient on chilled wheels is 27.57, and on steel wheels 20.94; the coefficient on chilled wheels is therefore 31.7 per cent greater than that on steel wheels. With Special Chilled shoes the corresponding values of the coefficient are 22.59 and 19.67, showing an excess on chilled wheels of 14.8 per cent. If we combine the results produced by both kinds of shoes we obtain as the overall average value of the coefficient on chilled wheels, 25.08, and on steel wheels, 20.31; in this case the excess on chilled wheels is 23.5 per cent. The general magnitude of the difference in performance on the two kinds of wheels is therefore indicated by the fact that in the 100 tests made (with both kinds of shoes at all the various pressures and speeds) on chilled wheels, the general average coefficient of friction is 23.5 per cent greater than in the 102 corresponding tests made on steel wheels. Specific comparisons are based upon the values shown in Table 21, which is explained in the next two paragraphs.

In Table 15, which embodies all the results of the constant speed tests, are given the average values of the coefficient of friction on new and used chilled wheels (A and C) and on new and used steel wheels (E and F), for each kind of shoe and under each combination of pressure and speed. These averages are transferred to Table 21, and there rearranged to permit convenient comparison of the coefficients produced on chilled wheels with those produced on steel wheels. The coefficients obtained with Diamond S shoes appear in columns 5 and 6, and the percentage excess of those produced on chilled wheels over those produced on steel wheels is given in column 7. The coefficients obtained with Special Chilled shoes appear in columns 10 and 11, and the percentage excess on chilled wheels in column 12. In further consideration of this excess attention may be confined to the percentages shown in columns 7 and 12.

Considering first the performance with Diamond S shoes (column 7), it is to be noted that in the tests made under 500 pounds pressure the excess of the coefficient on chilled wheels grows greater as the speed increases; but that under all other pressures the excess remains nearly the same at all speeds. The greatest excesses occur in the tests made under 1500 pounds shoe pressure; and the maximum difference for the entire test series, 47.3 per cent, falls in this group. At the six successive pressures the average excesses for all speeds under each pressure are, respectively, 15.7, 40.7, 42.9, 36.3, 31.2, and 28.4 per

TABLE 21

EXCESS OF COEFFICIENT OF FRICTION AND TANGENTIAL PULL OBTAINED ON CHILLED WHEELS OVER THOSE OBTAINED ON STEEL WHEELS IN CONSTANT SPEED TESTS

Shoe Pressure lb.	Wheel Speed m.p.h.	With Diamond S Shoes					With Special Chilled Shoes				
		Tangential Pull. Average on Both Wheels of Like Kind lb.		Coefficient of Friction. Average on Both Wheels of Like Kind per cent		Excess of Coefficient of Friction (or Tangential Pull) on Chilled Wheels over that on Steel Wheels per cent	Tangential Pull. Average on Both Wheels of Like Kind lb.		Coefficient of Friction. Average on Both Wheels of Like Kind per cent		Excess of Coefficient of Friction (or Tangential Pull) on Chilled Wheels over that on Steel Wheels per cent
		On Chilled Wheels A and C	On Steel Wheels E and F	On Chilled Wheels A and C	On Steel Wheels E and F		On Chilled Wheels A and C	On Steel Wheels E and F	On Chilled Wheels A and C	On Steel Wheels E and F	
1	2	3	4	5	6	7	8	9	10	11	12
500	20	181	172	36.25	34.48	5.1	176	155	35.22	31.08	13.3
	30	168	141	33.60	28.16	19.3	142	114	28.38	22.72	24.9
	40	154	122	30.75	24.30	26.5	120	102	23.99	20.42	17.5
Av. for 3 Speeds		...	...	33.53	28.98	15.7	...	...	29.20	24.74	18.0
1000	20	332	237	33.19	23.66	40.3	289	236	28.87	23.61	22.3
	30	281	200	28.11	19.96	40.8	228	190	22.80	19.03	19.8
	40	261	184	26.07	18.44	41.4	197	182	19.68	18.24	7.9
Av. for 3 Speeds		...	...	29.12	20.69	40.7	...	...	23.78	20.29	17.2
1500	20	460	329	30.69	21.96	39.8	370	313	24.64	20.85	18.2
	30	397	270	26.48	17.98	47.3	288	261	19.17	17.41	10.1
	40	359	252	23.93	16.79	42.5	261	241	17.42	16.05	8.5
Av. for 3 Speeds		...	...	27.03	18.91	42.9	...	...	20.41	18.10	12.8
2000	20	569	415	28.47	20.74	37.3	452	404	22.61	20.20	11.9
	30	467	344	23.33	17.18	35.8	380	337	19.01	16.86	12.8
	40	437	322	21.86	16.11	35.7	344	309	17.20	15.45	11.3
Av. for 3 Speeds		...	...	24.55	18.01	36.3	...	...	19.61	17.50	12.1
2500	20	667	506	26.66	20.24	31.7	569	488	22.76	19.51	16.7
	30	545	417	21.78	16.68	30.6	447	405	17.88	16.18	10.5
Av. for 2 Speeds		...	...	24.22	18.46	31.2	...	...	20.32	17.85	13.8
4000	20	895	697	22.37	17.42	28.4	770	698	19.25	17.45	10.3

cent. With Special Chilled shoes there is but little regularity in the variations of the excess, either with speed or with pressure; although it is, in general, greater at pressures of 500 and 1000 pounds than at the higher pressures. With these shoes the average excesses for the successive pressures are, respectively, 18.0, 17.2, 12.8, 12.1, 13.8, and 10.3 per cent.

The relationships shown in Table 21 are represented also in Figs. 19 and 20, in which the coefficients at the various pressures and speeds are plotted for both chilled and steel wheels. The values of the coefficient which define the lines in these figures are those given in columns 5 and 6 or columns 10 and 11 of Table 21. The general relations between the coefficients on chilled and steel wheels are represented in Fig. 21, in which the plotted coefficient values are the averages, at each speed, for the first four pressures. This figure consequently exhibits graphically the general superiority of the coefficient on chilled wheels.

The values of tangential pull shown in columns 3 and 4 or columns 8 and 9 in Table 21 are transferred from Table 15; they are, however, here given to the nearest unit instead of to the first place of decimals, as in Table 15. Because of the direct relation between coefficient and pull, these values, of course, show the same superiority of performance on chilled wheels as is shown by the values of the coefficient; and the percentages of excess given in columns 7 and 12 of Table 21 apply equally to them. Figures 22 and 23 likewise show the excess in tangential pull realized on the chilled wheels at each of the six shoe pressures. The values of pull plotted in these figures are those given in columns 3 and 4 or columns 8 and 9 of Table 21.

VII. Results of Fifteen-Minute Constant Speed Tests

The fifteen-minute constant speed tests constitute the last of the three series. They differ from the other constant speed tests chiefly in the duration of the application of the shoe. It will be recalled that in the latter there were ten applications, each lasting for 190 revolutions of the wheel, separated by cooling periods of a little more than three times the duration of the applications; whereas in the fifteen-minute tests the shoe was in continuous contact for fifteen minutes, one such application constituting a test.

There has long existed, among railroad men, an impression that under long-continued brake shoe applications there is a breakdown in the frictional quality of the shoe, it being assumed that the coefficient of friction decreased considerably on account of the heating of the shoe and wheel. The tests were undertaken in order to check the validity of this opinion. It may be stated at once that the test results lend no color to this view.

31. *Tabular Summary of Results.*—The fifteen-minute series comprises 28 tests—one test with each of two shoes, on each of two wheels, under each of seven combinations of pressure and speed. The tests were made on the used wheels only, wheels C and F. The test results are set forth in Table 22, which shows the values of tangential pull and coefficient of friction obtained under each combination of pressure and speed, first for Diamond S shoes on both wheels and then for Special Chilled shoes. The table shows also the average values of these quantities for each pressure and, in the last line, the general averages for all speeds and pressures.

