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FREIGHT TRAIN RESISTANCE ITS RELATION TO AVERAGE CAR WEIGHT

BY

EDWARD C. SCHMIDT

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BY

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UNIVERSITY
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PRESS

PREFATORY NOTE TO REPRINT

The following bulletin was first published in May, 1910, as Bulletin 43 of the Engineering Experiment Station of the University of Illinois. The results presented continue to be representative of normal operating conditions, as they include resistance data applicable to the great majority of cars in service, through the usual range of operating speeds. The general increase in weight of rail during the period since the original bulletin was published may render the resistance values slightly conservative, but most road-beds (representing a more important variable) have undergone little change in the period. Continuing requests for the bulletin have long since exhausted the original supply, and it is therefore presented herewith as a reprint. The form is practically identical with that of the original, except that certain tabular material has been omitted from Appendixes 2 and 5, the omissions being explained under those headings. A few notes have been added, in italics, to call to the reader's attention certain essential changes.

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FREIGHT TRAIN RESISTANCE: ITS RELATION TO AVERAGE CAR WEIGHT

PART I

I. Introduction

1. *Preliminary.*—Train resistance varies not only with the train speed, but also with the average weight of the cars of which the train is composed. At a given speed the tractive effort required for each ton of weight of the train will be greater, for example, for the train which is composed of cars of 20 tons average gross weight, than for the train composed of cars which weigh, on the average, 50 tons each.

While this fact has been known for some years, it has found inadequate expression and but little application. In the establishment of their tonnage ratings, many railroads have altogether ignored it. In the tonnage ratings of a few roads, this variation of resistance with car weight is recognized to the extent of allowing a difference in rating between trains composed of loaded cars and those consisting entirely or partially of empty cars. Generally, in such systems, a certain amount is allowed arbitrarily to be added to the weight of empty cars in determining, for the purpose of rating, the weight of the train in which they are found. In such rating no distinction is made between loaded cars of various weights although such weights vary from 25 to 70 tons. A still smaller group of railroads have fully recognized the significance of the facts above stated in establishing their tonnage ratings, which, in such cases, are usually termed "adjusted" or "equated" ratings.* Under these adjusted ratings, the actual weight of the train allotted to a particular locomotive varies according to the number of cars in the train. The ratings for the same locomotive, with trains of 40, 60, and 80 cars, for example, will be different in each of the three cases. This is, in effect, a variation of the rating with respect to the average car weights. Most of these adjusted ratings have been empirically determined. In the few cases where they rest upon experiments made to determine the variations in train resistance with respect to car weight, the data and results of such experiments have not been fully published. Existing train resistance formulas likewise fail in most cases to take into account these varia-

**Since the original publication of this bulletin, a large number of railways have adopted methods of tonnage rating which take car weight into account.*

tions of resistance with car weight, and probably much of the divergence among them is properly to be ascribed to this fact.

2. *Purpose of the Tests.*—In view of the facts just stated, it has seemed desirable to make the tests whose results are here recorded. They were planned to determine the resistance of freight trains under the usual conditions of operation; and they were designed to disclose at the same time, if possible, the relation existing, at any given speed, between train resistance and average car weight. Since the chief use of such information is in the production of locomotive ratings, the conditions of the tests have been made like those which prevail in normal freight train operation. The speed range, for example, is from 5 to 35 miles per hour; and the trains experimented upon were trains in regular service, and usual in their make-up. The track upon which the tests were made is believed to be representative of good main-line construction.

The tests have been conducted by the Railway Engineering Department of the University of Illinois as part of the research work of the Engineering Experiment Station. They were begun in April, 1908, and were completed in May, 1909. All tests were made by means of Test Car No. 17, a dynamometer car, owned jointly by the University of Illinois and the Illinois Central Railroad, and were carried out on the Chicago division of this road.

In Part I of this report, the aim has been to present as brief a statement of the results and conditions as is compatible with a clear understanding of the tests. It consists, accordingly, of a discussion of the results of the experiments, prefaced by a general statement of conditions and methods. The final results are exhibited in Fig. 11, in Table 3, and in Equations (1) to (13), on pages 37, 38, and 39. A summary of the test conditions and the conclusions is inserted on pages 11 and 12. Part II of the report has been added in order to complete the record so that those interested in the details may verify or modify the results and conclusions presented in Part I. It consists of appendixes in which the aim has been to state fully all the conditions of the track, weather, and train make-up,* as well as to present the test data, the methods of calculation, and the results.*

Throughout the report, the terms "resistance" and "train resistance" mean the number of pounds of tractive effort required for each

In the reprint, the tabular portions of Appendix 2 giving the details of the make-up of the various test trains, and of Appendix 5, showing the data taken directly from the dynamometer charts and the necessary steps in obtaining the resistance, have been omitted.

ton of the train in order to keep it in motion on straight and level track, at uniform speed, and in still air. The report deals exclusively with the resistance of the train behind the locomotive tender. Locomotive and tender resistance are not discussed.

3. *Acknowledgments.*—The tests have been made possible through the interest and coöperation of Mr. William Renshaw, Mr. J. G. Neuffer, and Mr. R. W. Bell, who were successively superintendents of machinery of the Illinois Central Railroad, during the period of planning and conducting the work. Many other officials of the Chicago division of the road have rendered generous assistance in the investigation, which has entailed for them not a little inconvenience and labor. Such interest and assistance are thoroughly appreciated by those of the University staff who have been concerned with the work.

