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FREIGHT TRAIN CURVE RESISTANCE ON A ONE-DEGREE CURVE AND ON A THREE-DEGREE CURVE

BY

EDWARD C. SCHMIDT

BULLETIN NO. 167

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EDWARD C. SCHMIDT
PROFESSOR OF RAILWAY ENGINEERING

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FREIGHT TRAIN CURVE RESISTANCE
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I. Introduction

1. *Introduction.*—When a train runs on curved track there is a certain excess of resistance over that encountered when it runs on straight track. This excess is termed curve resistance, and it is usually expressed in pounds per ton of train weight per degree of curve. Its magnitude is generally assumed to lie between the limits of 0.3 pound and 1.0 pound per ton per degree. Very frequently its general average value is assumed to be one-half pound per ton per degree.

There are few published records of direct determinations of curve resistance for American cars and track; and the scarcity of experimental data has seemed to warrant the publication of the results here presented. The practice of compensating curves on grades—that is, so reducing the grade through the curve that the combined grade and curve resistances remain equal to the grade resistance on the adjacent tangent—has, when successful, produced indirect evidence concerning the magnitude of curve resistance; and the Manual of the American Railway Engineering Association gives rules for compensating curves which imply a very detailed and definite knowledge of curve resistance. There remains, nevertheless, great divergence of opinion as to its amount.

This bulletin presents the results of tests made with five freight trains on a one-degree curve and a three-degree curve. The final results are given in Table 5 on page 26 and in Fig. 13 on page 27. The results are discussed in Chapter V and the discussion is summarized on pages 35 and 36.

The test results relate exclusively to the resistance of the cars composing the train—the curve resistance of the locomotive is not discussed. The results apply only to freight trains with four-wheeled trucks, although the resistance of our-wheeled truck passenger cars of similar wheel-base is probably not very different.

Throughout this report the terms "resistance" and "net resistance" mean the number of pounds of tractive force required for each ton of train weight in order to keep the train moving on straight and level track, at uniform speed, in still air. The term "resistance on the curve" means the number of pounds of tractive force required for each ton of train weight in order to keep the train moving on a level curve, at uniform speed, in still air. "Curve resistance" is the difference between resistance on the curve and net resistance, divided by the degree of curve; and it is expressed therefore in pounds per ton per degree of curve.

The tests were undertaken primarily to determine the relative merits of three designs of freight car trucks, that is, to determine the effects of truck design upon train resistance on straight track and on curves. In arranging the tests it was clear from the outset that they would provide an exceptional opportunity to measure curve resistance and they were so planned as to make this their secondary purpose. To this end provision was made to acquire and record such data as superelevation, rail wear, variation in gauge, and the like, which were not of first importance for the primary purpose.

2. *Acknowledgment.*—This investigation 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. E. C. SCHMIDT is the head.

II. TRACK AND TRAINS

3. *Test Track.*—Both the primary and the secondary purpose of the tests required that the trains tested be of a length at least comparable with that of short trains in service; and considerations of accuracy in the resistance determination demanded that its average value be measured over a distance of not less than about 1000 feet, with the entire train running on the curve. These requirements implied that the curves ought to be about 1800 feet long; which, of course, hampered the choice of the test track, and practically barred from consideration curves of great curvature. The track finally chosen for the tests consists of a three-degree left curve 1733 feet long, followed by 296 feet of tangent, which was followed by a one-degree curve 3137 feet long; this one-degree curve was followed in its turn by 3341 feet of straight track. The test track is represented in Fig. 1.

This track was especially surveyed for the purposes of this work immediately preceding the tests. Elevations on both rails were measured at stations 100 feet apart; and the curvature on each of the curves was determined for each 100-foot interval. On the one-degree curve the track gauge was measured every 200 feet; and on the three-degree curve, every 100 feet.

At the time the tests were made the test track was in fair condition. The roadbed was about ten years old; it was ballasted with gravel, had a 12-foot crown, and carried a single track. The ties were of untreated

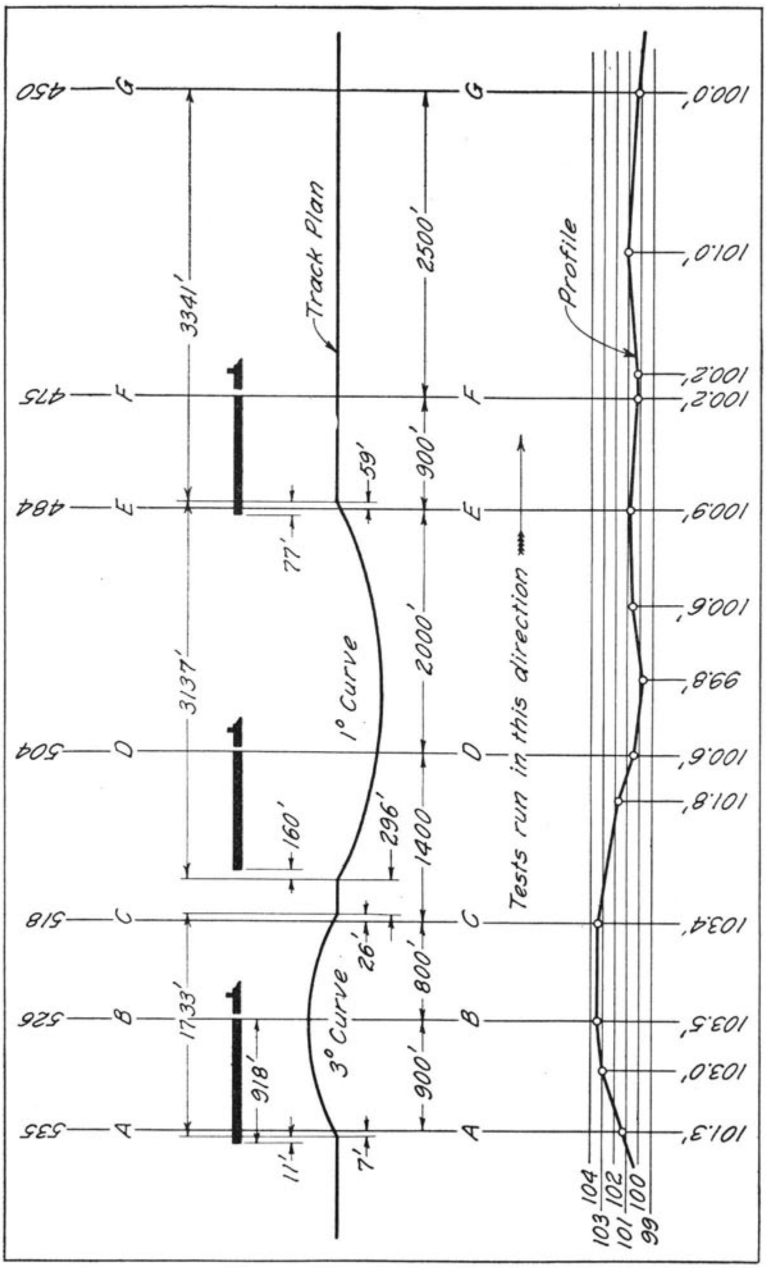

FIG. 1. DIAGRAM OF TEST TRACK

FIG. 2. TEST CAR AND TEST CREW

oak, about 7 in. x 9 in. x 8 ft., and were spaced about 21 in. center to center. The rails were Illinois Steel Company's section No. 7010, weighing 70 pounds per yard; they were laid with the joints staggered and joined by 22-in. angle splices, secured by four bolts at each joint. On the three-degree curve rail braces were applied, about 20 feet apart, on both rails.

All the calculations of resistance on the three-degree curve included in this bulletin relate to the period during which the head end of the train (the rear end of the dynamometer car) passed from point B to point C (Fig. 1), a distance of 800 feet; on the one-degree curve the results relate to the period while the head end passed from D to E, a distance of 2000 feet; and on the tangent the results relate to the interval from F to G—2500 feet. With the head end at B, 11 feet of the rear end of the train were on a tangent and the remainder of the train on the three-degree curve; with the head end at D, the entire train was on the one-degree curve; when the head end was at F, 77 feet of the rear of the train were still on the one-degree curve. This overhang of the train when it was about to enter the test stretches on the three-degree curve and on the tangent arose from failure accurately to forecast the train length when stations B and F were located, and its slight effect has been ignored in the calculations.

TABLE 1

TRAIN DATA

Train Number	Cars, Loaded or Empty	Type of Truck	Number of Cars in the Train *	Length of the Train Behind the Test Car Feet	Train Weight Tons	Average Weight Per Car Tons	Average Side-Bearing Clearance Inches
1	Loaded	A	21	918	1019.7	48.6	0.22
2	Loaded	C	21	918	1019.7	48.6	0.21
3	Loaded	B	21	918	1019.7	48.6	0.21
4	Empty	C	21	918	316.3	15.1	0.28
5	Empty	B	21	918	316.3	15.1	0.28

*The values given in columns 4 to 8 include the caboose; but they exclude the dynamometer car.

While the trains passed from B to C on the three-degree curve they were subjected to the effects of an average super-elevation of 3.71 inches and of an average track curvature of 2 deg. 58½ min., which, in deriving the values of curve resistance, has been taken as equivalent to 3.0 degrees. While the trains passed from D to E on the one-degree curve they were subjected to the effects of an average super-elevation of 0.89 inch and of an average track curvature of 1.0 degree.

A few additional details concerning the track appear in Appendix A.

4. *Trains.*—Tests were made with five trains whose principal characteristics are indicated in Table 1. The five trains differ solely in the construction of the trucks and in the presence or absence of load on the cars. They were all composed of 20 identical flat-car bodies arranged in the same order in all trains. Wheels, axles, and journal brasses were identical in all five trains; and in trains 1, 2, and 3 the load was the same and was composed of identical material on each car, namely, unfabricated rolled steel sections and castings.

The tests were begun with train No. 2 which was equipped with trucks of type C. Truck B, which was used on trains Nos. 3 and 5, is merely truck C with certain parts removed, and this removal was effected without dismounting the trucks, or disturbing the cars or their load; for train No. 4 truck B was re-converted into truck C by replacing these parts. Upon the completion of the tests with train No. 5, it was returned to the shops, the car bodies were lifted by a crane and the trucks removed —the wheels and axles and journal brasses being first withdrawn. Trucks of type A were then placed in position under the car and the wheels and axles and brasses were placed in the new trucks, care being taken to restore each axle to its original position, and each brass to its original journal. There was then replaced on each car the identical load it had

FIG. 3. ONE OF THE LOADED TRAINS ON THREE-DEGREE CURVE

borne in trains Nos. 2 and 3, and the cars were re-assembled in their original order. The train thus constituted is here designated as train No. 1.