TABLE 22

SUMMARY OF RESULTS OF FIFTEEN-MINUTE CONSTANT SPEED TESTS

Brake Shoe Pressure lb.	Speed m.p.h.	Diamond S Shoes						Special Chilled Shoes					
		Chilled Wheel C			Steel Wheel F			Chilled Wheel C			Steel Wheel F		
		Test No.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Average Tangential Pull lb.	Average Coefficient of Friction per cent	Test No.	Average Tangential Pull lb.	Average Coefficient of Friction per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1500	30	3258	344.5	22.96	3315	346.0	23.07	3251	312.2	20.81	3308	279.2	18.61
1500	40	3259	317.2	21.15	3316	340.8	22.72	3252	276.2	18.42	3309	259.6	17.31
Av. of 2 Speeds		....	....	22.06	Av. of 2 Speeds		22.90	Av. of 2 Speeds		19.62	Av. of 2 Speeds		17.96
2000	20	3260	524.6	26.23	3317	552.4	27.62	3253	451.7	22.59	3310	457.1	22.86
2000	30	3261	447.2	22.36	3318	431.3	21.57	3254	374.4	18.72	3312	348.2	17.41
2000	40	3262	409.4	20.47	3319	391.4	19.57	3255	358.9	17.94	3311	324.7	16.24
Av. of 3 Speeds		....	....	23.02	Av. of 3 Speeds		22.92	Av. of 3 Speeds		19.75	Av. of 3 Speeds		18.84
2500	20	3263	640.3	25.61	3320	652.1	26.09	3256	575.4	23.02	3313	535.4	21.42
2500	30	3264	584.5	23.38	3321	507.7	20.31	3257	465.3	18.61	3314	390.2	15.61
Av. of 2 Speeds		....	....	24.50	Av. of 2 Speeds		23.20	Av. of 2 Speeds		20.82	Av. of 2 Speeds		18.52
Av. of 7 Tests		....	....	23.17	Av. of 7 Tests		22.99	Av. of 7 Tests		20.02	Av. of 7 Tests		18.49

32. *Comparison of Results of Fifteen-Minute Constant Speed Tests and of Constant Speed Tests of Second Series.*—In view of the purpose for which these tests were undertaken, the discussion of their results in this chapter will be directed chiefly to comparing them with the results of the constant speed tests of the second series. For the sake of brevity the tests of the third series will be hereafter designated as "fifteen-minute tests," and those of the second series as "constant speed tests," although both series were run at constant wheel speed. Before proceeding with the comparison it may be well to restate the fact that during the fifteen-minute tests there was no attempt to cool either the shoe or the wheel. Such cooling as occurred was merely that arising from the normal radiation and the convection set up by the wheel rotating in the air of the laboratory. During all these tests the brake shoe became red-hot; sometimes for a fraction of an inch back from its contact face, sometimes throughout its entire body. During all tests minute particles of red-hot metal issued from beneath the shoe. Under the more severe combinations of pressure and speed the wheel tread likewise became red-hot over almost its entire width. It should be borne in mind, too, that in the constant speed tests the duration of any one of the ten applications was about 0.9 of a minute at wheel speeds of 20 miles per hour, and only half that time at 40 miles per hour; and that the duration of the application in the fifteen-minute tests was, consequently, from about 16 to about 32 times as great as in the other tests.

The comparable values of coefficient of friction for the two series are brought together in Table 23. The coefficients produced in the constant speed tests, shown in columns 3, 6, 9, and 12, are those given for wheels C and F in Table 15; the coefficients for the fifteen-minute tests, which appear in columns 4, 7, 10, and 13, are transferred from Table 22. The excess of one coefficient over the other is defined by the percentages given in columns 5, 8, 11, and 14.

Comparison of the coefficients which were produced in the two test series, and which appear side by side in Table 23, reveals at once that, in general, the coefficients obtained during the fifteen-minute tests are greater than those obtained in the constant speed tests; this is true of 24 of the 28 pairs of basic test results shown in the table. In the four* remaining pairs, the greater coefficient occurs in the constant speed tests. The general excess of the coefficient produced in the fifteen-minute applications varies from 0.7 of one per cent to as much as 37.4 per cent. With both kinds of shoes the greater excesses

*These four pairs are denoted in the table by the asterisks. The two averages similarly denoted are, of course, excluded from the statement.

TABLE 23

DIFFERENCE BETWEEN COEFFICIENTS OF FRICTION PRODUCED IN FIFTEEN-MINUTE CONSTANT SPEED TESTS AND THOSE PRODUCED IN CONSTANT SPEED TESTS OF SECOND SERIES

Shoe Pressure lb.	Wheel Speed m.p.h.	With Diamond S Shoes						With Special Chilled Shoes					
		On Chilled Wheel C			On Steel Wheel F			On Chilled Wheel C			On Steel Wheel F		
		Coefficient of Friction per cent		Percentage Excess of Coefficient in Fifteen-Minute Tests	Coefficient of Friction per cent		Percentage Excess of Coefficient in Fifteen-Minute Tests	Coefficient of Friction per cent		Percentage Excess of Coefficient in Fifteen-Minute Tests	Coefficient of Friction per cent		Percentage Excess of Coefficient in Fifteen-Minute Tests
		During Constant Speed Tests	During Fifteen-Minute Tests		During Constant Speed Tests	During Fifteen-Minute Tests		During Constant Speed Tests	During Fifteen-Minute Tests		During Constant Speed Tests	During Fifteen-Minute Tests	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1500	30	24.87	22.96	8.3*	17.45	23.07	32.2	19.61	20.81	6.1	16.51	18.61	12.7
	40	22.24	21.15	5.2*	16.54	22.72	37.4	17.34	18.42	6.2	15.73	17.31	10.0
Average of 2 Speeds...		23.56	22.06	6.8*	17.00	22.90	34.7	18.48	19.62	6.2	16.12	17.96	11.4
2000	20	27.27	26.23	4.0*	20.78	27.62	32.9	22.36	22.59	1.0	19.26	22.86	18.7
	30	21.97	22.36	1.8	16.49	21.57	30.8	19.22	18.72	2.7*	15.97	17.41	9.0
	40	20.33	20.47	0.7	15.34	19.57	27.6	16.97	17.94	5.7	14.62	16.24	11.1
Average of 3 Speeds...		23.19	23.02	0.7*	17.54	22.92	30.7	19.52	19.75	1.2	16.62	18.84	13.4
2500	20	24.30	25.61	5.4	20.08	26.09	29.9	22.52	23.02	2.2	17.98	21.42	19.1
	30	19.60	23.38	19.3	16.26	20.31	24.9	17.43	18.61	6.8	15.24	15.61	2.4
Average of 2 Speeds...		21.95	24.50	11.6	18.17	23.20	27.7	19.98	20.82	4.2	16.61	18.52	11.5

*In the instances denoted by the asterisks the greater coefficient was produced during the constant speed tests of the second series; and the percentages given in columns 5 and 11 show the excess over the coefficient obtained in the fifteen-minute tests.

TABLE 24

BRAKE SHOE WEAR IN CONSTANT SPEED TESTS AND IN FIFTEEN-MINUTE TESTS

Wheel	Kind of Shoes	In Constant Speed Tests		In Fifteen-Minute Tests	
		Foot-Pounds of Work Performed	Shoe-Wear, in Pounds per 100 Million Foot-Pounds of Work	Foot-Pounds of Work Performed	Shoe-Wear, in Pounds per 100 Million Foot-Pounds of Work
1	2	3	4	5	6
On Chilled Wheel C	Diamond S	159 098 800	0.346	136 279 600	0.396
	Special Chilled	170 936 800	0.497	127 939 100	0.649
On Steel Wheel F	Diamond S	122 636 400	0.530	122 161 100	0.327
	Special Chilled	150 908 600	0.583	102 878 600	0.642

occur in tests on the steel wheel; the disparity in this respect being greater with Diamond S than with Special Chilled shoes.

Obviously there is nothing in these facts to support the assumption of a breakdown in the frictional quality of shoe or wheel under long-continued brake applications made within the limits of speed and pressure employed in these tests; for the preponderating evidence from the tests leads to the opposite conclusion. There is little occasion for surprise in this outcome; for both experiment and experience show that with unlubricated materials the greater coefficient is frequently produced with the softer material—at any rate when one of the contacting materials is softer. In so far, therefore, as long-continued brake shoe applications may soften the shoe we should be warranted in anticipating just such an increase in the coefficient of friction as is shown by these tests.