Throughout the tests, the operation of the dynamometer car and the making of the calculations have been under the direct supervision of F. W. Marquis, Associate in the Railway Engineering Department, Engineering Experiment Station. Much of whatever accuracy and reliability have been attained in the investigation is due to his intelligent and painstaking care in making the tests and in systematizing the work of calculation. He has also rendered a great assistance in supervising the preparation of the tables and illustrations, and in the final checking of the manuscript.

II. Summary and Conclusions

4. *Summary.*—The report deals with the results obtained from tests of 32 ordinary freight trains, whose chief characteristics were as follows:

	Minimum	Maximum
Total weight, tons	747	2908
Average weight per car, tons	16.12	69.92
Number of cars in the train	26	89

The trains whose average weights were less than 20 tons or more than 60 tons were composed of cars of nearly uniform weight; while those whose average car weights were between 20 and 60 tons were either homogeneous or mixed as regards the weight of the individual cars.

The weather during the tests was generally fair. The minimum air temperature during any test was 34° F. the maximum 82° F. The approximate average wind velocity prevailing throughout one test was 25 miles per hour; during all the others it was less than 20 miles per hour.

The tests were made upon well-constructed and well-maintained main-line track, 94 per cent of which is laid with 85-lb. rail, the remainder being laid with 75-lb. rail. Except through station grounds, where screenings or cinders are used for ballast, the track is full ballasted with broken stone.

5. *Conclusions.*—The results of the tests are presented in Figs. 10 and 11, pp. 35 and 37, in Table 3 on p. 38, and in the equations on p. 39. The curves, the table, and equations are each different expressions of the same facts. It is believed that by their use the probable total resistance of *entire* freight trains at various speeds may safely be predicted, when running upon straight and level track of good construction, during weather when the temperature is above 30° F., and the wind velocity is not more than 20 miles per hour, provided the *average* weight of the cars composing the train be known.

The results are applicable to trains of all varieties of makeup to be met with in service. They may be applied, without incurring material error, to trains which are homogeneous and to those which are mixed as regards individual car weight.

The results are primarily applicable to trains which have been in motion for some time. When trains are first started from yards, or after stops on the road of more than about 20 minutes' duration, their resistance is likely to be appreciably greater than is indicated by the results here presented. In rating locomotives, no consideration need be given this matter, except in determining "dead" ratings for low speeds, and then only when the ruling grade is located within six or seven miles of the starting point or of a regular road stop.

It is to be expected that some trains to be met with in service will have a resistance about 9 per cent in excess of that indicated by Figs. 10 and 11, due to variations in make-up or in external conditions within the limits to which the tests apply. If operating conditions make it essential to reduce to a minimum the risk of failure to haul the allotted tonnage, then this 9 per cent allowance should be made. This consideration, like the one preceding, is important only in rating locomotives for speeds under 15 miles per hour. At higher speeds, the occasional excess in the resistance of individual trains will result in nothing more serious than a slight increase in running time. It should be emphasized that this allowance, if made, is to be added to the resistance on level track—not to the gross resistance on grades.

III. Methods and Means Employed in Conducting the Tests

6. *Test Car No. 17.*—The tests were carried on by means of the dynamometer car referred to as Test Car No. 17, which, when not in use, is held at Champaign, a district terminus. The car was operated from time to time in the regular trains leaving this point, and the trains selected were partly in the northbound, partly in the southbound traffic.

The plan was to determine, for each of the trains experimented upon, the relation of its resistance to its speed. This information was to be expressed finally as a resistance-speed curve such as is shown in Fig. 1 and in the various figures given in Appendix 5. The trains were so selected that their average car weights would vary throughout as great a range as possible. As will later appear, this range proved to be from the weight of an empty gondola to that of a fully loaded car of 100 000 lb. capacity. It was the expectation that when the resistance-speed curves of the individual tests were brought together, their analysis would reveal the relations existing between train resistance and car weight.

7. *Observed Data.*—During each test the following information was obtained:

(*a*) The draw-bar pull of the locomotive upon the train.
(*b*) The train speed.
(*c*) A continuous record of the time elapsed from the beginning of the test.
(*d*) The pressure existing in the brake cylinder of the test car.
(*e*) The direction of the wind relative to the direction of motion of the car.
(*f*) The velocity of the wind relative to the car.
(*g*) A record of the location of the test car upon the road.
(*h*) Air temperatures and other weather conditions.
(*i*) Data concerning the train, such as its weight, etc.

The information cited under items (*a*) to (*g*) was obtained in the form of continuous graphical records upon the chart which is produced by the apparatus of the dynamometer car. By means of this chart any of the quantities mentioned may be determined at any point upon the road.