These unusual arrangements to attain similarity among the trains were regarded as necessary to the primary purpose of the tests—the comparison of truck performance. While they were not essential to the determination of curve resistance, they have not made the curve resistance results less general in their application. All three types of truck were of cast steel construction, and they are representative of trucks encountered in service. Scores of thousands of trucks of types A and B are in freight service on American and Canadian railroads, and the special features in the construction of truck C do not make its action dissimilar to that of trucks in common use.

All three types of trucks had a wheel-base of 5 ft. 6 in.; and on all cars the distance from center to center of trucks was 30 feet. All wheels were of chilled cast iron and 33 in. in diameter, and all journals were 5 in. x 9 in. Certain additional information about the cars and the trains is given in Appendix A. Figure 3 shows one of the loaded trains standing on the three-degree curve.

TABLE 2

TEST PROGRAM

Train Number	Number of Tests Run			
	At 10 m.p.h.	At 20 m.p.h.	At 30 m.p.h.	At All Speeds
1	6	9	11	26
2	3	11	8	22
3	1	9	8	18
4	5	5	8	18
5	5	5	7	17
All Trains......	20	39	42	101

III. TEST PROCEDURE, METHODS, AND CONDITIONS

5. *Test Program.*—By "test," in this connection, is meant one continuous run with any of the trains from point B to point G on the test track (Fig. 1). Tests were run at three speeds—nominally 10, 20, and 30 miles per hour. Table 2 shows the number of tests made at each of these speeds with each of the trains.

It was the intention to run at each speed with each train enough tests to define a reliable average value of train resistance at that speed—reliability being largely judged by the agreement among the resistance values. It is to be observed that notwithstanding this intention, only one test is shown for train No. 3 at 10 miles per hour. Actually, however, five tests were run with this train at this speed; but during four of them the record on the one-degree curve was incomplete, and these four were rejected because it was desired that for each resistance value on the straight track there be a strictly comparable value on each of the curves. On this account reliance is placed in this instance upon a single test; that it is not misplaced is indicated by the fact that on the three-degree curve and on the tangent, where results for five tests are available, the average resistance for all five is nearly the same as the resistance in the single test. As was just intimated, each of the tests whose results are included in the bulletin gave results not only on the tangent, but on each curve; that is, for every value of net resistance on straight track here presented there are corresponding values of resistance on the two curves, obtained from the same train within the space of a few minutes and under almost identical conditions.

6. *Immediate Purpose of Tests.*—The immediate purpose of the tests was to determine the average gross tractive force required to move each train over the test sections. This was accomplished by means of

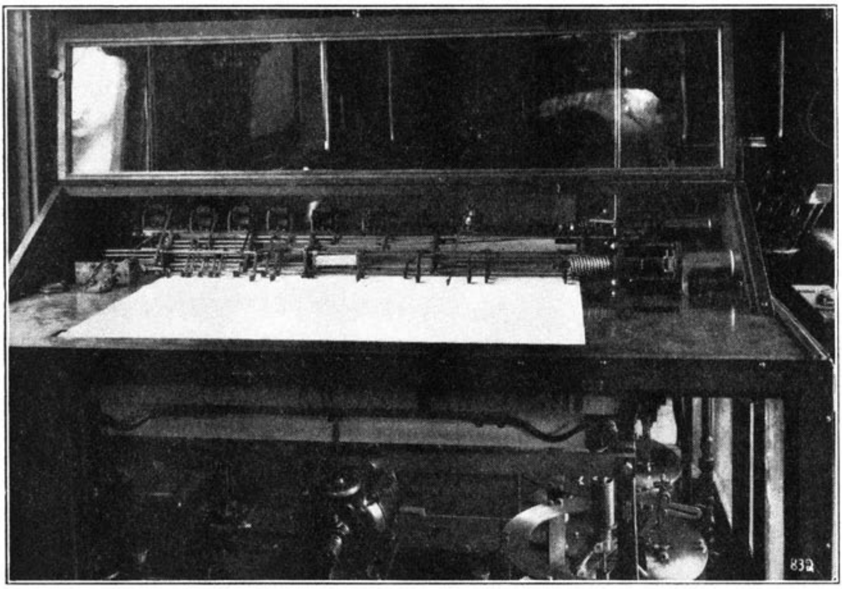

FIG. 4. RECORDING APPARATUS AND CHART IN DYNAMOMETER CAR

the University of Illinois dynamometer car, which measures and graphically records drawbar pull, speed, time, wind velocity, wind direction, train-line pressure, and brake-cylinder pressure. This car* is shown in Fig. 2 and its recording mechanism in Fig. 4.

From the test car records the average gross resistance was determined for the periods while the head of the train passed from B to C, from D to E, and from F to G (Fig. 1) on the three-degree curve, the one-degree curve, and the straight track, respectively. Correcting this gross resistance for grade and acceleration, we obtain the net resistance on straight track and the resistance on the curves; and the difference between these quantities is the desired curve resistance.

7. *Correction for Grade.*—By a process which is described in Appendix A, the heights of the center of gravity of the train were calculated for the positions when the head end entered and when it left the test sections. The difference between these heights defines the average grade and establishes the correction for grade

8. *Correction for Acceleration.*—The accurate determination of acceleration, important in all train resistance measurements, was of especial

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*A detailed description of the car appears in "Freight Train Resistance," Univ. of Ill. Eng. Exp. St. Bul. 43, and also in the Railway Age-Gazette, February 19, 1909.

importance in these tests, because the test sections were short and the work to produce acceleration might, if uncontrolled, constitute a large share of the total work performed on the train in moving it over these sections; and any errors in the determination of the acceleration correction might consequently occasion large errors in net resistance. For this reason precautions were taken to maintain as nearly uniform a speed as possible over the test track and to measure with as much accuracy as possible the speeds at entrance to and exit from the test sections.

To facilitate the control of speed, a speed indicator was installed in the locomotive cab and the engineer was instructed not only to approach the test track at the predetermined speed, but to maintain until the end of the run the speed at which he passed the point B (Fig. 1). While it proved impossible precisely to conform to these instructions, his efforts did result in a much more uniform speed and a smaller acceleration correction than would otherwise have been attained.

The speed at the limits of the test sections (points B, C, D, E, F, and G in Fig. 1) was measured by means of two chronographs, one of which was located in a station building near A and the other within the test car. Two chronographs were used in order that the data might still be complete in case either of them failed to give a useful record. At each section limit—point B, for example—were placed two circuit breakers or "trips," like the one shown in the middle foreground of Fig. 5. These trips were located equidistant from B; they were accurately spaced either 60 feet or 120 feet apart, depending on the speed at which the tests were to be run, and they were connected in series in an electric circuit which extended along the track. This circuit controlled a magnet mounted on the drum chronograph in the station at A, and the magnet operated a pen which drew a line on the chronograph chart. As the test car passed each trip its upper arm was displaced by a striking board mounted on the side of the car as shown in Fig. 5, and the circuit through the trip was thereby broken until the lower arm fell into the fork at the base and re-established it. This momentary interruption of the current caused an offset in the line drawn on the chronograph chart by the pen. The distance on the chart between these offsets represents, to some scale, the distance between trips. Another magnet-controlled pen drew on the chart a second line parallel to the one just mentioned. The magnet of this pen was actuated by a contact device in a clock, which broke contact every half second and thereby caused offsets in the time record at these intervals. By correlating the time and distance records on the chart the time elapsed in passing from trip to trip was evaluated and the average speed between

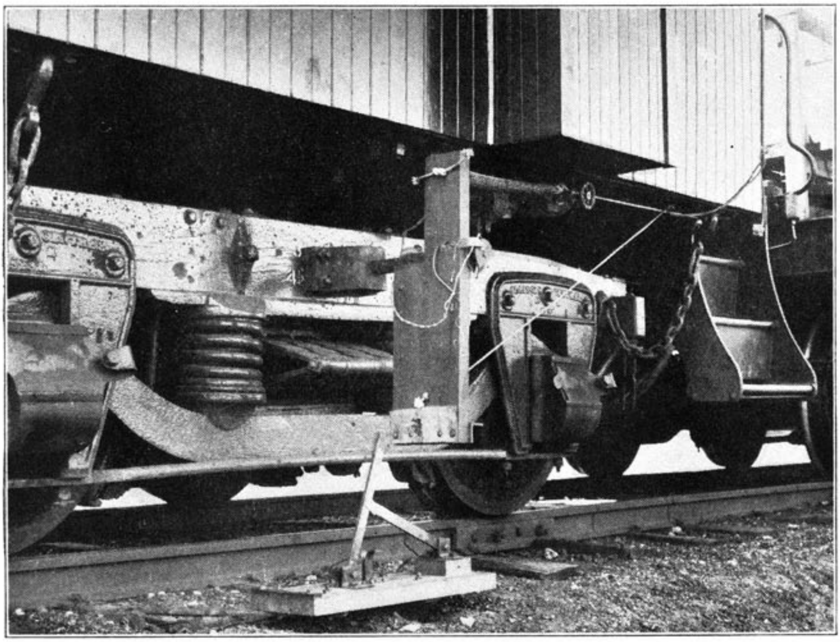

FIG. 5. CIRCUIT BREAKERS WHICH OPERATED PENS ON CHRONOGRAPHS

trips was calculated. This average speed is the speed at the instant the head of the train passed the point B, because even though speed variation might have occurred in passing from trip to trip, the rate of variation over so short a distance must have been substantially uniform. In similar manner the speeds as the train passed the other section limits were established. These speeds being known, the mean accelerations in passing from B to C, D to E, and F to G were determined and the corrections for acceleration resistance were calculated therefrom.