In this connection it is interesting to compare the brake shoe wear developed in the two test series. This is shown, for wheels C and F, in Table 24, where in columns 4 and 6 is shown the weight of material worn from each shoe in performing 100 million foot-pounds of work. The wear during the constant speed tests appears in column 4, and that during the fifteen-minute tests in column 6. With one exception, the wear is greater in the latter series. The quantity of work shown for each shoe in columns 3 and 5 is the total amount of work performed by the shoe in the entire test series; the values for the constant speed tests consequently include some work performed under combinations of pressure and speed which were not used in the fifteen-minute tests, and specific conclusions ought not, therefore, to be drawn from Table 24 as to the exact relation between rates of wear in the two series. The relations shown in the table do, however, warrant the conclusion that in general the rate of wear is greater under the long-continued applications, and this supports the inference previously drawn, namely, that the increase in coefficient in the fifteen-minute tests is caused by a softening of the shoe material.

33. *Variation of Coefficient of Friction with Speed and with Pressure.*—The fifteen-minute tests exhibit a decrease in the coefficient with speed and with pressure similar to the decrease developed in the two other test series. The decrease in the coefficient as the speed increases is shown in Table 22. Among the 28 tests there is no exception to the general tendency. With but two exceptions, these tests likewise show a decline in the coefficient with increasing shoe pressure, when we compare, for any wheel and shoe combination, the coefficients developed in tests at the same speed.

34. *Variations in Tangential Pull During Fifteen-Minute Periods of Application.*—The values of pull and coefficient given in Table 22 are average values for the whole period of application of the shoe. While the tests were in progress, question arose as to whether there was any considerable fluctuation in these quantities during the progress of the application, and the test records were therefore so analysed as to show these variations. For this purpose the chart of tangential pull was divided into sections, each of which corresponded to approximately 450 revolutions of the wheel;* within each of these sections the pull was then measured at ten equidistant points and the ten resulting values were averaged to find the average pull for the section. The successive values of pull thus determined are plotted in Figs. 25 and 26, the former applying to the tests with Diamond S, and the latter to those with Special Chilled shoes. Each of the fourteen lines in each figure applies to a particular combination of wheel, speed, and pressure.

Casual consideration of these figures may lead to the incorrect conclusion that the fluctuations in pull during tests represented by the upper lines in these figures were greater than in tests represented by the lower lines. The percentage deviation of the individual points from the general average for the test, however, is actually not very different among the various lines of Figs. 25 and 26. The apparent difference arises from the wide range in pull realized during the tests, and the consequent wide differences in the bases upon which the per-

*The duration of that part of the application corresponding to each section was:
For the tests made at 20 m.p.h., 2.2 minutes.
For the tests made at 30 m.p.h., 1.5 minutes.
For the tests made at 40 m.p.h., 1.1 minutes.

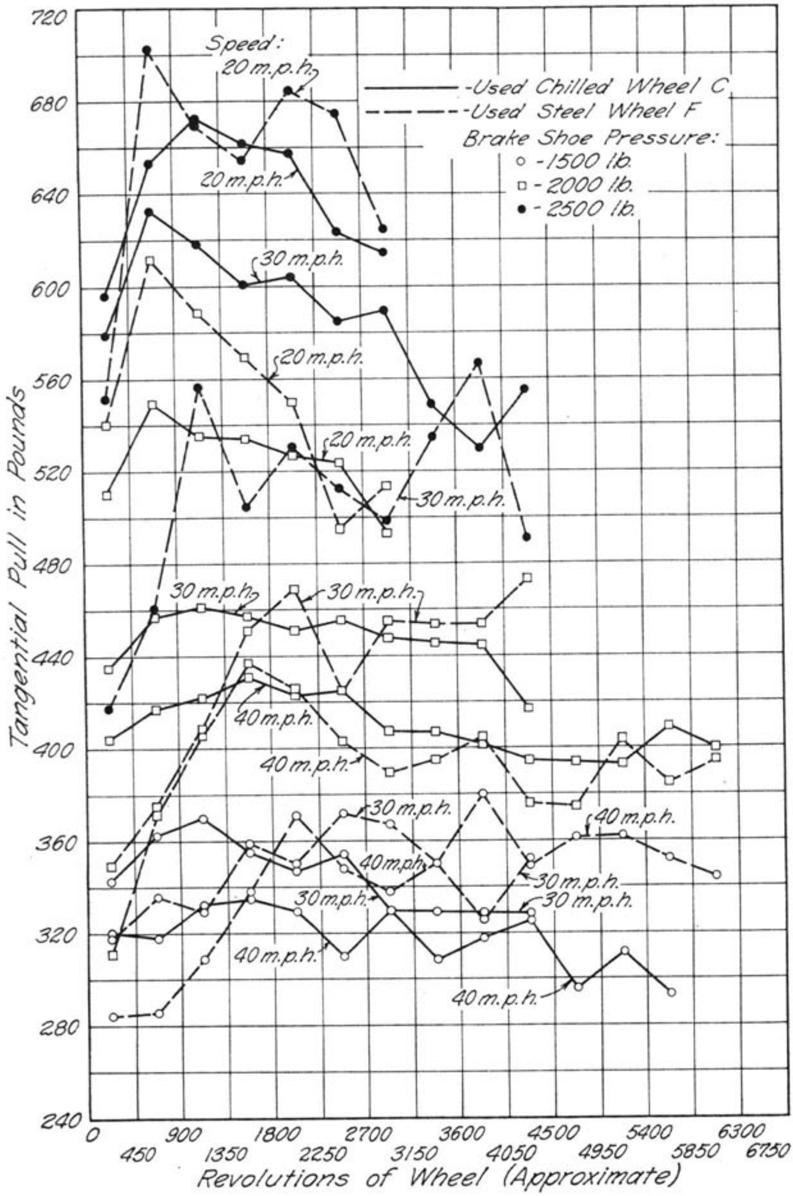


FIG. 25. VARIATION OF TANGENTIAL PULL WITH DURATION OF APPLICATION OF SHOE, AS DEFINED BY FIFTEEN-MINUTE CONSTANT SPEED TESTS

For Diamond S Shoes, on Both Used Wheels

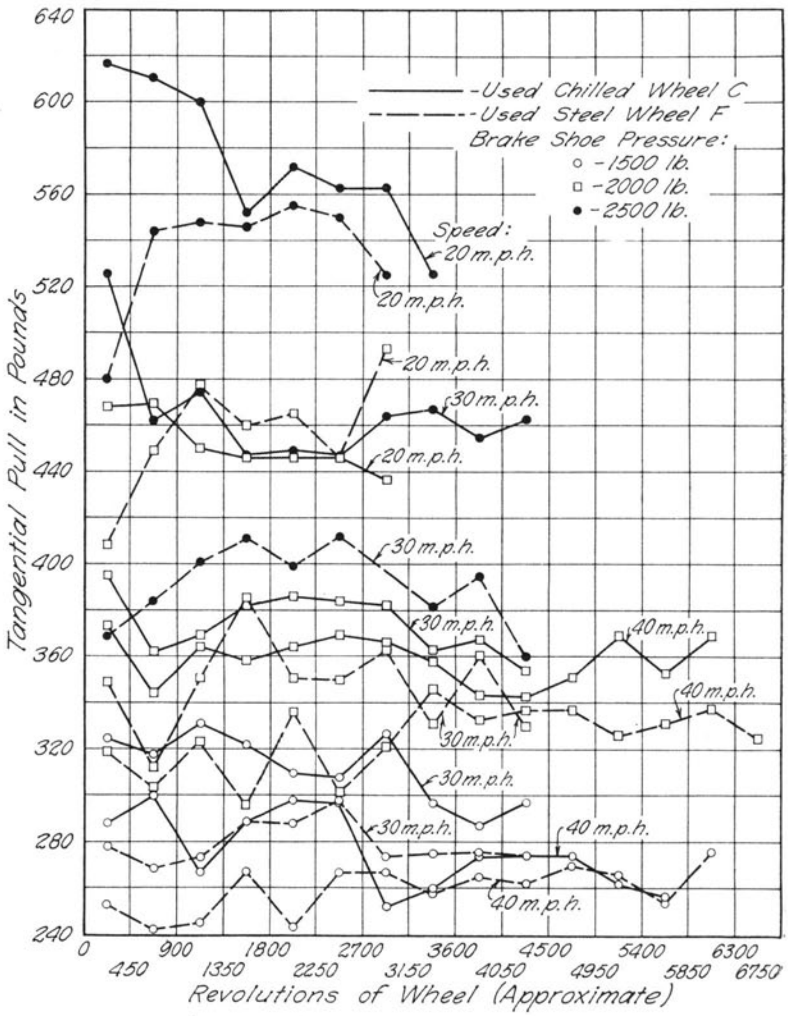


FIG. 26. VARIATION OF TANGENTIAL PULL WITH DURATION OF APPLICATION OF SHOE, AS DEFINED BY FIFTEEN-MINUTE CONSTANT SPEED TESTS