The curves of draw-bar pull and speed provide the information essential to the investigation. Supplemented by an accurate profile and a record of train weight, they enable net train resistance to be calculated at any position of the train upon the road. The time record provides a means of calibrating and checking the speed curve. The pressure in the brake cylinder was recorded merely to make it possible to distinguish those periods during the test when the brakes were applied to the train; it being obviously necessary to ingnore such portions of the record when making the calculations. The relative wind velocity and relative wind direction were obtained by means of an anemometer and a wind vane mounted on the roof of the test car. When compounded with the known speed and direction of motion of the car, these data permit the determination of the actual wind direction and wind velocity with respect to the track. In Appendix 5, for each test, there are recorded this actual wind velocity and actual wind direction with respect to the track for each point at which train resistance was determined. It is probable that these wind data are, under some circumstances, subject to a considerable error. Considering the length of the run made with each train and the length of time it was on the road, it is believed that the wind data thus obtained are, nevertheless, more reliable than those which might have been recorded by stationary instruments located at one or two points along the track. Item (*g*), the location of the car upon the road, was defined by marking upon the test car record the position of mile posts and stations at the moment they passed the car. By means of this record, it is possible to correlate any position of the train with the road profile. Data concerning the train were obtained by one or two observers who had no other duties. With the one exception noted beyond, all trains were weighed, to determine their tonnage. In addition to its weight, there was recorded for each train, its length,* and for each car, its number, kind, stenciled "light weight," gross weight, capacity, and the initials of the owning road.

All test car instruments were calibrated before the tests, and their calibrations were frequently checked during the progress of the investigation. All observers were men experienced in the operation of the test car and many of them had participated also in the work of calculation and were consequently aware of the points at which alertness and care were especially needed. No effort has been spared, in conducting the tests, to insure accuracy in the data. These facts are here mentioned as having some significance to any one who may undertake to estimate the reliability of the results. Appendix 1 con-

*Train length was determined by counting, during the test, the number of rail lengths corresponding to the length of the train and multiplying this number by 30 feet, which is the rail length for this track.

tains an illustration of one of the test car charts and a detailed description of the car itself.

This report includes the data and results from tests of 32 different trains. For the purposes of this research, tests were made of twelve other freight trains; but their results were finally excluded from the report. Three of these additional tests were rejected because of uncertainty about the train weights; one, because of a break-down in the test car recording apparatus during the progress of the test; and eight were disregarded because the temperatures prevailing were below the range for which it was intended the results should apply, the low temperature in some cases being coupled with high wind.

IV. Test Conditions and Train Data

8. *The Trains Tested.*—The test trains were all of such make-up as naturally resulted from the traffic conditions in the Champaign yards. For most of the tests the test car was simply coupled into the trains selected by the trainmaster, solely with reference to his convenience in operating and in returning the test car. As the investigation progressed, it became apparent that the accumulated data left certain gaps in the range of average car weights. There were at this stage, for example, few trains experimented upon with average car weights near 25 to 30 tons, and none with an average car weight of 70 tons. The last six or eight trains were therfore made up especially to supplement the data at these points. It should be understood, however, that nothing in this process resulted in a train make-up which was in any respect unusual. All the trains tested are, therefore, such as one might expect to find upon any road where the traffic conditions are normal. They include trains made up almost entirely of empty gondolas,* others with considerable variation in both load per car and kind of car, and still others composed almost entirely of loaded box cars or of loaded gondolas.

Test S-1018 demands special mention in this connection. The train for this test included Illinois Central Railroad locomotives No. 423 and No. 732, weighing respectively 145 200 and 223 600 lb. Their combined weight constituted 13.6 per cent of the total train weight.

*In all parts of the report except Appendix 2, cars are designated as box, stock, gondola, flat, and tank cars. The term box car is made to include refrigerator cars, the test car and the caboose. The term gondola includes all unroofed cars with sides, such as coal cars, hopper cars, etc. In the tonnage records in Appendix 2, further distinctions are made.

Note that in the reprint the references to Appendix 2 are without significance, due to the omission of the train make-up lists.

These locomotives with their tenders were being hauled "dead" and had the main rods disconnected, as is usual in such cases. The first is of the 2-6-0 type, the second of the 2-8-0 type, and they and their tenders had therefore together 17 axles in operation. For the purpose of determining the average car weight for this train, these two locomotives were assumed to be equivalent, in their resistance, to a number of cars having a like number of axles, i.e., 4¼ cars. The results of the calculations warrant the belief that this view of the situation has resulted in no material error. A study of Table 1 will make clear the diversity in the composition of the trains.

All trains except Nos. S-1016, S-1018, S-1030A, and S-1030B were weighed upon one of the two track scales at Champaign. This weighing was done in the usual manner, by pulling the train over the scales and weighing the cars successively without uncoupling them. These track scales were in good condition and were each inspected four times during the test period. These inspections disclosed a maximum error in one scale of —⅕ per cent, in the other of—½ per cent. The train in test S-1016, composed entirely of empty cars, by an error in arrangements, left the yards without being weighed. The weights stenciled on the cars were accepted as correct in this case. The train in test S-1018 was weighed upon track scales in the Chicago yards; and the trains of tests S-1030A and 1030B were weighed in the yards at Centralia. In test S-1021, after leaving the yards, two cars were added to the train, for which the weights were determined from the stenciled weights and the way-bills. In tests S-1030B and S-1048 the weights of one and two cars respectively were similarly determined, and in test S-1061 the stenciled weight was used for one empty car. Obviously no important errors in the total tonnage have resulted from possible inaccuracies in the weights of these cars.

All cars of all trains were of course provided with the usual four-wheeled truck. Presumably the majority of the cars had journals conforming to the specifications of the Master Car Builders' Association, which for some years have required that freight car journals be either 3¾ in. by 7 in., 4¼ in. by 8 in., 5 in. by 9 in. or 5½ in. by 10 in. in size, depending upon the car capacity. It is safe to assume that all trucks were provided with wheels of 33-in. standard diameter.