As already stated a second chronograph was installed within the test car. On the paper ribbon of this instrument there were also drawn a distance record and a time record by pens controlled by electromagnets. One of these magnets was connected in series with a circuit breaker mounted on the end of the trunnion which supported the striking board hung from the side of the test car, as shown in Fig. 5. This breaker opened at the instant the board struck the track trip and it was closed again as the board was drawn back into striking position by the spring shown in the figure. This interruption of the current caused offsets in the distance record corresponding to the positions of the track trips. The time record on the car chronograph was obtained by means similar

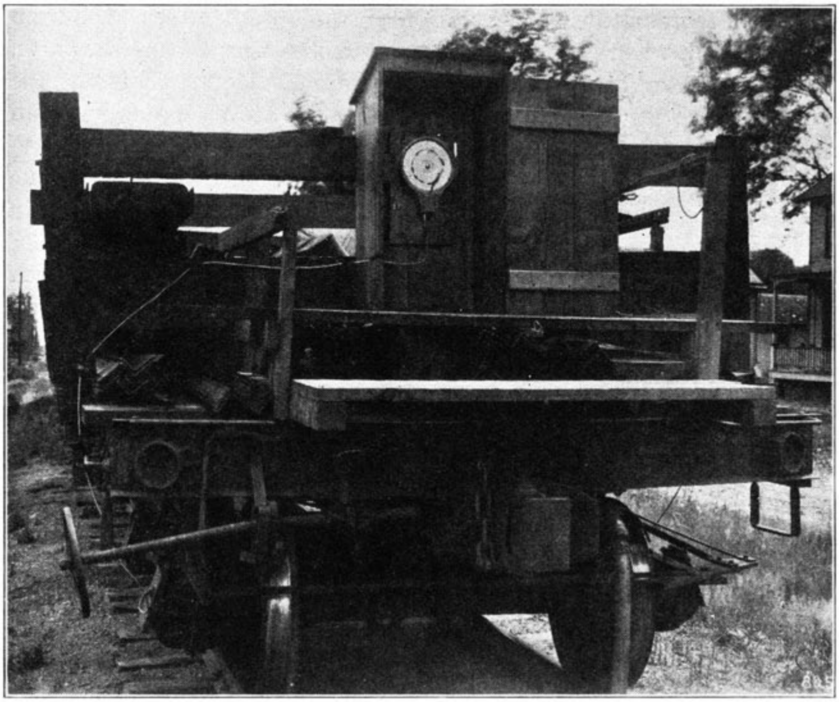

FIG. 6. RECORDING THERMOMETER USED TO MEASURE CAR JOURNAL TEMPERATURE

to those used on the station instrument, except that in this case the time intervals were marked by a contact-breaking chronometer which operated every one-fifth of a second. Because of its superior time record, most of the speed calculations are based upon records obtained from this chronograph in the test car, the records from the station instrument being resorted to only when the former were incomplete.

9. *Journal Temperature.*—Journal temperature has an important influence on train resistance, and the resistance of a train running at any given speed will steadily decrease until its journals reach their maximum temperature. In order, therefore, to ensure uniformity of operating conditions in this respect a recording thermometer was mounted on the first car of the test trains, the bulb of the instrument being inserted in a hole drilled in the brass of one of the journals of the leading axle. The arrangement is shown in Fig. 6. In preparation for each test the train was backed up several miles from the entrance to the test track and was run a sufficient distance at the test speed to bring

its journal temperature to a condition of equilibrium; that is, the train was run until, when it reached the point A, the temperature shown on the thermometer had reached the maximum value attainable at the speed at which the test was to be run. All tests at like speeds were run under journal temperatures very nearly alike, and all the results presented in the bulletin show the train resistance when, for the various speeds, temperature equilibrium had been nearly or quite attained in the journals.

This journal thermometer broke at the beginning of the tests with train No. 4 and could not be replaced until the conclusion of the tests with train No. 5. During the tests with these two empty trains, therefore, reliance was placed upon the temperature record obtained from a similar thermometer regularly carried on the test car and connected to one of the test car journals. The test car journals are more heavily loaded than the journals in the empty trains, and it is not certain that the latter had always fully attained equilibrium temperatures when the test car journals had done so. It is safe, nevertheless, to assume that when temperature equilibrium was established in the test car journals, the temperature of the train journals bore an invariable relation to the temperature of the test car journals, and that consequently the tests with these two trains, at any of the three nominal speeds, were all run at like journal temperature—even though this temperature may have been slightly below the maximum.

10. *Correction for Wind Resistance.*—Net resistance and resistance on the curve, while they necessarily include the resistance due to still air, ought properly to be corrected for the resistance due to such winds as prevailed during each test. Although from the test car records the velocity of the wind and its angle with respect to the track have been calculated for each test, no attempt has been made to apply such corrections. The failure to do so is justified by the facts that the winds were unusually light, that their effects on flat cars are small, and that the uncertainty concerning the magnitude of wind resistance might have introduced errors almost as great as the corrections themselves. Furthermore, while the wind velocity during any one test did not always remain the same on the curves and on the straight track, it did not vary greatly, and the wind resistance errors remaining in the resistance on the curve and in the resistance on the straight track were generally substantially the same for each test; consequently, since curve resistance is the difference between these two quantities, the wind resistance errors are practically eliminated from the calculated curve resistance by the process of subtraction.

TABLE 3

SUMMARY OF TEST CONDITIONS

Train Number	Number of Tests Made			Air Temperature		Wind Velocity	
	Total Number	Number in Dry Weather	Number in Rain or On Wet Rail	Minimum Deg. F.	Maximum Deg. F.	Minimum m.p.h.	Maximum m.p.h.
1	26	21	5	62	89	0.7	13.1
2	22	22	0	64	94	4.0	18.0
3	18	17	1	72	88	3.5	11.9
4	18	17	1	66	90	2.5	14.4
5	17	17	0	84	95	3.9	19.5
All Trains..	101	94	7	62	95	0.7	19.5

11. *Weather Conditions.*—The weather during the tests was generally fair and warm, and favorable to the development of uniform and minimum train resistance. Only 7 of the 101 tests were run during rain or on wet rails. In only two tests did the wind velocity exceed 15 miles per hour. The range in weather conditions for tests with each of the five trains is presented in Table 3.

12. *Methods of Calculation.*—The methods used in deriving the final results of the tests are, in general, the same as those described on pages 86-95 of Bulletin 43 of the Engineering Experiment Station of the University of Illinois; one exception, however, deserves mention. In Bulletin 43, in establishing the equation for calculating the resistance due to acceleration in the rotation of the wheels and axles, there were used for the weight and for the radius of gyration of one pair of wheels and their axle, values which are approximate averages for the various wheels and axles ordinarily encountered in freight service. For the tests here under discussion, however, these quantities were especially determined for the particular wheels in use on these trains. For this purpose one pair of wheels and their axle were removed from the train, weighed, suspended by links from a horizontal axis about five feet above the axle center, and vibrated about this axis in order to measure the time of oscillation. From the oscillation period thus determined and the weight, the radius of gyration about the axle center line was calculated and used in the equation referred to.

IV. RESULTS OF TESTS

13. *Immediate Results.*—The immediate results of each test are three values of resistance—one for the straight track, one for the one-

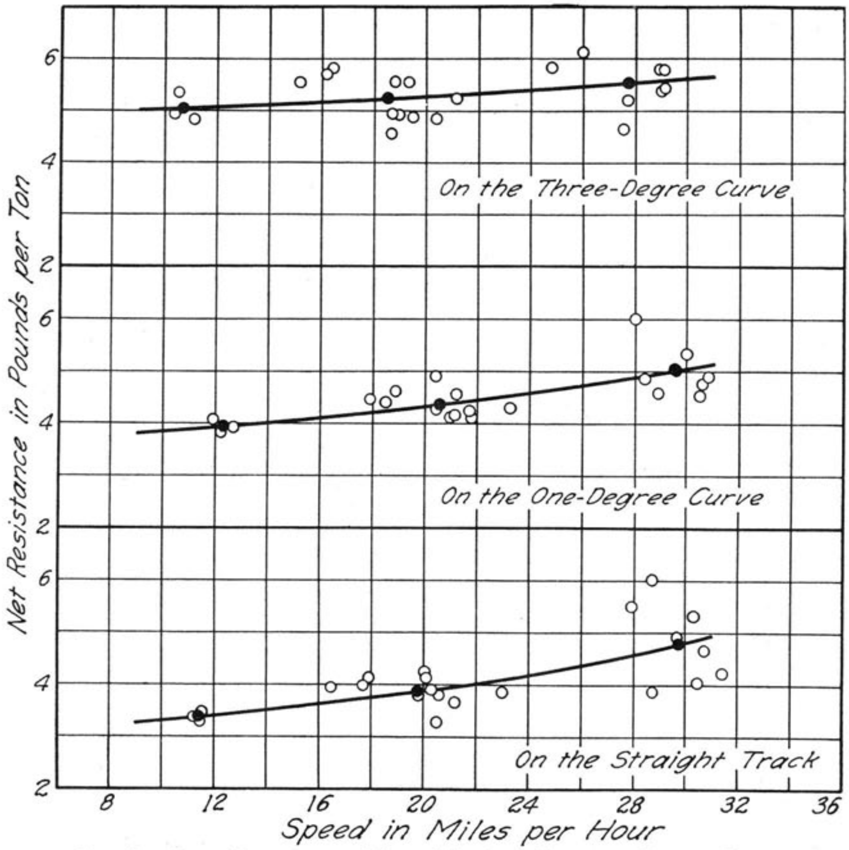

FIG. 7. TEST RESULTS FOR TRAIN NO. 2 ON STRAIGHT TRACK, ONE-DEGREE CURVE, AND THREE-DEGREE CURVE

degree curve, and another for the three-degree curve—together with three corresponding values of speed. These values of resistance and speed, for each of the five trains, are given in Tables 8 to 12 in Appendix B. For train No. 1, for example, Table 8 shows that during test 135, while the train passed from F to G on the straight track, its mean net resistance was 3.64 pounds per ton of train weight and its mean speed, 11.10 miles per hour. The seventh line in Table 8 shows that for all six tests made with this train at the nominal speed of 10 miles per hour, the *average* net resistance on the straight track was 3.50 pounds per ton, and the *average* speed was 10.85 miles per hour. Table 8 provides similar individual and average values of resistance and speed for train No. 1 on each of the two curves; and Tables 9, 10, 11, and 12 give the same sort of information for the other four trains. These five tables embody all the direct results of the tests.

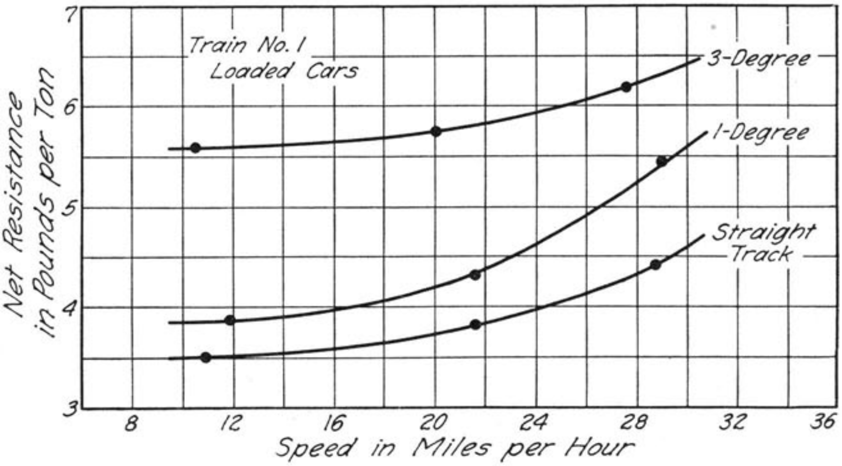

FIG. 8. NET TRAIN RESISTANCE FOR TRAIN NO. 1 ON STRAIGHT TRACK AND BOTH CURVES

14. *Graphical Presentation of Immediate Results.*—The next step in deriving curve resistance was to plot, as in Fig. 7, the corresponding values of resistance and speed derived from Tables 8 to 12. In Fig. 7, which is derived from Table 9 applying to train No. 2, the results of the individual tests on the straight track are plotted at the bottom of the figure. The three tests made at the nominal speed of 10 miles per hour give the three points shown as circles at the left of this diagram; the eleven tests at 20 miles per hour provide the middle group of points; and the eight tests at 30 miles per hour give the right-hand group—all these points being defined by the co-ordinates given in the third and fourth columns of Table 9. In each group of points the black dot represents the average value of the co-ordinates of the points in that group, and it is plotted from the "average values" shown in Table 9. The curve shown in the figure has been drawn to pass through these black dots, and this curve is accepted as defining the relation between net resistance and speed for train No. 2 when running on the straight track. In similar manner, using the co-ordinates from columns 5 and 6 of Table 9, the curve in the center of Fig. 7 was drawn to define the relation between resistance and speed on the one-degree curve; while the curve at the top, plotted from the co-ordinates in the last two columns of Table 9, represents this relation on the three-degree curve.