For Special Chilled Shoes, on Both Used Wheels

centage deviation must be calculated. This point is illustrated in Fig. 27, in which two of the "curves" of Fig. 25 are reproduced to the same scale, their average values shown, and the greatest deviations above and below the average stated. The upper curve in Fig. 27 is the one next to the highest in Fig. 25; and the lower one is the third full-line curve from the bottom of that figure. Despite the greater

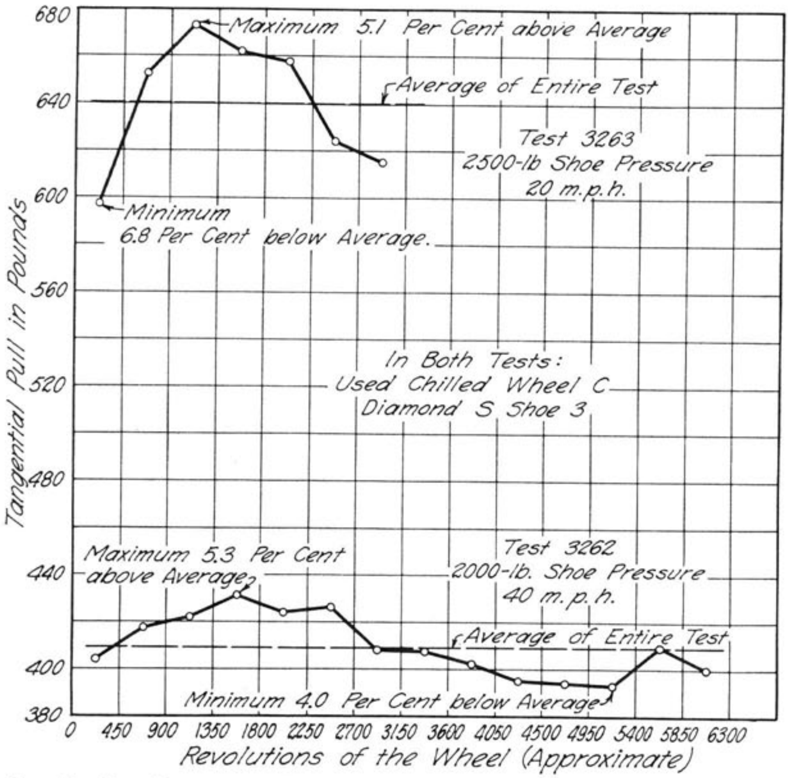


FIG. 27. TWO TANGENTIAL PULL CURVES FROM FIG. 25, SHOWING MAXIMUM AND MINIMUM DEVIATIONS FROM AVERAGE PULL FOR TEST

approach to straightness in the lower curve of Fig. 27, its deviations above and below the average (5.3 and 4.0 per cent) are nearly as great as in the upper curve, which is much more broken, but in which, nevertheless, the deviations are only 5.1 and 6.8 per cent.

Returning now to Figs. 25 and 26, it is first to be observed that with neither Diamond S nor Special Chilled shoes is there any constant tendency for the pull steadily to fall or steadily to rise during the progress of the fifteen-minute applications. It does either or neither with about equal frequency. If there were any basis for the assumption of a universal breakdown in pull under long-continued application, we would expect to find that decrease more marked in the tests made under 2500 pounds pressure than in those under lower pressures; but the high-pressure tests show no more uniformity in this respect than the others.

One fairly consistent tendency is revealed by the lines in Fig. 25; this is a tendency for the pull to increase during the early part of the application. Among the 14 tests with Diamond S shoes represented in this figure, there is only one in which this initial increase does not occur. Among the tests made with Special Chilled shoes (Fig. 26), however, there is a contrary tendency, for nine of the fourteen tests reveal an initial decrease in pull.

VIII. Summary of Test Program and Results

This chapter consists of a very brief statement of the test purposes, program, and procedure, and a summary of the results. It is of necessity a restatement of what has been said elsewhere in more detail. Its purpose is to provide a general view of the procedure and results for those who may wish some perspective of the research before studying the detailed report.

The investigation was undertaken in order to determine the tangential pull and the coefficient of friction produced by two kinds of brake shoes on both chilled iron wheels and steel wheels; and to find the variations of the pull and the coefficient with speed, with pressure, and with duration of application, and also their differences on the two kinds of wheels.

The shoes used were Diamond S shoes and Special Chilled shoes, the former being a cast iron shoe with an embedded steel mesh, the latter a plain cast iron shoe; both had chilled ends. The tests were made on four wheels—two chilled iron wheels, one of which was new and the other partly worn, and two steel wheels, one new and one partly worn.

Three kinds of tests were made during the investigation, namely,

Series 1—Stop Tests
Series 2—Constant Speed Tests
Series 3—Fifteen-Minute Constant Speed Tests

In the stop tests the shoe was applied when the wheel in the testing machine had attained the desired speed; and the wheel and the attached rotating parts of the machine were brought to rest under the action of the shoe. Five such stops under identical conditions of pressure and speed constituted one test; and the series comprises 169 tests, or 845 stops. These tests simulate the conditions under which a train is brought to rest by the application of the brakes.

In the constant speed tests the wheel of the testing machine was kept running at uniform speed by means of the testing machine engine, while the shoe was alternately applied and released; the duration of the application being 190 revolutions of the wheel, and of the release period 610 revolutions. Ten such applications constituted one test, and the series comprises 202 tests. These test conditions simulate those which prevail in bringing a train down a long grade.

The third series, the fifteen-minute tests, was a modification of the second. In them the shoe was continuously applied to the wheel for fifteen minutes, the wheel being driven at uniform speed and no attempt made to cool either the shoe or the wheel. One such application constituted a test; and the series includes 28 tests, each made under a different combination of wheel, pressure, and speed. These tests were made on two of the four test wheels only.

In the three series the range in speed and in pressure was as follows:

	Range in Speed m.p.h.	Range in Pressure lb.
Stop Tests	20 to 60	2250 to 4500
Constant Speed Tests	20 to 40	500 to 4000
Fifteen-Minute Tests	20 to 40	1500 to 2500

Since the general trends in the variation of the coefficient of friction with speed, pressure, kind of shoe, and the like, are similar in the stop tests and in the constant speed tests, the results of these two series are stated together in the paragraphs which immediately follow. The results of the fifteen-minute tests are stated at the end of this chapter.

35. *Variation of Coefficient of Friction with Speed.*—In both the stop tests and the constant speed tests there was a marked decrease in coefficient of friction and in tangential pull as the wheel speed was increased under any given test pressure. This is true of the results produced by both kinds of shoes on all four wheels. This decrease with speed has been discussed in detail in Sections 17 and 25, in Chapters V and VI respectively.

36. *Variation of Coefficient of Friction with Shoe Pressure.*—In both series the pull and the coefficient decline, in general, as the shoe pressure is increased. In the stop tests the decline is somewhat irregular and less in amount than in the constant speed tests. In the latter the decline is not only greater, but it occurs almost invariably with both kinds of shoes and all four wheels. In the constant speed tests the coefficient at 2000 pounds shoe pressure was only about two-thirds as great as at 500 pounds pressure. The facts with respect to this decrease with pressure are set forth in Sections 20 and 27.

37. *Difference in Performance of Diamond S and Special Chilled Shoes.*—In both the stop tests and the constant speed tests, the coefficient of friction produced by Diamond S shoes is greater than

that produced by Special Chilled shoes under the same conditions of shoe pressure, speed, and kind of wheel; and whatever is here said of the coefficient is, of course, equally true of the tangential pull.

In the stop tests, among 40 pairs of comparable average values of the coefficient there are only five pairs in which the coefficient produced by Diamond S shoes is not greater than that produced by Special Chilled shoes; and in the constant speed tests there is only one such exception among 30 pairs of comparable values. The excess with Diamond S shoes is frequently of notable amount, running as high as 32 per cent in the stop tests, and 38 per cent in the constant speed tests. This difference in performance of the two kinds of shoes is discussed at length in Sections 21 and 28.