Throughout each test, observations were repeatedly made to discover such irregularities as hot journal boxes, brakes which were not free from the wheels, and trucks which did not freely follow the track. Such things occurred to the usual extent; a hot-box or two or an unreleased brake being occasionally found on some of the trains, while others were entirely free from such defects. The record of such matters was given consideration in making the calculations; but, as was anticipated, the results showed no discrepancies which could be explained by such causes.

The range over which the train data for all of the tests varied is as follows:

	Minimum	Maximum
Total train weight, tons	747	2908
Average weight of cars composing the train, tons	16.12	69.92
Number of cars in the train	26	89
Train length, feet	1120	3480

Complete information concerning each train is given in Appendix 2.*

9. *The Track.*—The track upon which the experiments were carried on extends from Gilman to Mattoon, Illinois, a distance of 91 miles, and lies upon the Chicago division of the main line of the Illinois Central Railroad. Until about ten years ago this was a single track road, and one of the oldest in the State. At that time a second track was constructed, and the roadbed for both tracks is now well settled and in good condition. The maximum grade against northbound traffic is 29 ft. per mile and against southbound traffic, 31.9 ft. per mile. In all the 91 miles there are only 7850 ft. of curved track.

Through station grounds the tracks are ballasted with screenings or cinders; all other portions of both tracks (about 83 of the 91 miles) are full ballasted with broken limestone. The cross-ties are of oak, laid 20 in. center to center. About 10¼ miles of the west track are laid with 75-lb. A. S. C. E. rail, put down in 1894 and 1895; while the remainder of the west track and all of the east track are laid with 85-lb. A. S. C. E rails, the oldest of which was put down in 1900. During eight months of the year there is employed in maintaining this portion of the road a force of men which averages one man per mile of track; during the other four months this force is reduced to one man for each two miles. Further details concerning the track are given in Appendix 3. As regards both its construction and maintenance this track is such as one may expect to find upon the main lines of first-class railroads.

These 91 miles of track were especially surveyed, immediately preceding the tests, by the Railway Engineering Department of the University for the purposes of this and similar investigations. The levels were run on the east track and readings were taken to 0.1 ft. at stations 300 ft. apart; and turning points were taken at every fourth station where levels were read to 0.01 ft. The results of the survey

*Of the original bulletin.

TABLE 1
A SUMMARY OF TEST CONDITIONS AND TRAIN DATA

Test No. Laboratory Serial No.	Test Date	Weather Conditions						Train Data										
			Air Temperature degrees F.		Average Approximate Wind Velocity miles per hour	Range of the Direction of the Wind with Respect to the Track		Train Length, feet	Weights		Total Number of Cars in the Train	Train Make-Up						
												Conditions of Loading			Kind of Cars—In Percentages of the Total Number of Cars			
			At Beginning of Test	At End of Test		from	to		Gross Train Weight tons	Average Gross Weight Per Car tons		Number of Empty Cars	Number of Loaded Cars	Loaded Cars in Percentage of Total Number	Box Cars per cent	Gondola Cars per cent	Flat Cars per cent	Tank Cars per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
S-1013	4-27-08	Wet	42	44	19	+35°L	90°L	2784	2549	38.04	67	10	57	85	82	13	0	5
S-1015	4-29-08	Fair	40	48	10	+25°L	−80°L	2520	2489	36.08	69	8	61	88	68	6	16	10
S-1016	4-30-08	"	44	48	10	+15°R	+60°R	3030	1161	16.12	72	72	0	0	3	97	0	0
S-1017	5- 1-08	Wet	48	54	16	+45°L	−80°L	2670	2532	38.44	66	13	53	80	95	5	0	0
S-1018	5- 2-08	Fair	40	45	11	+10°R	+85°R	2130	1353	25.40*	49*	34	15	31	61	6	16	17
S-1019	5- 9-08	"	44	62	25	+20°R	+45°R	3480	1572	17.72	89	75	14	16	34	58	7	1
S-1021	5-13-08	Wet	66	70	17	+60°R	+80°R	2400	2908	46.16	63	10	53	84	32	60	5	3
S-1023	5-23-08	Fair	62	74	17	+75°R	−80°R	2320	2243	38.72	58	17	41	71	45	52	0	3
S-1027	7- 2-08	Wet	64	80	14	−50°R	+70°R	1710	2185	47.44	46	3	43	94	22	76	2	0
S-1030A	7- 8-08	Fair	60	68	6	+20°R	+65°R	1380	2036	59.88	34	2	32	94	6	94	0	0
S-1030B	7- 8-08	"	68	72	7	+20°R	+65°R	1650	2342	57.12	41	3	38	93	20	80	0	0
S-1031	7-22-08	"	70	82	5	+ 0°	+40°L	1425	747	20.72	36	30	6	17	94	3	3	0
S-1033	9-26-08	"	66	82	12	+ 5°L	+15°R	1710	2275	51.70	44	2	42	95	5	95	0	0
S-1034	10-3-08	"	42	60	4	− 0°	+85°L	3015	1259	16.56	76	76	0	0	1	99	0	0
S-1036	10-10-08	"	40	62	6	+15°R	−15°R	2010	1961	37.72	52	8	44	85	73	25	2	0
S-1038	10-15-08	"	58	72	16	+ 5°L	+25°L	1650	2144	52.28	41	3	38	93	22	78	0	0
S-1040	10-24-08	Wet	57	53	11	+15°R	+40°R	1830	2152	45.76	47	2	45	96	49	49	0	2
S-1043	11-7-08	Fair	38	53	8	+ 5°R	+65°R	2580	1118	16.92	66	65	1	2	24	74	0	2
S-1048	11-28-08	"	36	39	6	+ 5°R	+30°L	a2175	2443	45.24	54	8	46	85	37	63	0	0
S-1050	1-23-09	"	53	66	8	+ 0°	−25°R	b2100	2355	45.24	52	8	44	85	38	62	0	0
								1620	1618	40.44	40	16	24	60	75	25	0	0