Similar diagrams showing the relation between resistance and speed on the tangent and both curves were drawn for each of the other four trains; but these diagrams are not here presented. As regards

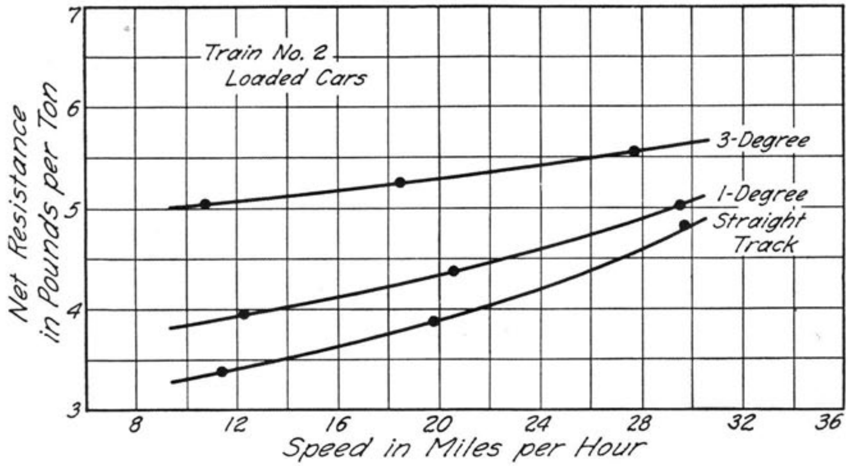

FIG. 9. NET TRAIN RESISTANCE FOR TRAIN NO. 2 ON STRAIGHT TRACK AND BOTH CURVES

concordance among the plotted values of resistance, Fig. 7 is fairly representative of the diagrams for the four other trains. The agreement is better than that which generally prevails among train resistance measurements, and this fact is, no doubt, to be ascribed to the precautions previously referred to.

It may be useful to restate briefly some of the facts relating to the results of the individual tests plotted in Fig. 7. Each point represents the mean resistance for a period during which the train ran entirely on straight track, entirely on the one-degree curve, or entirely on the three-degree curve. For each point representing resistance on the straight track, there are two corresponding points representing resistance on the curves, all three resistance values being derived from measurements made within a period of a few minutes and from the same train operating under nearly identical conditions. For each point the resistance value has been corrected for resistance due to grade and acceleration, but not for the slight wind resistance which may have existed.

While the production of diagrams like Fig. 7 was designated as the first step in deriving curve resistance from the test results, the plotting of the points representing the results of individual tests is not essential to the process; for the curves in these diagrams can be drawn —and they actually were so drawn—by limiting consideration to the three points (the black dots) which represent for each nominal speed the average relation between resistance and speed. Figure 7, with its

TABLE 4

VALUES OF RESISTANCE ON STRAIGHT TRACK AND ON CURVES AT 10, 20, AND 30 MILES PER HOUR, AND DERIVED VALUES OF CURVE RESISTANCE

Train Numbers	Speed m.p.h.	Resistance on the Straight Track and on the Curves. Pounds per Ton			Total Resistance Due to Curvature Pounds per Ton		Curve Resistance Lb. per Ton per Degree	
		On the Straight Track	On the One-Degree Curve	On the Three-Degree Curve	On the One-Degree Curve Col. 4 − Col. 3	On the Three-Degree Curve Col. 5 − Col. 3	On the One-Degree Curve Col. 6 ÷ 1.0	On the Three-Degree Curve Col. 7 ÷ 3.0
1	2	3	4	5	6	7	8	9
1	10	3.50	3.85	5.59	0.35	2.09	0.35	0.70
	20	3.73	4.20	5.75	0.47	2.02	0.47	0.67
	30	4.60	5.60	6.43	1.00	1.83	1.00	0.61
2	10	3.30	3.84	5.02	0.54	1.72	0.54	0.57
	20	3.89	4.35	5.30	0.46	1.41	0.46	0.47
	30	4.83	5.08	5.64	0.25	0.81	0.25	0.27
3	10	3.33	3.90	4.97	0.57	1.64	0.57	0.55
	20	4.00	4.50	5.36	0.50	1.36	0.50	0.45
	30	4.67	5.27	6.11	0.60	1.44	0.60	0.48
4	10	5.09	5.55	7.16	0.46	2.07	0.46	0.69
	20	6.85	6.97	8.48	0.12	1.63	0.12	0.54
	30	8.96	9.48	9.83	0.52	0.87	0.52	0.29
5	10	4.25	4.91	6.35	0.66	2.10	0.66	0.70
	20	4.99	5.74	7.25	0.75	2.26	0.75	0.75
	30	8.08	8.47	9.31	0.39	1.23	0.39	0.41

plotted results of the individual tests, is presented chiefly to illustrate the agreement among the points which has been referred to.

If consideration be limited to the *average* values of resistance and speed for train No. 2, we may plot these values as in Fig. 9, and draw the three curves there shown to define the resistance-speed relations for this train. These curves in Fig. 9 are identical with those in Fig. 7. In like manner, curves showing these relations for the four other trains have been produced and they are presented in Figs. 8, 10, 11, and 12. In all five figures the points are plotted by using the co-ordinates designated as "average values" in Tables 8 to 12 in Appendix B. The relation between the figures, the trains, and the tables is as follows:

Fig. 8, applying to Train No. 1, is derived from Table 8
Fig. 9, applying to Train No. 2, is derived from Table 9
Fig. 10, applying to Train No. 3, is derived from Table 10
Fig. 11, applying to Train No. 4, is derived from Table 11
Fig. 12, applying to Train No. 5, is derived from Table 12