38. *Difference in Brake Shoe Performance on New Wheels and Used Wheels.*—Since in Series 1 and Series 2 tests with each kind of shoe were made on each of two new wheels and on each of two used wheels, there are in each series four pairs of combinations of shoe and wheel. In each of these pairs the only difference is that the tests in one instance were made on a new wheel, and in the other, on a used wheel.

In the stop tests, in one of these pairs (Diamond S shoes on chilled wheels) the greater coefficient was produced on the new wheel, the excess over that on the used wheel being 11.2 per cent. In the three other pairs the excess occurs in tests made on the used wheels, and it ranges from 6.5 to 15.5 per cent.

In the four corresponding pairs of general average values of the coefficient produced in the constant speed tests, the coefficient is, without exception, greater on the new wheels, the excess ranging in amount from 0.1 to 11.8 per cent. These comparisons, in both series, rest upon general average values at all speeds and all pressures. When we deal with comparable values derived under particular combinations of pressure and speed, there are exceptions to the general tendencies which have just been cited. These differences on new and used wheels are discussed in Sections 22 and 29.

39. *Difference in Brake Shoe Performance on Chilled Wheels and Steel Wheels.*—The results of both stop tests and constant speed tests disclose a notable difference in performance on the two kinds of wheels. With exceptions so infrequent as to be practically negligible, both the coefficient of friction and the tangential pull are greater on chilled wheels than on steel wheels under identical conditions of shoe pressure and speed, with both kinds of shoes.

Dealing with average values of coefficient and pull on new and used wheels of like kind, there are in the results of the stop tests 40 pairs of comparable values of these two quantities. Among these 40 pairs there are only three in which the coefficient and pull are not greater on chilled wheels than on steel wheels, and in these three exceptions the general tendency is just barely reversed, the excesses on the steel wheels being respectively only 1.0, 1.5, and 2.0 per cent; whereas in the remaining 37 pairs of values the excess on the chilled wheels ranges from 0.1 to as much as 36.5 per cent. For the entire stop test series the general average excess on chilled wheels is 16.7 per cent.

The results of the constant speed tests likewise exhibit a marked superiority of coefficient and pull obtained on chilled wheels; and in this series not only is the excess somewhat greater than in the stop tests, but there are no exceptions whatever to the general tendency. The coefficient and pull are greater on the chilled than on the steel wheels, whether we deal with the results produced by Diamond S shoes or Special Chilled shoes, on either new wheels or used wheels. The excess ranges from 5.1 per cent to as much as 47.3 per cent. Comparing the general average values of pull and coefficient produced during 100 constant speed tests on chilled wheels, with the corresponding average values produced in 102 tests on steel wheels, the average excess on the chilled wheels is 23.5 per cent. These differences in performance on the two kinds of wheels are discussed in Sections 23 and 30, and they are exhibited in the tables and figures presented in those sections.

40. *Results of Fifteen-Minute Constant Speed Tests.*—These tests were undertaken in order to try to check the validity of an opinion long prevalent among railroad men, namely, that in long-continued brake shoe applications there is a general breakdown in the coefficient of friction. These fifteen-minute tests were made under some of the combinations of pressure and speed used in the constant speed tests of the second series, and their results are directly comparable with the corresponding results of that series. The duration of the fifteen-minute tests was from 16 to 32 times as great as the duration of the individual applications of the constant speed tests.

The results of these tests lend no support to the opinion just cited; they not only disclose no breakdown in the value of the coefficient of friction, but in 24 of the 28 long-continued tests the average coefficient was greater than in the constant speed tests run under identical pressures and speeds—by amounts which vary from 0.7 to 37.4 per cent.

APPENDIX

Auxiliary Tests Made to Check Uniformity of Test Shoes

1. *Purpose of Auxiliary Tests, and of This Appendix.*—As has been stated in the body of the report, of the four Diamond S and the four Special Chilled brake shoes chosen for this work, one of each kind was assigned to each of the four wheels used, fitted to that wheel, and constantly used with it for all tests. (See pages 24 and 25). The purpose of this appendix is to justify the procedure of thus using a particular shoe with a particular wheel; and to explain how the test shoes were chosen.

It should be borne in mind that, in a research of this scope, a single shoe of each kind used on all four wheels would have had to be re-fitted with each shift from wheel to wheel; and it would have been worn out before the conclusion of the tests. It would have then been necessary to find a means of choosing another shoe of the same frictional quality; so that the procedure adopted for these tests merely anticipated a difficulty which under any other procedure would have had to be met and solved in some way.

To thus assign a particular shoe to each wheel and, after fitting it thereto, to continue to use it for all tests with that wheel affords two advantages: (a), it makes likely a better fit of shoe to wheel; and (b), it results in less wear in the test shoes and, consequently, in less likelihood of change in the frictional quality of the shoe as the tests progress—both of which tend to produce greater uniformity and concordance among the test results.

The first—the more uniform shoe fit—is an important advantage; for, as stated in the Introduction, there is reason to suspect that discordances among the results of previous tests are in large measure due to shifting test shoes from wheel to wheel without exercising enough care to maintain on all wheels an equally good fit. This in any case is a difficult thing to do—with the varying tread contour of different wheels—and one which, furthermore, entails much grinding of the shoe and consequent shortening of its life. The importance of uniformity of shoe fit as a means of securing harmony among test results can hardly be exaggerated, especially in view of the fact that even the most perfect fit is in constant danger of being impaired by the warping of the shoe as it heats up.

The second advantage cited above—less shoe wear during the progress of the research—also tends toward greater uniformity in the coefficient of friction of the shoe and greater agreement among test results. As the shoe wears away, the unchilled body material may change in frictional quality due to inherent differences in hardness between the metal on the original face and that in the interior of the shoe. A slight variation in this respect is disclosed by a comparison of columns 4 and 7 of Table 1. Shoe wear is likely to produce even greater variation in the frictional quality of the chilled metal at the ends of the shoe, for the hardening effect of the chilling block diminishes from the surface inward—as is well illustrated by a comparison of the hardness values in columns 3 and 6 of Table 1. Furthermore, the heat generated in tests under heavy pressures and high speeds is sufficient to have some annealing effect on both the chilled and unchilled material. One additional effect of shoe wear on the average coefficient of the shoe arises from a decrease in the surface area* of the chilled ends of the shoes as the shoe wears away.

All these considerations seemed at the outset to justify the use of four shoes of a kind, instead of one only, and the assignment of each of these shoes to a particular wheel; and the uniformity of the test results seems now to indicate that this procedure was well warranted. If, however, among the results obtained under this procedure, comparisons are to be drawn between those involving different wheels and different shoes, or if general average values of coefficient of friction involving various shoes are to be compared, we must be assured that all of the four test shoes of each kind were substantially alike in their frictional quality. The precautions taken to ensure this equivalence among the test shoes are explained in the following section.

2. *Choice of Test Shoes, and Their Equivalence in Frictional Quality.*—As stated in Chapter III, precautions were taken in casting the test shoes in order to increase the likelihood of their being equal in frictional quality. In order, however, to determine whether substantial equality in this respect had actually been attained, they were subjected to preliminary "check tests" before beginning the main experiments. For this purpose six Diamond S shoes and six Special Chilled shoes were subjected to stop tests on new chilled wheel A. The shoes thus tested were Nos. 1, 2, 3, 5, 6, 7, and Nos. 25, 26, 28, 30, 31, 32, respectively. The preliminary stop tests made with these twelve shoes were conducted in the same manner as the main stop

*The cross-section of the chilled volume, in the plane of the wheel, 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 wears, the base of the triangle—and consequently the chilled contact area—diminishes.