TABLE 1 (*Concluded*)

A Summary of Test Conditions and Train Data

Test No. Laboratory Serial No.	Test Date	Weather Conditions						Train Data										
			Air Temperature degrees F.			Range of the Direction of the Wind with Respect to the Track			Weights			Train Make-Up						
												Conditions of Loading			Kind of Cars—In Percentages of the Total Number of Cars			
			At Beginning of Test	At End of Test	Average Approximate Wind Velocity miles per hour	from	to	Train Length, feet	Gross Train Weight tons	Average Gross Weight Per Car tons	Total Number of Cars in the Train	Number of Empty Cars	Number of Loaded Cars	Loaded Cars in Percentage of Total Number	Box Cars per cent	Gondola Cars per cent	Flat Cars per cent	Tank Cars per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
S-1052	1-28-09	Wet	36	40	11	−45°L	+70°L	2430	1514	24.80	61	44	17	28	61	38	1	0
S-1057	3- 6-09	Fair	34	40	10	+20°R	−35°L	1830	2107	41.32	51	8	43	84	49	43	6	2
S-1061	3-13-09	"	41	38	7	+45°L	−85°L	1785	2252	51.20	44	3	41	93	5	84	11	0
S-1063	3-19-09	Wet	39	40	12	+20°R	+40°R	3060	1484	20.04	74	70	4	5	7	93	0	0
S-1070	4-17-09	Fair	58	71	4	+ 0°	−65°L	2400	1622	24.60	66	49	17	26	58*	42	0	0
S-1072	5- 1-09	"	35	37	17	+70°L	90°L	1200	1859	66.40	28	1	27	96	4	96	0	0
S-1073	5- 4-09	"	53	63	10	+25°L	+70°R	1200	1880	67.16	28	1	27	96	4	96	0	0
S-1074	5- 7-09	"	45	60	10	+65°L	−80°L	3180	1340	16.56	81	81	0	0	2	98	0	0
S-1076	5-11-09	"	51	67	16	+40°R	+75°R	1120	1818	69.92	26	1	25	96	4	96	0	0
S-1077	5-14-09	"	64	70	13	−25°R	−75°R	2145	1505	28.40	53	35	18	34	74	26	0	0
S-1079	5-18-09	"	65	68	18	+65°R	−85°R	2070	1685	33.04	51	14	37	73	90	10	0	0
S-1080	5-21-09	"	50	70	11	+ 0°	+45°L	2550	1347	21.40	63	57	6	10	16	84	0	0

Notes: 1. Columns 7 and 8—Direction is designated by the angle made with the track. A wind any component of whose velocity helps the train forward is marked +; winds with opposing velocity components are marked −. Winds from the right side of the track are designated as R, from the left side as L. Thus +40°R means a wind blowing from the rear and from the right hand side, whose direction makes an angle of 40° with the track.
2. *Columns 11 and 12—Train has two "dead" locomotives and tenders in addition to cars noted.
3. *Column 16—includes 15 stock cars classed as box.
4. All data apply to the train only—engine and tender are excluded.
5. Columns 9 to 19: a.—from Champaign to Rantoul; b.—from Rantoul to Gilman..

are expressed in a profile drawn to a scale of ¼ in. to 100 ft., which was used in making the test calculations.

10. *The Weather Conditions.*—In Table 1 the weather prevailing during each test is designated as either fair or wet, wet weather meaning either continuous or intermittent rain. During 7 of the 32 tests the weather was wet. The lowest air temperature recorded at any time during any test is 34° F.; and the highest recorded temperature is 82° F.

The column headed "average wind velocity" in Table 1 presents the averages of the calculated wind velocities derived for each point or section of the test in question for which the train resistance was determined. An inspection of the tables in Appendix 5 shows a considerable variation between the wind velocities at different points during the same test. The approximate maximum average wind velocity prevailing during any test was 25 miles per hour; the minimum was 4 miles per hour. The actual wind direction (with respect to the track) varied during the tests, as would be expected, through the entire 360°. The tables in Appendix 5 show this direction for each point at which train resistance was computed; but it seems impossible to make any useful generalization of the data there presented.

It was intended to so select the tests that the weather conditions, the temperatures, and the wind velocities would be such as usually prevail in most parts of the country from the middle of spring until the middle of autumn when the basic or "summer" tonnage ratings are in force—such conditions, in short, as would give rise to no appreciable difficulties in train operation.