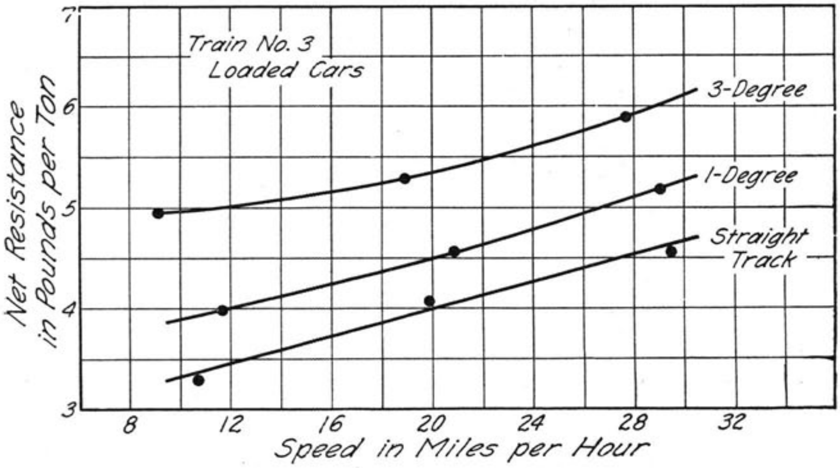

FIG. 10. NET TRAIN RESISTANCE FOR TRAIN NO. 3 ON STRAIGHT TRACK AND BOTH CURVES

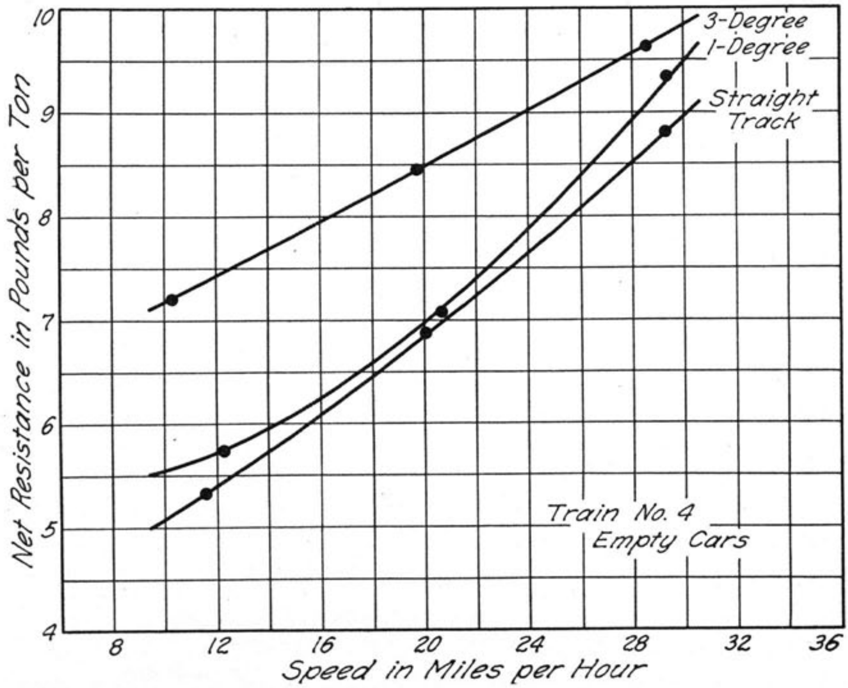

FIG. 11. NET TRAIN RESISTANCE FOR TRAIN NO. 4 ON STRAIGHT TRACK AND BOTH CURVES

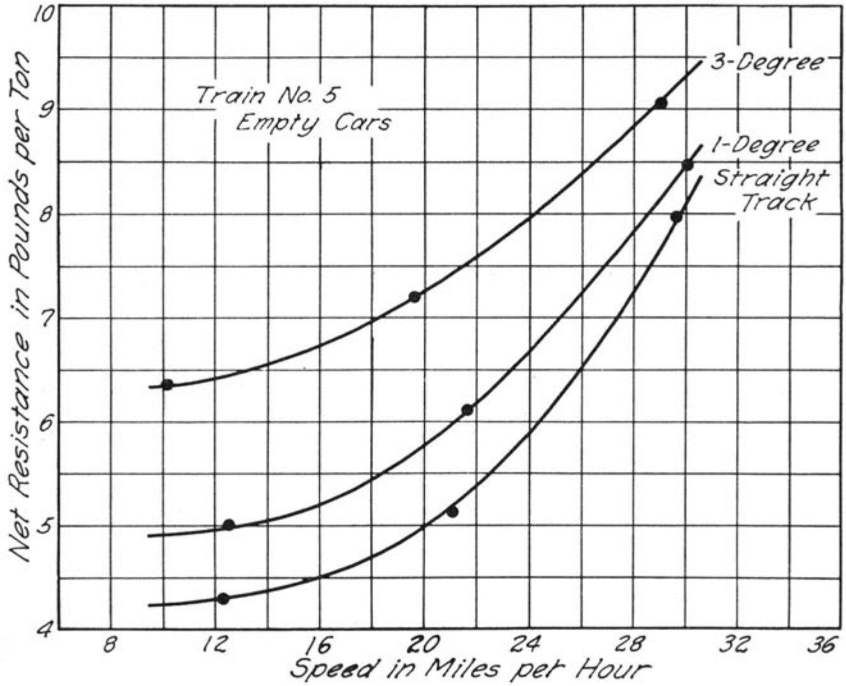

FIG. 12. NET TRAIN RESISTANCE FOR TRAIN NO. 5 ON STRAIGHT TRACK AND BOTH CURVES

15. *Final Results—Curve Resistance.*—The resistance due to track curvature being the difference between the resistance on straight track and the resistance on the curve, the differences, at any speed, between the ordinates of the three lines drawn in Fig. 8, for example, will give the values of resistance due to track curvature at that speed for train No. 1. In this discussion, however, the values of resistance due to curvature are presented only for three speeds which closely approach the general average test speeds, namely, 10, 20, and 30 miles per hour; because, since the lines in the figure are defined by only three points, their validity is questionable except in the immediate vicinity of those points.

In Fig. 8 the three lines cross the ordinate corresponding to the speed of 10 miles per hour at points whose resistance values are 3.50, 3.85, and 5.59 pounds per ton, which are respectively the values of resistance for train No. 1 on the straight track, on the one-degree curve, and on the three-degree curve. These values are assembled in Table 4, in the first line of columns 3, 4, and 5; and the values for speeds of 20 and 30

TABLE 5

FINAL VALUES OF CURVE RESISTANCE, AT VARIOUS SPEEDS FOR EACH OF THE FIVE TRAINS, AND AVERAGE VALUES FOR ALL TRAINS

Train Numbers	Curve Resistance———Pounds per Ton Per Degree					
	On the One-Degree Curve			On the Three-Degree Curve		
	10 m.p.h.	20 m.p.h.	30 m.p.h.	10 m.p.h.	20 m.p.h.	30 m.p.h.
1	0.35	0.47	1.00	0.70	0.67	0.61
2	0.54	0.46	0.25	0.57	0.47	0.27
3	0.57	0.50	0.60	0.55	0.45	0.48
4	0.46	0.12	0.52	0.69	0.54	0.29
5	0.66	0.75	0.39	0.70	0.75	0.41
Average for All Trains	0.52	0.46	0.55	0.64	0.58	0.41
Average, Disregarding Distinctions in Speed	0.51			0.54		

miles per hour, similarly determined, are assembled in this table, in the second and third lines respectively. For the other trains, similar values of resistance on the tangent and the curves, derived from Figs. 9, 10, 11, and 12, are likewise presented in Table 4.

The differences between these tabulated values give the final values of curve resistance. Recurring to the resistance values for train No. 1 at 10 miles per hour, just cited, we find the resistance on the one-degree curve to be 3.85 pounds per ton and on the tangent 3.50 pounds; the difference, 0.35 pounds per ton, is the resistance due to the curvature on the one-degree curve. Since in this instance the degree of curve is 1.0, this value (0.35) is likewise the final value of curve resistance in pounds per ton per degree. On the three-degree curve the resistance is 5.59, and the difference between this and 3.50 (resistance on the tangent) gives 2.09 pounds per ton as the total resistance due to curvature; in this instance, the curvature being 3.0 degrees, the value of curve resistance is $2.09 \div 3 = 0.70$ pounds per ton per degree. Similar values of resistance due to curvature, similarly derived, for all trains and all speeds, are given in columns 6 and 7 of Table 4. The final values of curve resistance (found by dividing the values in columns 6 and 7 by 1.0 and 3.0 respectively) are presented in columns 8 and 9 of this table. These are the final results of this investigation.

These final results are reassembled in Table 5 in somewhat more convenient form. In this table the curve resistance, expressed in pounds

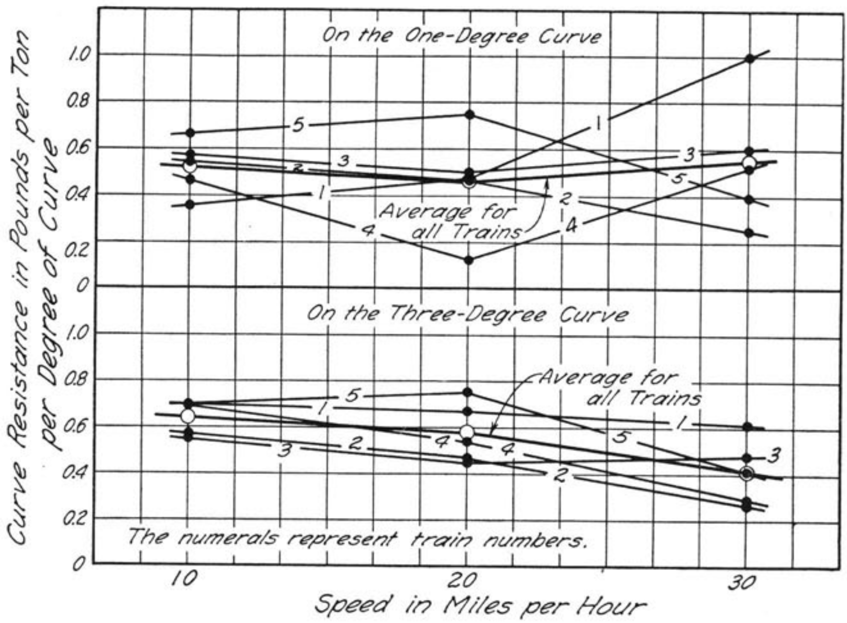

FIG. 13. CURVE RESISTANCE AT 10, 20, AND 30 MILES PER HOUR FOR EACH OF THE FIVE TRAINS, AND AVERAGE VALUES FOR ALL TRAINS

per ton per degree of curve, is given for each of the five trains in the first five lines of the table. The sixth line presents the average values of curve resistance at the three speeds for all trains; and the last line gives the average results on each curve for all trains, when speed distinctions are ignored.

16. *Final Results in Graphical Form.*—By plotting the values of curve resistance for each of the trains, as given in Table 5, we obtain the diagrams of Fig. 13—the upper diagram giving the final results on the one-degree curve, and the lower diagram those on the three-degree curve. In this figure the lines marked "average" show, for each curve, the average values of curve resistance for all five of the trains. Figure 13, like Table 5, presents the final results of these tests.

V. DISCUSSION OF RESULTS

17. *Divergence Among Final Results.*—Inspection of the final results, as exhibited in Fig. 13, discloses a considerable divergence among them on the one-degree curve, the minimum value of curve

resistance being 0.12 pound per ton per degree, and the maximum value, 1.0 pound. On the three-degree curve there is less divergence.

Reasons for this divergence have been sought in the following differences in the trains and in the conditions under which they were operated: namely,

(a) Difference in the average weight of the cars composing the trains

(b) Difference in truck construction

(c) Difference in wind resistance

(d) Difference in the condition of the rail—whether dry or wet

While car weight influences net resistance, it does so chiefly through its effect on journal friction and this effect is nearly, if not quite, the same on straight track and on curves. The effect will consequently not appear in the curve resistance, which is derived by subtracting the resistance on straight track from the resistance on the curve. Nevertheless, a reason for the divergence among the results has been sought in the difference in car weight by averaging the results separately for the three loaded trains and the two empty trains. These averages are tabulated below.

Average Values of Curve Resistance for the Loaded and the Empty Trains

Pounds per Ton per Degree

Train Numbers	Average Car Weight Tons	On the One-Degree Curve			On the Three-Degree Curve		
		10 m.p.h.	20 m.p.h.	30 m.p.h.	10 m.p.h.	20 m.p.h.	30 m.p.h.
Nos. 1-2-3 Loaded Cars	48.6	0.49	0.48	0.62	0.61	0.53	0.45
Averages		0.53			0.53		
Nos. 4-5 Empty Cars	15.1	0.56	0.44	0.46	0.70	0.65	0.35
Averages		0.48			0.56		

There is nothing in the relations between these values to warrant the inference that variation in car weight is responsible for the variation in the results of the tests.

The trucks in the different trains differed in the stiffness of their construction, and this might have affected the curve resistance. The trucks on trains Nos. 3 and 5 were identical and less stiff than the others. While the values for train No. 5 are high on both curves, those for train No. 3 are normal on the one-degree curve and slightly low on the three-degree curve; and no satisfactory explanation of the divergence among the results may be drawn from these facts.

The possible influence of wind resistance is obvious; but a detailed study of the original wind data discloses no tenable explanation for the variation among the lines of Fig. 13.

All theories of curve resistance agree in ascribing it to the work absorbed by friction between the rail head and the flanges and treads of the wheels; and it would seem probable that when these surfaces are wet, the lubricating effect of the water would reduce the curve resistance. Of the 101 tests, upon whose results this report is based, seven were run on wet rails; and of these seven tests five are included among the eleven tests run with Train No. 1 at 30 miles per hour. The values of curve resistance for this train at this speed have been separately calculated for the tests on the wet rail and for those on the dry rail, with the following results:

CURVE RESISTANCE OF TRAIN NO. 1 AT 30 MILES PER HOUR

Pounds per Ton per Degree

	On the One-Degree Curve	On the Three-Degree Curve
Average for the 5 tests run on wet rail	0.87	0.57
Average for the 6 tests run on dry rail	1.17	0.65
Average for all 11 tests (as in Table 5)	1.00	0.61

The relation between these values lends some support to the inference just drawn, namely, that curve resistance is probably diminished when rails and wheels are wet. The showing does not, however, help to explain the divergence among the test results exhibited in Fig. 13; for, instead of having a low curve resistance, train No. 1 at 30 miles per hour has a higher resistance on both curves than any other train. Whatever may be the influence of the wet rail, it has obviously been over-topped in this instance by some other influence.