TABLE 25
RESULTS OF STOP TESTS MADE TO CHECK EQUIVALENCE OF TEST SHOES

Brake Shoe Pressure lb.	Speed m.p.h.	Diamond S Shoes					Special Chilled Shoes				
		Brake Shoe No.	No. of Stops	Average Revolutions per Stop	Average Coefficient of Friction per cent	Deviation of Coefficient for Each Shoe from Average for All 4 Test Shoes per cent	Brake Shoe No.	No. of Stops	Average Revolutions per Stop	Average Coefficient of Friction per cent	Deviation of Coefficient for Each Shoe from Average for All 4 Test Shoes per cent
1	2	3	4	5	6	7	8	9	10	11	12
2250	30	2	5	75.3	25.3	+1.2	26	5	76.1	23.9	−1.6
		3	3	79.5	24.8	−0.8	28	3	76.6	24.2	−0.4
		6	3	78.2	24.8	−0.8	30	3	75.9	24.5	+0.8
		7	3	77.9	24.9	−0.4	31	3	77.6	24.6	+1.2
Average of Shoes Used				77.7	25.0	.....	Av. of Shoes Used		76.6	24.3	.....
		1	5	78.3	24.7	.....	25	5	73.3	25.7	.....
		5	5	70.8	26.4	.....	32	5	71.8	26.0	.....
3750	60	2	5	261.8	17.2	+0.6	26	3	306.6	15.0	−1.3
		3	3	270.1	17.3	+1.2	28	4	296.5	15.5	+2.0
		6	5	268.7	16.6	−2.9	30	3	303.3	14.9	−2.0
		7	3	263.5	17.3	+1.2	31	3	306.8	15.2	0.0
Average of Shoes Used				266.0	17.1	.....	Av. of Shoes Used		303.3	15.2	.....
		1	5	276.4	16.4	.....	25	5	300.6	15.1	.....
		5	3	265.2	17.3	.....	32	5	291.8	15.6	.....

tests, described in Section 12 of Chapter IV. Two combinations of shoe pressure and speed were used, namely, 2250 lb. and 30 m.p.h., and 3750 lb. and 60 m.p.h. From 3 to 5 stops were made with each shoe under each of these combinations. The results of these check tests are set forth in Table 25, which shows in columns 6 and 11 the average coefficient of friction developed by each of the twelve shoes.

On the basis of these coefficient values—taking into account the relative standing of the shoes under both sets of test conditions—the four shoes of each kind most nearly alike in coefficient of friction were chosen for the main tests. Those so chosen were Diamond S shoes Nos. 2, 3, 6, and 7, and Special Chilled shoes Nos. 26, 28, 30, and 31. Shoes Nos. 1, 5, 25, and 32 were rejected. In the further consideration of Table 25 attention will be confined to the eight chosen test shoes here cited.

In columns 6 and 11 of the table, in addition to the coefficient for each shoe, there appear averages of the coefficients for the four chosen shoes of each kind under each set of test conditions, these averages being designated as "Average of Shoes Used." The coefficients of each shoe have been compared with these averages and their percentage deviation therefrom is set down for each shoe in columns 7 and 12. These deviations are accepted as measures of the differences in frictional quality among the various shoes. For convenience in comparing them they are repeated in the following tabulation, which presents in addition, in the last column, the deviations of the general average coefficient for each shoe (derived by averaging its coefficients for *both* sets of test conditions) from the general average for all four shoes similarly derived.

Deviation of the Coefficient of Friction of Each Test Shoe from the Average of the Coefficients for All Four Shoes, Expressed as a Percentage of This Average

	Under Tests at 2250 lb. and 30 m.p.h.	Under Tests at 3750 lb. and 60 m.p.h.	From Tests* Under Both Combinations of Pressure and Speed
Diamond S Shoe No. 2	+1.2	+0.6	+1.1
Diamond S Shoe No. 3	−0.8	+1.2	+0.1
Diamond S Shoe No. 6	−0.8	−2.9	−1.5
Diamond S Shoe No. 7	−0.4	+1.2	+0.3
Special Chilled Shoe No. 26	−1.6	−1.3	−1.4
Special Chilled Shoe No. 28	−0.4	+2.0	+0.6
Special Chilled Shoe No. 30	+0.8	−2.0	−0.1
Special Chilled Shoe No. 31	+1.2	None	+0.9

*These percentages, although derived from the coefficient values of Table 25, are not given in that table.

Considering the first and second columns of this tabulation, the range in deviation among like shoes is seen to be from 2.0 per cent above the average to 2.9 per cent below it. Probably a better indication of the correspondence among the shoes is presented by the deviation percentages in the third column; for there we have measures of their similarity when tested under both sets of test conditions instead of one only. This column shows the variation to have ranged from 1.1 per cent above the average to 1.5 per cent below it.

These variations among the shoes are smaller than was anticipated and they show that the precautions taken in their manufacture produced shoes of substantially equal frictional quality. Small as are these variations among the coefficients of friction of the various shoes, it is, for our present purpose, of equal or even greater significance that these variations are smaller than those which occur among the results of tests made with the same shoe under identical test conditions—not only in the check stop tests here under discussion, but in the main stop tests as well. For example, for Diamond S shoe No. 6, which in columns 1 and 2 of the foregoing table shows the maximum deviation (2.9 per cent), the coefficient used in the tabulation in deriving this percentage is the average of five stops made at 3750 lb. pressure and an initial speed of 60 m.p.h. Among these five stops—made under identical conditions and one directly after the other—the coefficient* for the stop producing the highest coefficient was 3.6 per cent greater than the average for all five stops, and for the stop producing the lowest value the coefficient was 3.0 per cent less than this average. Under these conditions, therefore, the variations of the coefficient for shoe No. 6 from the coefficients for other Diamond S shoes are less than the variations among successive determinations made with this shoe itself. If we draw for Special Chilled shoe No. 31 a similar comparison when tested at 2250 lb. and 30 m.p.h., we find, from the first column of the tabulation, that it differs from the average for all four shoes of this kind by 1.2 per cent; whereas among the three individual stops upon which its coefficient is based the variations range from plus 2.4 to minus 2.8 per cent—or about twice as much as the variation of shoe No. 31 from its mates. Similar comparisons for all the other test shoes show that the differences among successive coefficient determinations made with the same shoe under identical conditions are generally greater than the differences among the average coefficients for the various shoes of like kind.

One further fact of interest in this connection is disclosed by comparisons of the coefficients shown in Table 25 or of the deviations shown in the tabular summary derived from that table. This is that the relative standing of the four shoes of like kind changes as we pass from one set of test conditions to the other. If we rank the shoes in the order of magnitude of their coefficients of friction, among Diamond S shoes No. 2 is first when tested at 2250 lb. and 30 m.p.h., second at 3750 lb. and 60 m.p.h., and first again if we consider average coefficients under both sets of conditions. Similarly rated, Special Chilled shoe No. 26 is fourth, then third, and finally fourth again in rank; and No. 30 is second, then fourth, then third. Here too the variations in coefficient which arise from changes in test conditions overtop the slight differences in frictional quality which exist among the shoes.

All these facts make it obvious that among successive determinations of coefficient of friction, made with any one of the shoes under identical conditions and using the same precautions, we may expect to find differences greater than the differences in coefficient among the four test shoes of each kind as disclosed by these preliminary check tests. Obviously the differences between the coefficients of the chosen test shoes are less than the differences arising from varia-

*The coefficients for individual stops are not given in this report; but they are, of course, available among the original data for these check tests.

TABLE 26
RESULTS OF CONSTANT SPEED TESTS MADE TO CHECK EQUIVALENCE OF TEST SHOES

Brake Shoe Pressure lb.	Speed m.p.h.	Diamond S Shoes: Test No.	Diamond S Shoes: Brake Shoe No.	Diamond S Shoes: Average Coefficient of Friction per cent	Diamond S Shoes: Deviation of Coefficient for Each Shoe from Mean Coefficient for Pair per cent	Special Chilled Shoes: Test No.	Special Chilled Shoes: Brake Shoe No.	Special Chilled Shoes: Average Coefficient of Friction per cent	Special Chilled Shoes: Deviation of Coefficient for Each Shoe from Mean Coefficient for Pair per cent
1	2	3	4	5	6	7	8	9	10
1500	20	3044	6	21.53	±2.89	3021	30	22.43	±1.06
1500	20	3053	2	22.81		3037	26	22.91	
1500	30	3045	6	19.73	±1.65	3019	30	18.23	±0.76
1500	30	3054	2	20.40		3036	26	18.51	
1500	40	3046	6	18.39	±1.34	3020	30	17.15	±0.65
1500	40	3055	2	18.89		3035	26	16.93	
Av. of 3 Speeds			6	19.88	±2.02	Av. of 3 Speeds	30	19.27	±0.46
			2	20.70			26	19.45	
2500	20	3050	6	19.62	±0.72				
2500	20	3056	2	19.34					
2500	30	3051	6	17.32	±1.87				
2500	30	3057	2	17.98					
Av. of 2 Speeds			6	18.47	±0.48				
			2	18.66					

tions which, in spite of all precautions, continue to inhere in the testing process, and which probably are caused by changes in contact area between shoe and wheel due to the warping of the shoe by the heat generated by friction, and also by momentary changes in the character of the contact surfaces as the metal wears away. In other words, the slight variation among the coefficients of friction of the test shoes is well within the limits of uncertainty inhering in all the test results.