V. Methods Employed in Calculating the Results

11. *The General Process.*—The immediate purpose in making the calculations was to produce for each test a curve showing the relation between resistance and speed, for as great a variety of speeds as the data would permit. This involves calculating the train resistance at various positions of the train upon the track, and the first step towards this end is the inspection of the test car record in order to select suitable points or sections at which the resistance may be calculated. The considerations of first importance in this selection are that the points represent finally as great a speed range as possible, and that the speeds be approximately evenly distributed within this range. Points and sections were selected only where the entire train was running and

continued to run upon straight track; resistance due to track curvature is therefore entirely eliminated. The data essential to the process of calculation are the draw-bar pull of the engine, the train speed and its acceleration, the tonnage, and the profile. The pull and the speed, as previously stated, are determined from continuous curves drawn on the test car chart. Two processes have been used, designated here as Method 1 and Method 2. By Method 1, the momentary values of pull, speed, acceleration, and grade were determined for a particular position of the train upon the road; by Method 2 the average values of these quantities were determined for the period during which the test car was passing over a definite section of the track.

12. *Method 1: Resistance at a Point on the Road.*—The point having been chosen, the pull and the speed were found by direct readings from the chart. This pull divided by the tonnage gives the gross train resistance at this speed, and this gross resistance was next corrected for both acceleration and grade resistances. The acceleration was determined by graphical methods from the speed curve, and the grade was found by correlating the train's position with the profile. The points were all so selected that at the moment under consideration the entire train was on a nearly uniform grade. Method 1 results in momentary values of train resistance at the points considered.

13. *Method 2: Average Resistance over a Section.*—By this method the average value of train resistance was determined for the period during which the test car at the head of the train was passing a selected section of the track. This track section corresponds to a certain length or section on the test car record. It was so selected that the speed of the car when entering was nearly equal to its speed at exit, and further so that no considerable variations in speed occurred during transit over the section. The sections chosen have varied in length from about ¼ mile to 1 mile. The variations in speed in passing the section have generally amounted to less than 2.0 miles per hour, and the maximum variation over any selected section is 11.7 miles per hour. In only 58 cases out of a total of 560 does this speed variation exceed 5.0 miles per hour. These portions of the chart having been chosen, the average pull was next found by determining the average ordinate of the curve of draw-bar pull, and the average speed was found by means of the section length and the time record. Gross resistance in pounds per ton was next derived by dividing this value of pull by the tonnage, and this gross resistance was then corrected for the resistances due to acceleration and grade, as in Method 1.

In this case the average acceleration is found by consideration of the speeds at entrance to and exit from the section. In order to correct for grade, the elevation of the center of gravity* of the train was determined for that position of the train at which the test car entered the section, and again for the position at which the car left the section. The difference between these elevations establishes the effective average grade, which either helps or opposes the locomotive while the train passes the section. These elevations of the center of gravity of the train may not be determined with sufficient accuracy unless the train at the moment is on a practically uniform grade. The section limits were therefore so chosen.

Method 2 results in a value of *average* train resistance for the *average* speed at which the train passes the section under consideration. It would be rigidly correct if train resistance varied uniformly with speed, in other words, if the curve showing the relation of resistance to speed were a straight line. This, of course, is not the case, and the process therefore gives results which are slightly in error. However, as stated above, the section was so chosen that the difference between the speeds at entrance to and exit from the section was small; and for the speed range represented by this difference, the curve of train resistance deviates but little from a straight line. Such error as does result from the process is, therefore, very small and is of no moment whatever when compared with variations, due to natural causes, which occur in the resistance itself.

14. *Comparison of the Two Methods.*—The two methods are fundamentally alike. Although the first is the less laborious, it requires the determination of acceleration at a point on the speed curve, which it is sometimes difficult to make accurately. For this reason the second method is generally preferable. Method 2 is also to be preferred because it deals with average values and therefore tends to eliminate from the results the incidental momentary variations which occur in the resistance itself. Consequently, the second method has been employed whenever possible, and the first method has been resorted to, as a rule, only in those cases where the limitations imposed in the selection of sections for Method 2 would have resulted in too few values from which to plot the resistance curves. Of all the individual resistance values incorporated in the report, only 32 per cent were determined by Method 1. The care exercised in the calculations,

*The location in the train of its center of gravity was determined thus: Assume a train which weighs 1800 tons, is 2400 feet long, and is composed of 60 cars. By inspection of the tonnage record we find that one-half of this weight (900 tons) lies in the first 25 cars. Hence the center of gravity is located $\frac{25}{60} \times 2400 = 1000$ ft. from the front end.

and a study of the plotted values obtained by both processes, seem to warrant the conclusion that their results are equally reliable. In Fig. 1 and in the figures in Appendix 5, the circles represent values derived by Method 1, and the circular black spots represent values obtained by Method 2.

15. *General Considerations.*—Even in freight train operation the tractive effort required to produce acceleration in the speed is frequently greater than that required to overcome all other resistances combined. To produce, for example, an acceleration of 0.1 mile per hour per second, requires a tractive effort of about 9 lb. per ton, in addition to that required by net train resistance and grade resistance. Since the acceleration resistance may constitute so large a proportion of the gross resistance, it is important that its determination be made with great care. This fact has been impressed upon all who were concerned with these tests. In calculating the acceleration resistance, both the force required to produce acceleration in the rotation of the wheels and axles, and the force required to produce the acceleration in the motion of translation of the train as a whole were determined.