It is a common experience in measuring train resistance to find that, for a given train, it will vary from time to time even under conditions which are apparently identical. Such variation is commonly attributed to momentary changes in flange resistance and oscillatory resistances; and if any of the divergent points of Fig. 13 were based upon one test only, its divergence could plausibly be attributed to such changes. There is in Fig. 13 only one point based on a single test—the one which defines the curve resistance for train No. 3 at 10 miles per hour; but this point in the diagram for the one-degree curve nearly coincides with the average for all trains, and on the diagram for the three-degree curve it is not notably divergent. All other values plotted in Fig. 13 are averages of the results from three or more tests and, consequently, the momentary or periodic variations in train resistance referred to above offer no acceptable explanation for the variation in the test results.

The information at our disposal seems inadequate to account for the differences in the curve resistance of the five trains as exhibited in Table 5 and Fig. 13. Some of the variation may be due to inaccuracies in the test appliances and methods; but much of it must be regarded as unaccounted for, and likely to be encountered in trains in service. The total range in curve resistance for all tests is from a minimum of 0.12 to a maximum of 1.00 pound per ton per degree of curve. If from the results on the one-degree curve we exclude the two most divergent —those for train No. 1 at 30 m.p.h., and for train No. 4 at 20 m.p.h.— the general range in the value of curve resistance on both curves is from 0.25 to 0.75 pound per ton per degree.

18. *Influence of Track Curvature.*—The best available measure of the influence of track curvature on curve resistance afforded by these tests is the average result for all trains, irrespective of speed. This average is presented in the last line of Table 5. For the one-degree curve it amounts to 0.51 pound per ton per degree of curve; and for the three-degree curve, 0.54 pound per ton per degree. Obviously the only conclusion to be drawn from these results is that the sharpness of the curve has no effect on curve resistance expressed in pounds per ton per degree of curve. Whether this conclusion would hold good for curves of a curvature greater than three degrees cannot be determined from these tests. It is to be regretted that the test program did not include tests on curves of greater curvature; but, as has been intimated, it was impracticable to do so.

19. *Influence of Speed on Curve Resistance.*—If in Fig. 13 we confine our attention to the lines representing the average curve resistance for all five trains, we find on the one-degree curve no regular variation of curve resistance with speed. From 10 miles per hour to 20 miles per hour the curve resistance decreases, but it increases as we pass from 20 to 30 miles per hour. If, however, we exclude from consideration the apparently abnormal value for train No. 1 at 30 miles, the curve resistance constantly declines with speed, and at a fairly uniform rate—the values being 0.52, 0.46, and 0.44 at 10, 20, and 30 miles per hour, respectively. Considering the individual trains on the one-degree curve we find no regularity in the variation with speed, except for train No. 2.

On the three-degree curve the average values of curve resistance decrease regularly with the speed, being respectively 0.64, 0.58, and 0.41; the rate of decrease between 10 and 20 miles is the same as on the one-degree curve, but between 20 and 30 miles it is considerably greater. Three of the individual trains show on the three-degree curve a similar decrease of resistance with speed; but trains Nos. 3 and 5 present results which vary irregularly.

While these results do not warrant an unqualified conclusion concerning the influence of speed, they do support the inference that in passing from 10 to 30 miles per hour there is, in general, a decrease in curve resistance on both curves. The well-known action of the wheel flanges on curves, and common experience in operating freight trains on curves super-elevated for high speed trains also support this inference —for the reasons developed below.

On any curve whose outer rail is super-elevated there is, for any car, one speed of operation at which the car trucks have no more tendency to run toward either rail than they have on straight track, where both rail-heads are at the same level. At lower speeds the trucks tend constantly to run down against the inside rail of the curve, and thereby increase the flange friction; while at higher speeds they run toward the outer rail, with the same effect. This may be made clearer by reference to Fig. 14, which represents the forces which operate on a car at its center of gravity O. With the car at rest on the curve there is a component of the weight W which tends to move the car down toward the inner rail. This component is represented by the line Oe, equal to bd. When the car moves along the track centrifugal force C comes into play, and the car action is controlled by the force R which is the resultant of W and C. The force R likewise has a component gf which, although smaller than bd, still tends to move the car toward the inner rail. This tendency persists until, with increasing speed, the value of C becomes great enough to cause the line of operation of R to coincide with OA, the center line of the track perpendicular to the plane of the rails. At this critical or balancing speed the component gf is reduced to zero and there is no longer any tendency of the trucks to run toward either rail. If the speed be still further increased, the component gf arises again, but now on the opposite side of the center line OA and of opposite sense, causing the trucks to tend toward the outer instead of the inner rail, and thereby reviving the extra flange friction. It should be emphasized that the flange friction arising from the play of the forces here under discussion is distinct from and in excess of the flange friction which arises from the action of the flanges in forcing the truck to follow the track curvature. This excess being a variable element of curve resist-

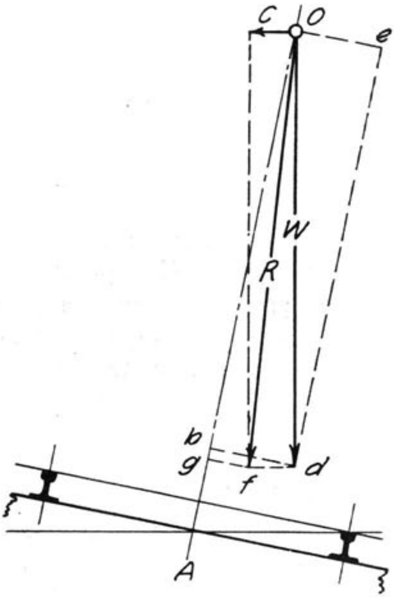

FIG. 14. DIAGRAM OF FORCES ACTING ON CAR ON CURVE

ance, we may expect to find that curve resistance reaches a minimum value when this excess reduces to zero, that is, when the car speed reaches the critical value referred to.

This critical speed depends only on the super-elevation, the track gauge, and the radius of track curvature. Using the appropriate values for these quantities, the critical speeds have been calculated for these tests and found to be 36 miles per hour on the one-degree curve, and 43 miles per hour on the three-degree curve. Since curve resistance probably reaches its minimum value at these speeds, and since they both lie beyond the maximum speed attained on any of the tests, we might expect to find that, within the range of the test speeds, there would be a general decrease of curve resistance with speed such as has been disclosed in the discussion of Fig. 13.

20. *Applicability of Results in Freight Service.*—Question may very properly be raised as to whether the results of these tests are generally applicable to all ordinary freight trains or whether, because of some of the conditions surrounding the tests, their results are limited in their application. The conditions with respect to which such doubt may be entertained are:

(a) The track construction was inferior to that of most main line track.

(b) The average load per car varied from 15.1 to 48.6 tons—a little more than one-half of the usual freight service range.

(c) The weather was warm.

(d) The wear of the rails may not be typical.

(e) The super-elevation may differ from that usually encountered.

The first three of these items may be disposed of in the same manner and they are therefore considered together. Rail weight and general track construction can influence only two elements of train resistance, namely, rolling resistance and the so-called track resistance. Average weight per car influences resistance only through its effect on journal friction. The air temperature, likewise, influences resistance through its effect on journal friction. All three of these effects will undoubtedly be of the same magnitude on straight track and on curves. Suppose, for illustration, that any of the trains had been run on better track and that consequently the net resistance on straight track would have been, say one-half pound per ton less than it actually was during the tests, under some particular set of conditions. It seems certain that under these same conditions, on the curved track, the total resistance on the curve would likewise have been one-half pound less than it actually was during the tests. In deriving curve resistance, however, we subtract resistance on straight track from total resistance on the curve, and in this process the half-pound difference referred to would obviously disappear, and the resulting value of curve resistance would have been the same as it actually was on the inferior track. The same sort of argument may be applied to the effects of car weight and air temperature—and the same conclusion drawn. We may therefore conclude that the test results are equally applicable to track of varying excellence of construction, to the entire range of car weight encountered in service, and to winter as well as summer temperatures.

There are reasons for assuming that curve resistance is affected by the condition of the rail-head, as regards its wear. While there is, obviously, no standard of rail wear with which the wear of the rails on the test curves may be compared, inspection of Fig. 15 indicates that, under general practice, the rails were not ready to be replaced, that they may be regarded as having served about one-half their life, and that they were consequently in "average" condition.

The effect of super-elevation has been discussed in the preceding section, the discussion indicating that excessive super-elevation will cause an increase in curve resistance up to the critical or balancing speed, which lies generally beyond the maximum speed of freight trains. While

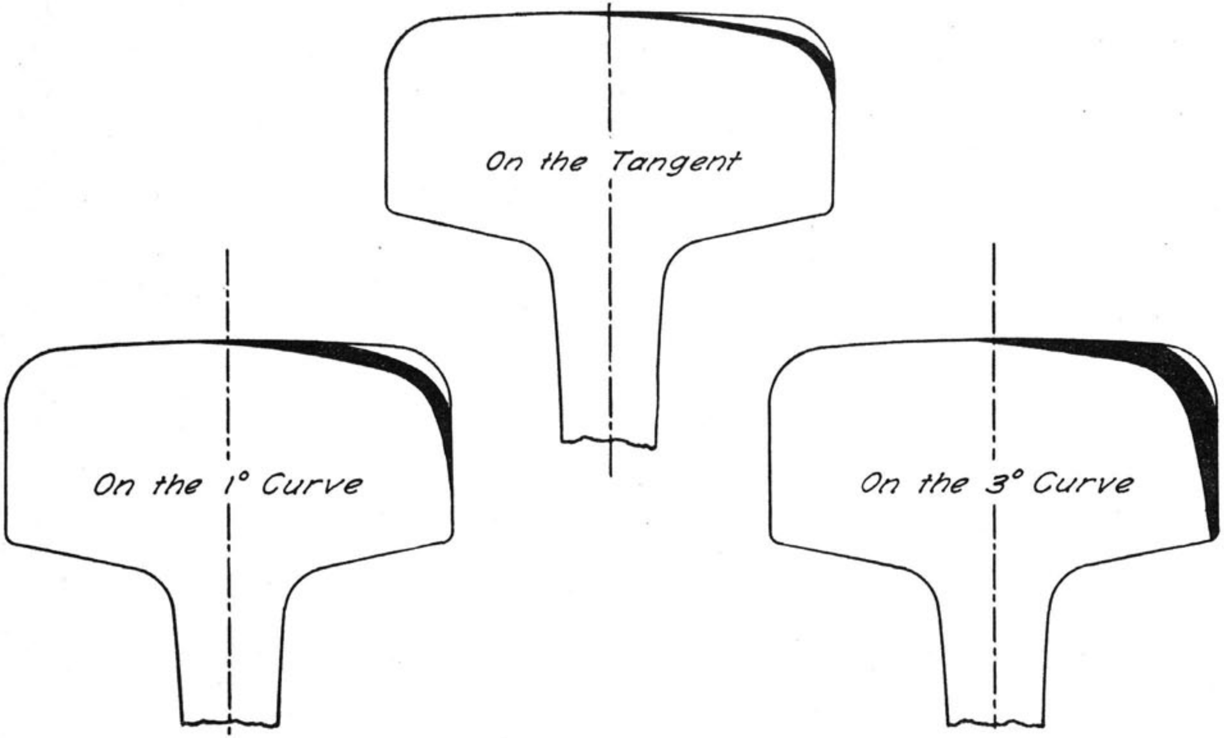

FIG. 15. CONTOUR LIMITS OF WORN RAIL HEADS ON TANGENT AND CURVES

practice varies considerably, super-elevation lies usually between the limits of ¾ in. and 1 in. per degree of curve. On the one-degree curve of the test track the average super-elevation, 0.89 in., lies within these limits. On the three-degree curve, however, the super-elevation was 3.71 in., which is in excess of these ordinary limits. We may infer, therefore, that the curve resistance results on the three-degree curve are slightly greater than those ordinarily to be encountered on curves of this curvature.