If this view be accepted we are warranted in regarding the test shoes as alike in frictional quality. In the discussion of the test results in the body of the bulletin they have been so regarded; and in comparing tests made with various shoes of like kind, no attempt has been made to correct for the slight variations which have here been under discussion.

3. *Supplementary Check Tests.*—While the preliminary check tests discussed in the preceding section gave satisfactory evidence of the original equivalence of the frictional properties of the test shoes, the

question of their equality again presented itself as the tests progressed. Four of the shoes were therefore subjected to tests on one wheel when the research was about half finished, in order to find out whether the original equality among the shoes had persisted.

Two shoes of each kind were chosen for this purpose—Diamond S shoes Nos. 2 and 6, and Special Chilled shoes Nos. 26 and 30. These are the shoes which, during the main tests, were being used with the two new wheels. Instead of again subjecting them to stop tests, they were this time subjected to constant-speed tests at 1500 pounds pressure, and speeds of 20, 30, and 40 miles per hour; and the two Diamond S shoes were, in addition, tested at 2500 pounds pressure and at 20 and 30 miles per hour. These constant speed tests were all made, in the usual manner, on new steel wheel E. The coefficients of friction thus determined—each of which is the average of the coefficients from ten applications of the shoe—are presented in Table 26, in columns 5 and 9. In columns 6 and 10 is given, for each of the various combinations of pressure and speed, the percentage deviation of the coefficient of each shoe from the average coefficient of the pair of shoes to which it belongs.

Since these supplementary check tests were made at constant speed, whereas the preliminary check tests were stop tests, direct comparisons between the coefficients given in Tables 25 and 26 may not be made; but the *relative* standing of the two pairs of shoes in both sets of tests may properly be compared. For this purpose the deviation percentages shown in columns 6 and 10 of Table 26 may be compared with those shown in columns 7 and 12 of Table 25. They vary in these supplementary check tests from 0.65 per cent to 2.89 per cent; whereas under the preliminary check tests (Table 25) the deviations among all eight shoes varied from plus 2.0 to minus 2.9. The variation among four of the shoes halfway through the research is obviously of about the same order as it was originally among all eight shoes.

A more satisfactory comparison may be made, however, by limiting consideration, in Table 25, to the same four shoes as were tested in the supplementary check tests. This comparison may be made by reference to the following tabulation in which are assembled the deviation percentages for shoes 2 and 6 and shoes 26 and 30 for both the preliminary and the supplementary check tests; the former being calculated from the coefficient values in Table 25, and the latter being taken from columns 6 and 10 of Table 26.

Deviations of the Coefficients of Friction of Diamond S Shoes Nos. 2 and 6, and Special Chilled Shoes Nos. 26 and 30, as Determined by Both the Preliminary and Supplementary Check Tests, Expressed for Each Shoe as a Percentage of the Deviation of Its Coefficient from the Average for the Pair

	From Preliminary Stop Tests			From Supplementary Constant Speed Tests			
	2250 lb. and 30 m.p.h.	3750 lb. and 60 m.p.h.	Both Conditions	1500 lb. and 20 m.p.h.	1500 lb. and 30 m.p.h.	1500 lb. and 40 m.p.h.	All Three Conditions
Shoes Nos. 2 and 6..........	1.00	1.78	1.33	2.89	1.65	1.34	2.02
Shoes Nos. 26 and 30.........	1.24	0.33	0.64	1.06	0.76	0.65	0.46

If in this tabular summary we compare, for each pair of shoes, the values in the first three columns with those in the last four columns, it is obvious that no change of consequence has taken place in the relationship of either shoes 2 and 6 or of shoes 26 and 30; the shoes of each pair, midway in the investigation, were substantially as nearly alike as they had been originally.

When we compare the coefficients* for the ten individual applications which were averaged to determine the coefficient for each shoe presented in Table 26, we find (as we did in considering the individual stops leading to the coefficients in Table 25) that the variation among these applications is frequently greater than the deviation between the shoes of each pair in these supplementary tests; which leads to the same conclusion as that expressed in the preceding section.

All these considerations warrant the conclusion that shoes Nos. 2 and 6 and also Nos. 26 and 30, which had been equal in frictional quality at the beginning of the tests, had remained equal up to this point in the work, and probably so thereafter; and it seems also fair to assume that the four other shoes not included in the supplementary tests (Nos. 3, 7, 28, and 31) had likewise maintained their original equality.

There is therefore in the results of these supplementary check tests nothing to cause us to modify either the general conclusion or the analysis procedure stated in the last paragraph of Section 2 of this appendix.

*These coefficient values are not given in the bulletin.

RECENT PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION†

Bulletin No. 207. The Flow of Air through Circular Orifices with Rounded Approach, by Joseph A. Polson, Joseph G. Lowther, and Benjamin J. Wilson. 1930. *Thirty cents.*

Circular No. 20. An Electrical Method for the Determination of the Dew-Point of Flue Gases, by Henry Fraser Johnstone. 1929. *Fifteen cents.*

Bulletin No. 208. A Study of Slip Lines, Strain Lines, and Cracks in Metals under Repeated Stress, by Herbert F. Moore and Tibor Ver. 1930. *Thirty-five cents.*

Bulletin No. 209. Heat Transfer in Ammonia Condensers. Part III, by Alonzo P. Kratz, Horace J. Macintire, and Richard E. Gould. 1930. *Thirty-five cents.*

Bulletin No. 210. Tension Tests of Rivets, by Wilbur M. Wilson and William A. Oliver. 1930. *Twenty-five cents.*

Bulletin No. 211. The Torsional Effect of Transverse Bending Loads on Channel Beams, by Fred B. Seely, William J. Putnam, and William L. Schwalbe. 1930. *Thirty-five cents.*

Bulletin No. 212. Stresses Due to the Pressure of One Elastic Solid upon Another, by Howard R. Thomas and Victor A. Hoersch. 1930. *Thirty cents.*

Bulletin No. 213. Combustion Tests with Illinois Coals, by Alonzo P. Kratz and Wilbur J. Woodruff. 1930. *Thirty cents.*

Bulletin No. 214. The Effect of Furnace Gases on the Quality of Enamels for Sheet Steel, by Andrew I. Andrews and Emanuel A. Hertzell. 1930. *Twenty cents.*

Bulletin No. 215. The Column Analogy, by Hardy Cross. 1930. *Forty cents.*

Bulletin No. 216. Embrittlement in Boilers, by Frederick G. Straub. 1930 *None available.*

Bulletin No. 217. Washability Tests of Illinois Coals, by Alfred C. Callen and David R. Mitchell. 1930. *Sixty cents.*

Bulletin No. 218. The Friability of Illinois Coals, by Cloyde M. Smith. 1930. *Fifteen cents.*

Bulletin No. 219. Treatment of Water for Ice Manufacture, by Dana Burks, Jr. 1930. *Sixty cents.*

Bulletin No. 220. Tests of a Mikado-Type Locomotive Equipped with Nicholson Thermic Syphons, by Edward C. Schmidt, Everett G. Young, and Herman J. Schrader. 1930. *Fifty-five cents.*

**Bulletin No. 221.* An Investigation of Core Oils, by Carl H. Casberg and Carl E. Schubert. 1931. *Fifteen cents.*

**Bulletin No. 222.* Flow of Liquids in Pipes of Circular and Annular Cross-Sections, by Alonzo P. Kratz, Horace J. Macintire, and Richard E. Gould. 1931. *Fifteen cents.*

Bulletin No. 223. Investigation of Various Factors Affecting the Heating of Rooms with Direct Steam Radiators, by Arthur C. Willard, Alonzo P. Kratz, Maurice K. Fahnestock, and Seichi Konzo. 1931. *Fifty-five cents.*

**Bulletin No. 224.* The Effect of Smelter Atmospheres on the Quality of Enamels for Sheet Steel, by Andrew I. Andrews and Emanuel A. Hertzell. 1931. *Ten cents.*

**Bulletin No. 225.* The Microstructure of Some Porcelain Glazes, by Clyde L. Thompson. 1931. *Fifteen cents.*

Bulletin No. 226. Laboratory Tests of Reinforced Concrete Arches with Decks, by Wilbur M. Wilson. 1931. *Fifty cents.*

**Bulletin No. 227.* The Effect of Smelter Atmospheres on the Quality of Dry Process Enamels for Cast Iron, by A. I. Andrews and H. W. Alexander. 1931. *Ten cents.*

Circular No. 21. Tests of Welds, by Wilbur M. Wilson. 1931. *Twenty cents.*

Bulletin No. 228. The Corrosion of Power Plant Equipment by Flue Gases, by Henry Fraser Johnstone. 1931. *Sixty-five cents.*

---

*A limited number of copies of bulletins starred are available for free distribution.