The test car records make it possible to distinguish those portions of each test where the brakes were applied. Such places, few in number, were of course avoided in selecting points and sections for determining resistance. The records also show where hot-boxes and unreleased brakes were discovered in the train, and such defects were given consideration in making the calculations. They occurred infrequently and their effect could not be distinguished in the results. While therefore such portions of the record were avoided if convenient, sections and points on the charts, otherwise suitable for calculation, were not rejected on these accounts.

16. *The Effect of Stops in Limiting the Selection of Points and Sections.*—Early in the progress of this work, when low air temperatures were first encountered, it became apparent that when the train was first started from rest, its resistance, calculated for a number of points at which the speed was the same, was occasionally unusually high. This was true not only for those portions of the run made immediately after leaving the yards, but also for those portions immediately following stops on the road. In a certain test, for example, the values of net resistance, calculated at various points, at all of which the speed was 20 miles per hour, varied between 6.8 lb. and 5 lb. per ton—a difference of 27 per cent—for points selected within the first 9 miles of the run; whereas values of resistance at the same speed,

determined later in the test, differed by only 10 per cent. The air temperature during this test (not included in the report) varied between 22° and 26°.

For a number of tests such resistance values were plotted with respect to the distances from the yards of the points to which they apply. This process disclosed a surprisingly regular decrease in the resistance until a distance of approximately ten miles was reached, after which the resistance had settled down to a fairly uniform value. Similar variations were found to occur to some extent during tests when the air temperature was as high as 50° or 60°. This study* led to the conclusion that this difference in resistance was due to variations in the conditions of lubrication of the car journals, and that such variations were chiefly caused by changes in journal temperature. All this is, of course, in accord with the common belief of those experienced in train operation. The reason for discussing it in this place is that the facts stated have influenced the procedure in making calculations for this series of tests.

Since the variations in resistance are so great during the early part of the run, no point or section has been selected for calculation within about the first ten miles of any test. If other points or sections, located farther from the start, were near stops, such points were rejected unless further investigation proved that at these places the train resistance had become nearly uniform in value. Fortunately, the operating conditions were such as to entail few stops on the road, and the selection of points and sections for the calculations has not been unduly limited on these accounts.†

The effect of these limitations is to make the results of this investigation primarily applicable to trains which have been in motion for some time. Since, however, stops are not usually made upon ruling grades, and since, if stops are made at other places on the road, the locomotive has available tractive power in excess of the requirements, the results of these tests are generally applicable in the solution of tonnage rating problems, except where the ruling grade occurs near a yard or other point where the trains are made up. In such cases the

*Further investigation of this matter is in progress and the results will probably be published soon. (*These results were published in Bulletin 59 of the Engineering Experiment Station, entitled "The Effects of Cold Weather on Train Resistance and Tonnage Rating," by Edward C. Schmidt.*)

†During the 32 tests included in the investigation only 68 stops, all told, were made after leaving the yards. Of these, one was of 55 minutes duration, nine lasted between 20 and 40 minutes, twenty-two between 10 and 20 minutes, and thirty-six less than 10 minutes.

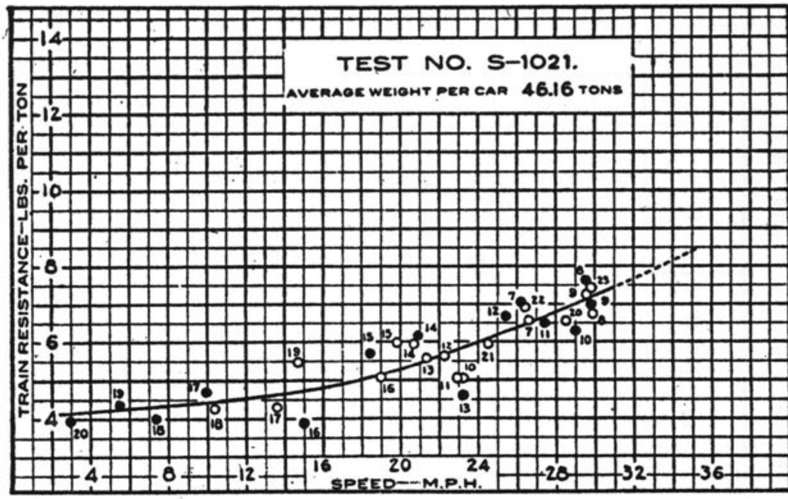


FIG. 1. THE RELATION OF RESISTANCE TO SPEED FOR TEST S-1021

tonnage determined from the resistance curves here presented may prove to be somewhat too great.

17. *The Derivation of the Resistance Curves.*—The calculations result, for each test, in a series of values of net train resistance at a variety of speeds. These values of resistance were plotted with respect to speed, and gave such a diagram as in Fig. 1. The curve, such as is shown there, was next drawn to express, for the test in question, the relation existing between resistance and speed. In order to draw this curve, the plotted points were assumed to be arranged in a number of groups, and for each group the averages of the values of speed and of resistance were determined. By these averages a new point or "center of gravity" of the group was then plotted. The curve was drawn by confining attention to the few points thus determined. The groups of points were arbitrarily selected so that the resulting "centers of gravity" would be distributed nearly equidistantly throughout the speed range. All curves presented in the report, except those exhibited in Fig. 11, were drawn by this process.