VI. SUMMARY

21. *Summary and Conclusions.*—The bulletin presents the results of 101 tests made with five freight trains in order to find the excess of their resistance on curved track over that on straight track. This excess, termed curve resistance, was determined on a one-degree curve and a three-degree curve; it is expressed throughout in pounds per ton per degree of curve. On each curve tests were made with each train at three speeds—nominally 10, 20, and 30 miles per hour.

The tests were made on track of fair construction, laid with 70-pound rails. The average gross weight of the cars composing the test trains varied from 15.1 tons to 48.6 tons. The tests were run during warm weather, the air temperature varying from 62 to 95 deg. F. During only two tests did the wind velocity exceed 15 miles per hour. All but seven of the tests were run when wheels and rails were dry.

The average values of curve resistance derived from the test results are presented in Table 5 and in Fig. 13. Both the table and the figure gives the results for each train at each of the three speeds, and also the average results for all trains. All the results apply to periods during which the entire train ran upon curved track.

On the one-degree curve the curve resistance amounted to 0.52, 0.46, and 0.55 pound per ton per degree of curve, at speeds of 10, 20, and 30 miles per hour, respectively. On the three-degree curve it amounted to 0.64, 0.58, and 0.41 pound per ton per degree at the respective speeds. Disregarding distinctions in speed, the general average curve resistance for all trains was 0.51 pound per ton per degree on the one-degree curve, and 0.54 pound per ton per degree on the three-degree curve.

Since the super-elevation on the three-degree curve was a little greater than is customary, it is probable that the results for this curve are somewhat greater than the curve resistance ordinarily to be encountered on this curvature. The excess is probably slight.

Excluding the results obtained on the one-degree curve with one train at 30 miles per hour, the average results for all trains show, on both curves, a decrease in curve resistance as the speed increases. The rate of decrease is not great, nor is it uniform.

The general average curve resistance, disregarding speed distinctions, was practically the same on the two curves. The test results offer no clue as to whether the curve resistance would have varied with track curvature had it been practicable to test the trains on a greater variety of curves.

The few tests run on wet rail afford some evidence that curve resistance is diminished when rails and wheels are wet.

The analysis of the results presented in Chapter V indicates that they may safely be applied to predict the curve resistance of all freight trains, running on either good or poor track, and under either summer or winter temperatures. It is not certain whether the results are applicable to track curvatures much in excess of three degrees.

Appendix A

Test Track and Trains

22. *Curvature.*—Curvature was determined for each 100-foot station interval on both curves. Excepting the first 100 feet at A (Fig. 1), on which the curvature was 1 deg. 36 min. the curvature on the three-degree curve varied from 2 deg. 58 min. to 3 deg. 4 min., and the average curvature over the whole curve was 2 deg. 55 min. This average is not, however, the average curvature to which the train was subjected while its head end passed from B to C, the interval to which the resistance measurements apply. To find this latter average the train was assumed to be divided into ten sections—nine sections of 100 feet each and a rear end section 18 feet in length. While the head end passed from B to C (station 526 to station 518), a distance of 800 feet, these ten train sections passed over different stretches of track. The first section, for example, passed between stations 526 and 518—a stretch for which the average curvature was 3 deg. 0 min.; whereas the third train section passed between stations 528 and 520—a stretch for which the average curvature was 2 deg. 59 min. The average curvature to which the entire train was subjected is the average of the curvatures to which the ten train sections were subjected as the head end passed from B to C. In determining this final average, due consideration was given to the fact that the last train section was only 18 feet long whereas

the others were each 100 feet long. On the three-degree curve this final average was 2.97 degrees. On both curves this average is practically the same as the average curvature on the whole length of curve, and the latter might have been used without causing appreciable error in the calculated curve resistance; this fact was not apparent, however, until the process here described had been carried through.

On the one-degree curve the curvature varied from a minimum of 0 deg. 58 min. to a maximum of 1 deg. 6 min., the average curvature over the entire curve being 1.00 deg. The average curvature to which the train was subjected in passing from D to E—derived in the manner just described—was also 1.00 deg.

23. *Super-elevation.*—On each curve the super-elevation of the outer rail was determined at stations 100 feet apart. On the three-degree curve it was 1.4 in. at point C and 2.5 in. at the adjacent station; over the remainder of the curve it varied from 3.1 in. to 4.3 in., and its average for the whole curve was 3.49 in. On the one-degree curve the super-elevation varied from 0.1 in. to 1.9 in. and its average for the whole curve was 0.86 in.

The average super-elevation to which the train was subjected in passing over the distance for which the train resistance was measured was derived by a process like that described in the discussion of curvature. It amounted for the three-degree curve to 3.71 in., and for the one-degree curve to 0.89 in.

24. *Track Gauge.*—The gauge was measured every 100 feet on the three-degree curve. It varied from 56.5 in. to 57.2 in., and its average for the whole curve was 56.8 in. On the one-degree curve the gauge, measured every 200 feet, varied from 56.4 in. to 57.1 in., and its average was 56.7 in.

These facts with respect to curvature, super-elevation, and gauge may be summarized thus:

	On the One-degree Curve	On the Three-degree Curve
Average curvature over the entire curve..	1.0 degree	2.92 degrees
Average curvature to which the trains were subjected while their resistance was measured..........................	1.0 degree	2.97 degrees
Average super-elevation over the entire curve..............................	0.86 inches	3.49 inches
Average super-elevation to which the trains were subjected while their resistance was measured.....................	0.89 inches	3.71 inches
Average gauge over the entire curve......	56.7 inches	56.8 inches

TABLE 6

TONNAGE RECORD FOR ALL TRAINS

Order of Cars in Train	Car Number	Initials of the Owning Railroad	Scale Weights—pounds	
			Empty	Loaded
1	32 578	N. Y. C. & H. R.	30 600	101 100
2	32 582	N. Y. C. & H. R.	30 200	102 300
3	33 424	M. C.	30 000	102 500
4	33 460	N. Y. C. & H. R.	30 000	98 500
5	33 445	N. Y. C. & H. R.	30 000	101 100
6	33 439	N. Y. C. & H. R.	30 200	102 800
7	33 274	M. C.	29 800	101 100
8	33 115	N. Y. C. & H. R.	30 100	101 900
9	33 297	M. C.	30 400	101 200
10	32 653	N. Y. C. & H. R.	30 000	102 100
11	33 481	N. Y. C. & H. R.	30 700	101 800
12	32 925	N. Y. C. & H. R.	29 900	98 400
13	33 076	M. C.	29 900	98 500
14	74 773	C. I. & S.	29 600	98 400
15	74 698	C. I. & S.	29 700	98 700
16	74 576	C. I. & S.	30 300	103 100
17	32 994	N. Y. C. & H. R.	29 900	97 400
18	74 830	C. I. & S.	30 100	99 000
19	32 778	N. Y. C. & H. R.	30 200	99 500
20	74 607	C. I. & S.	29 900	99 000
21	Caboose		31 000	31 000
	Total Train Weight...............		632 500	2 039 400

25. *Profile.*—A condensed profile of the test track is given in Fig. 1. For the purpose of calculating the net resistance and resistance on the curve, the correction due to grade was determined by use of the tonnage record and the original large-scale profile, by means of which the height of the center of gravity of the train was determined at entrance to and exit from the test sections. On the three-degree curve, for example, the height of the center of gravity of the train was calculated for the position when its head end was at B. This height was found by correlating the train length with the profile, assuming it to be broken into sections whose ends were at the points where the grade changed, and then calculating, for each of these sections, the height of its center of gravity above an assumed reference plane and its moment about that plane. The sum of these moments divided by the train weight gives the height of the center of gravity of the whole train. This height when the head of the train was at C was similarly calculated. The difference between these heights defines the average grade and the resistance correction due to grade for the test stretch on the three-degree curve.

26. *Rail Wear.*—On the three-degree curve the contours of the rail heads were determined on every fourth rail; and on the one-degree curve, on every eighth rail. These contours are shown in Fig. 15. The worn

contours lie within the blackened areas of these diagrams; the diagram outlines represent the contour of the unworn rail. The sections as printed are of full size.

27. *Train Tonnage.*—To determine the train weight each car was weighed upon track scales—not only when loaded, but also when empty. These weights appear in the tonnage record in Table 6. The maximum difference between the weights of the loaded cars is 5700 pounds, and of the empty cars, 1100 pounds. Since the dynamometer car was continually run with its measuring drawbar toward the rear of the train, its own resistance was not included in the record and its weight is therefore excluded from the train weight.

28. *Car Dimensions.*—All cars were steel-underframe flat cars built from the same designs. Some of their principal dimensions are as follows:

Height from rail to top of deck	4 ft.-0$\frac{5}{8}$ in.
Length over striking plates	41 ft.-6 in.
Length between pulling faces of coupler knuckles	43 ft.-6 in.
Center to center of trucks	30 ft.-0 in.
Truck wheel-base	5 ft.-6 in.
Wheel diameter	33 in.
Size of journal	5 in. × 9 in.
Average height of center of gravity of empty cars above the rail	29.3 in.
Average height of center of gravity of loaded cars above the rail	53.5 in.
Average weight of empty cars	30 075 lb.
Average weight of car body	16 375 lb.
Average weight of each truck, complete with wheels and axles (same for all three types)	6850 lb.

29. *Condition of Wheels and Bearings.*—The cars and all trucks were comparatively new; and the brasses, journals, wheel treads, and wheel flanges were in general in excellent condition. Upon the completion of the tests all truck parts were examined. Tested by the Master Car Builders' gauge, no sharp flanges were found; six flat spots, varying in length from one inch to two inches, were found on the wheel treads; on five brasses, out of the 160 in the trains, there was evidence of the brass having recently run hot; and in four brasses the babbit was worn through. The end play between the brasses and the journal collars varied throughout the trains from $\frac{1}{4}$ in. to $\frac{5}{8}$ in.