†Copies of the complete list of publications can be obtained without charge by addressing the Engineering Experiment Station, Urbana, Ill.

**Bulletin No. 229.* The Effect of Thermal Shock on Clay Bodies, by William R. Morgan. 1931. *Twenty cents.*

Bulletin No. 230. Humidification for Residences, by Alonzo P. Kratz. 1931. *Twenty cents.*

**Bulletin No. 231.* Accidents from Hand and Mechanical Loading in Some Illinois Coal Mines, by Alfred C. Callen and Cloyde M. Smith. 1931. *Twenty-five cents.*

**Bulletin No. 232.* Run-Off Investigations in Central Illinois, by George W. Pickels. 1931. *Seventy cents.*

**Bulletin No. 233.* An Investigation of the Properties of Feldspars, by Cullen W. Parmelee and Thomas N. McVay. 1931. *Thirty cents.*

**Bulletin No. 234.* Movement of Piers during the Construction of Multiple-Span Reinforced Concrete Arch Bridges, by Wilbur M. Wilson. 1931. *Twenty cents.*

Reprint No. 1. Steam Condensation an Inverse Index of Heating Effect, by Alonzo P. Kratz and Maurice K. Fahnestock. 1931. *Ten cents.*

**Bulletin No. 235.* An Investigation of the Suitability of Soy Bean Oil for Core Oil, by Carl H. Casberg and Carl E. Schubert. 1931. *Fifteen cents.*

**Bulletin No. 236.* The Electrolytic Reduction of Ketones, by Sherlock Swann, Jr. 1931. *Ten cents.*

**Bulletin No. 237.* Tests of Plain and Reinforced Concrete Made with Haydite Aggregates, by Frank E. Richart and Vernon P. Jensen. 1931. *Forty-five cents.*

**Bulletin No. 238.* The Catalytic Partial Oxidation of Ethyl Alcohol, by Donald B. Keyes and Robert D. Snow. 1931. *Twenty cents.*

**Bulletin No. 239.* Tests of Joints in Wide Plates, by Wilbur M. Wilson, James Mather, and Charles O. Harris. 1931. *Forty cents.*

**Bulletin No. 240.* The Flow of Air through Circular Orifices in Thin Plates, by Joseph A. Polson and Joseph G. Lowther. 1932. *Twenty-five cents.*

**Bulletin No. 241.* Strength of Light I Beams, by Milo S. Ketchum and Jasper O. Draffin. 1932. *Twenty-five cents.*

**Bulletin No. 242.* Bearing Value of Pivots for Scales, by Wilbur M. Wilson, Roy L. Moore, and Frank P. Thomas. 1932. *Thirty cents.*

**Bulletin No. 243.* The Creep of Lead and Lead Alloys Used for Cable Sheathing, by Herbert F. Moore and Norville J. Alleman. 1932. *Fifteen cents.*

**Bulletin No. 244.* A Study of Stresses in Car Axles under Service Conditions, by Herbert F. Moore, Nereus H. Roy, and Bernard B. Betty. 1932. *Forty cents.*

**Bulletin No. 245.* Determination of Stress Concentration in Screw Threads by the Photo-Elastic Method, by Stanley G. Hall. 1932. *Ten cents.*

**Bulletin No. 246.* Investigation of Warm-Air Furnaces and Heating Systems, Part V, by Arthur C. Willard, Alonzo P. Kratz, and Seichi Konzo. 1932. *Eighty cents.*

**Bulletin No. 247.* An Experimental Investigation of the Friction of Screw Threads, by Clarence W. Ham and David G. Ryan. 1932. *Thirty-five cents.*

**Bulletin No. 248.* A Study of a Group of Typical Spinels, by Cullen W. Parmelee, Alfred E. Badger, and George A. Ballam. 1932. *Thirty cents.*

**Bulletin No. 249.* The Effects on Mine Ventilation of Shaft-Bottom Vanes and Improvements in Air Courses, by Cloyde M. Smith. 1932. *Twenty-five cents.*

**Bulletin No. 250.* A Test of the Durability of Signal-Relay Contacts, by Everett E. King. 1932. *Ten cents.*

**Bulletin No. 251.* Strength and Stability of Concrete Masonry Walls, by Frank E. Richart, Robert B. B. Moorman, and Paul M. Woodworth. 1932. *Twenty cents.*

**Bulletin No. 252.* The Catalytic Partial Oxidation of Ethyl Alcohol in the Vapor Phase. The Use of a Liquid Salt Bath for Temperature Control, by Donald B. Keyes and William Lawrence Faith. 1932. *Ten cents.*

**Bulletin No. 253.* Treatment of Water for Ice Manufacture, Part II, by Dana Burks, Jr. 1933. *Forty-five cents.*

**Bulletin No. 254.* The Production of Manufactured Ice at Low Brine Temperature, by Dana Burks, Jr. 1933. *Seventy cents.*

**Bulletin No. 255.* The Strength of Thin Cylindrical Shells as Columns, by Wilbur M. Wilson and Nathan M. Newark. 1933. *Fifty cents.*

**Bulletin No. 256.* A Study of the Locomotive Front End, Including Tests of a Front-End Model, by Everett G. Young. 1933. *(In press.)*

**Bulletin No. 257.* The Friction of Railway Brake Shoes, Its Variation with Speed, Shoe Pressure and Wheel Material, by Edward C. Schmidt and Herman J. Schrader. 1933. *One dollar.*

---

*A limited number of copies of bulletins starred are available for free distribution.

This page is intentionally blank.

This page is intentionally blank.

UNIVERSITY OF ILLINOIS

Colleges and Schools at Urbana

College of Liberal Arts and Sciences.—General curriculum with majors in the humanities and sciences; specialized curricula in chemistry and chemical engineering; general courses preparatory to the study of law and journalism; pre-professional training in medicine, dentistry, and pharmacy.

College of Commerce and Business Administration.—Curricula in general business, trade and civic secretarial service, banking and finance, insurance, accountancy, transportation, commercial teaching, foreign commerce, industrial administration, public utilities, and commerce and law.

College of Engineering.—Curricula in ceramics, ceramic engineering, chemical engineering, civil engineering, electrical engineering, engineering physics, gas engineering, general engineering, mechanical engineering, metallurgical engineering, mining engineering, and railway engineering.

College of Agriculture.—Curricula in agriculture, floriculture, general home economics, and nutrition and dietetics.

College of Education.—Curricula in education, agricultural education, home economics education, and industrial education. The University High School is the practice school of the College of Education.

College of Fine and Applied Arts.—Curricula in architecture, landscape architecture, music, and painting.

College of Law.—Professional curriculum in law.

School of Journalism.—General and special curricula in journalism.

School of Physical Education.—Curricula in physical education for men and for women.

Library School.—Curriculum in library science.

Graduate School.—Advanced study and research.

Colleges in Chicago

College of Medicine.—Professional curriculum in medicine.

College of Dentistry.—Professional curriculum in dentistry.

College of Pharmacy.—Professional curriculum in pharmacy.

Experiment Stations and Scientific Bureaus at Urbana

Agricultural Experiment Station
Engineering Experiment Station
Bureau of Business Research
Bureau of Educational Research
State Geological Survey
State Natural History Survey
State Water Survey

For general catalog of the University, special circulars, and other information, address

The Registrar, University of Illinois,
Urbana, Illinois