30. *Side-Bearing Clearance.*—For each of the trains the clearance in each of the 80 side-bearings was measured. The range in clearance and the average for each train appear in Table 7.

TABLE 7

SIDE-BEARING CLEARANCE

Train Number	Number of Bearings in Contact	Side-Bearing Clearance—Inches		
		Minimum	Maximum	Average
1	25	1/8	5/8	0.22
2	25	1/8	11/16	0.21
3	25	1/8	11/16	0.21
4	5	1/8	5/8	0.28
5	5	1/8	5/8	0.28

APPENDIX B

IMMEDIATE RESULTS OF TESTS

The immediate results of the tests are embodied in Tables 8, 9, 10, 11, and 12 of this appendix. As has been indicated, the calculations made from the original test data provide, for each test, a value of mean resistance and a corresponding value of mean speed on the straight track, a similar pair of values on the one-degree curve, and a third pair on the three-degree curve. Tables 8 to 12 present these values of resistance and speed for each of the five trains. The values are arranged in the tables in three groups, one group for each of the three speeds at which the tests were run—nominally 10, 20, and 30 miles per hour.

The tables also show for each of the groups the average values of resistance and speed for all tests included in the group. These average values are the co-ordinates of the points plotted in Figs. 8 to 12 in the body of the bulletin.

TABLE 8

VALUES OF RESISTANCE AND SPEED OBTAINED FROM TESTS MADE WITH TRAIN NO. 1

Nominal Speed m.p.h.	Test Numbers	On the Straight Track		On the One-Degree Curve		On the Three-Degree Curve	
		Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton
10	135	11.10	3.64	12.12	3.01	10.64	5.15
	136	10.62	3.67	12.20	4.32	9.95	5.75
	137	11.18	3.65	11.87	4.21	10.17	5.77
	138	10.91	3.67	11.68	4.33	10.06	5.99
	139	10.34	3.67	10.83	3.97	10.12	6.15
	146	10.97	2.69	12.24	3.29	12.24	4.70
Average Values		10.85	3.50	11.82	3.86	10.53	5.59
20	127	21.64	3.99	21.43	4.87	20.95	5.92
	128	22.09	3.90	21.48	4.33	20.32	5.28
	129	23.32	4.30	23.20	4.16	20.52	6.43
	130	20.77	3.84	20.76	4.31	19.20	6.18
	131	21.28	3.84	21.60	4.58	19.65	5.81
	132	21.06	3.15	20.81	3.88	19.13	4.82
	133	22.08	3.60	22.24	4.14	20.63	5.49
	134	21.50	3.95	21.89	4.59	20.54	6.34
	145	20.84	3.85	20.83	3.99	19.26	5.52
Average Values		21.62	3.82	21.58	4.32	20.02	5.75
30	117	25.90	4.33	26.42	5.63	25.22	5.41
	118	27.82	5.26	27.93	6.13	25.90	6.44
	119	28.25	3.90	28.55	4.41	26.40	5.81
	120	28.13	4.49	28.75	5.32	27.25	6.97
	121	28.85	5.00	29.25	5.61	27.20	6.57
	122	29.34	4.97	29.49	5.31	28.21	6.27
	123	28.00	3.55	28.46	5.04	27.00	5.66
	124	30.05	4.01	29.96	6.04	29.60	5.67
	125	30.25	4.86	30.27	5.39	29.45	6.60
	142	29.77	4.23	29.95	5.52	28.40	6.31
	144	29.70	4.01	29.98	5.51	28.76	6.39
Average Values		28.73	4.42	29.00	5.45	27.58	6.19

TABLE 9

VALUES OF RESISTANCE AND SPEED OBTAINED FROM TESTS MADE WITH TRAIN NO. 2

Nominal Speed m.p.h.	Test Numbers	On the Straight Track		On the One-Degree Curve		On the Three-Degree Curve	
		Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton
10	28	11.56	3.47	11.92	4.08	10.54	5.36
	55	11.20	3.38	12.20	3.84	10.36	4.92
	56	11.46	3.29	12.74	3.92	11.10	4.84
Average Values		11.41	3.38	12.29	3.95	10.67	5.04
20	8	16.47	3.94	17.89	4.49	16.39	5.84
	10	17.75	3.98	18.45	4.41	15.08	5.57
	12	17.92	4.11	18.83	4.62	16.10	5.73
	26	20.06	4.22	21.18	4.59	18.60	4.58
	27	20.13	4.13	20.42	4.92	18.62	4.97
	42	19.83	3.79	20.43	4.28	18.77	5.58
	48	23.02	3.86	23.24	4.31	21.12	5.24
	49	21.21	3.66	21.78	4.12	19.33	5.57
	51	20.59	3.80	21.70	4.25	20.36	4.86
	52	20.50	3.28	20.95	4.11	18.93	4.96
	54	20.33	3.90	21.13	4.15	19.45	4.90
Average Values		19.80	3.88	20.55	4.39	18.43	5.25
30	4	28.70	6.02	28.00	6.02	24.76	5.86
	6	30.34	5.31	30.49	4.55	28.89	5.82
	31	27.97	5.50	28.37	4.88	25.98	6.12
	43	30.72	4.67	30.60	4.79	28.96	5.40
	44	30.44	4.03	29.55	5.03	27.69	5.21
	45	28.71	3.88	28.89	4.60	27.54	4.69
	47	31.42	4.23	30.85	4.91	29.05	5.45
	50	29.71	4.90	30.00	5.36	29.03	5.83
Average Values		29.75	4.82	29.59	5.02	27.74	5.55

TABLE 10

VALUES OF RESISTANCE AND SPEED OBTAINED FROM TESTS MADE WITH TRAIN NO. 3

Nominal Speed m.p.h.	Test Numbers	On the Straight Track		On the One-Degree Curve		On the Three-Degree Curve	
		Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton
10	24	10.73	3.29	11.64	3.99	9.06	4.95
20	19	21.90	4.49	22.78	4.26	19.98	6.40
	21	22.22	4.37	23.30	5.22	20.65	5.23
	57	17.66	4.51	19.35	4.99	17.63	5.65
	62	20.41	4.12	20.88	4.82	18.36	5.60
	66	19.67	3.74	20.93	4.01	18.97	4.79
	67	20.20	3.88	21.10	4.50	19.62	4.60
	68	18.76	3.94	19.25	4.40	17.33	5.15
	69	18.48	3.54	19.46	4.18	18.65	4.88
	70	19.80	3.93	20.61	4.70	18.88	5.27
Average Values		19.90	4.06	20.85	4.56	18.90	5.29
30	18	32.44	4.11	28.86	4.46	26.72	5.18
	20	29.08	4.97	28.66	4.67	27.32	4.85
	23	27.72	4.95	28.05	5.32	26.55	5.79
	58	28.92	4.28	28.92	5.66	27.49	5.26
	59	29.34	4.48	29.79	5.42	28.59	7.17
	60	30.80	4.69	30.52	5.31	29.12	6.59
	63	28.91	4.36	28.77	5.19	28.05	6.02
	64	28.68	4.65	28.80	5.48	27.73	6.30
Average Values		29.49	4.56	29.05	5.19	27.70	5.90

TABLE 11

VALUES OF RESISTANCE AND SPEED OBTAINED FROM TESTS MADE WITH TRAIN NO. 4

Nominal Speed m.p.h.	Test Numbers	On the Straight Track		On the One-Degree Curve		On the Three-Degree Curve	
		Speed m.p.h.	Resistance lb.per Ton	Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton
10	90	11.20	5.69	11.32	5.18	10.63	7.30
	91	11.32	5.63	12.76	6.02	10.85	7.75
	92	11.37	5.61	11.68	5.95	9.82	7.17
	93	11.92	4.73	12.71	5.42	10.22	6.66
	94	12.04	4.99	12.81	6.15	10.15	7.14
Average Values		11.57	5.33	12.26	5.74	10.33	7.20
20	82	20.59	7.13	20.89	7.29	19.07	8.70
	83	20.58	6.26	21.12	6.45	20.25	8.24
	84	19.79	6.72	21.15	7.04	19.90	8.41
	86	20.49	7.96	20.17	7.93	20.10	8.55
	88	18.91	6.29	19.95	6.57	19.60	8.34
Average Values		20.07	6.87	20.66	7.06	19.78	8.45
30	73	28.53	8.57	28.46	9.62	27.35	9.26
	74	29.28	9.43	29.92	10.83	29.17	10.42
	75	29.54	9.37	29.31	10.65	28.69	10.50
	76	29.32	9.98	29.43	9.89	29.15	10.33
	77	29.10	8.70	29.93	9.33	28.27	9.59
	78	29.39	8.86	29.34	9.59	28.63	10.01
	79	30.15	7.99	29.41	7.46	28.82	8.13
	80	29.01	7.49	29.13	7.31	28.34	8.77
Average Values		29.29	8.80	29.37	9.34	28.55	9.63

TABLE 12

VALUES OF RESISTANCE AND SPEED OBTAINED FROM TESTS MADE WITH TRAIN NO. 5

Nominal Speed m.p.h.	Test Numbers	On the Straight Track		On the One-Degree Curve		On the Three-Degree Curve	
		Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton	Speed m.p.h.	Resistance lb. per Ton
10	112	12.25	4.17	12.26	4.35	10.10	5.72
	113	13.86	3.93	14.05	4.52	10.37	5.88
	114	12.15	4.40	12.55	5.04	10.23	6.38
	115	11.35	4.74	11.75	6.20	9.80	7.34
	116	11.86	4.19	11.91	4.87	9.97	6.44
Average Values ……		12.29	4.29	12.50	5.00	10.09	6.35
20	107	20.90	5.34	21.46	5.85	20.30	7.40
	108	22.06	5.37	22.41	6.77	20.27	8.01
	109	20.83	4.92	21.33	6.05	19.05	6.87
	110	21.32	4.98	21.70	6.13	19.45	7.30
	111	20.42	5.06	21.43	5.73	19.10	6.40
Average Values ……		21.11	5.13	21.67	6.11	19.63	7.20
30	96	28.63	8.01	29.09	9.01	28.31	9.42
	98	31.33	8.36	31.68	9.96	30.30	9.78
	99	29.68	7.98	30.23	8.40	29.20	8.44
	100	29.10	7.85	29.23	8.19	29.00	8.78
	101	28.93	8.11	29.40	8.54	28.50	9.24
	102	29.30	7.72	29.70	7.50	28.35	8.85
	104	30.71	7.78	31.02	7.68	29.65	8.90
Average Values ……		29.67	7.97	30.05	8.47	29.04	9.06

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