All reasonable precautions have been taken to attain accuracy in the calculations. In determining each value of resistance, each step in the process was duplicated at a different time and generally by a different person. The transcription of all tables, the plotting of points, and the drawing of curves have been similarly checked.

VI. Results of the Tests

18. *Results of the Individual Tests.*—The immediate result of each test is a curve which shows for the train under consideration the relation existing between train resistance and speed. Figure 1 is such a curve derived from test S-1021; similar curves for the other tests are exhibited in Appendix 5. Figure 1 is fairly representative of the entire group of curves, and such discussion of it as follows is general in its application.

The plotted points* show unmistakably an increase in resistance as the speed increases, and the curve drawn represents the mean relation between resistance and speed. In Fig. 1 the maximum variation from this mean of any calculated value of resistance is about 20 per cent; the next largest variation is 16 per cent and other calculated values of resistance differ from the values determined from the curve by generally less than 10 per cent. In a majority of the tests the maximum variation is less than in Fig. 1, and the general agreement between the calculated values of resistance and the ordinates of the curve is better than in the test chosen for illustration.

It has been thought desirable to express more specifically this variation between the calculated values of resistance and the mean values as derived from the curves drawn. To this end, for all tests, all calculated values of resistance for speeds between 8 and 12 miles per hour were compared with the ordinates of the curves at the corresponding speeds and the percentage difference was determined in each case. These percentages were then arranged in two groups and averaged. The one group included the results from all points lying above the curve, the other from those lying below it. The whole process was next repeated for speeds between 28 and 32 miles per hour. The results are as follows:—

Average Deviation (for all tests) of Calculated Resistance from the Mean Values Derived from the Curves—Expressed in Percentage of the Mean Values

Speed	Above the Mean	Below the Mean
8 to 12 m.p.h.	6.4 per cent	7.6 per cent
28 to 32 m.p.h.	5.6 per cent	6.6 per cent

Such variation seems not unduly great for this class of experimental work.

*The numbers shown near the points are the item numbers of the tables in Appendix 5. The tables exhibit the calculated values of resistance and speed, which are the coördinates of the plotted points. (*These tables are omitted in thr reprint.*)

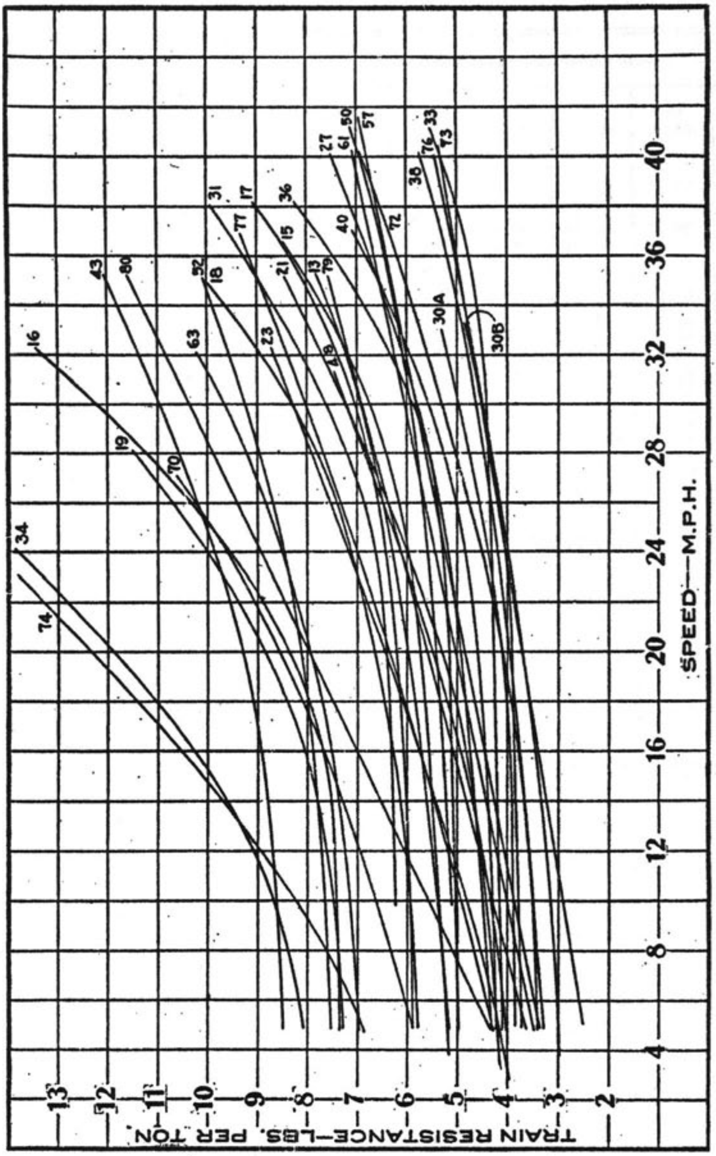


FIG. 2. CURVES SHOWING THE RELATION BETWEEN RESISTANCE AND SPEED FOR EACH OF THE TESTS

These differences may be due in part to accumulated errors in instruments or in the calculations. In all cases, however, where the calculated value of resistance varied by an unusual amount from the mean, all calculations leading thereto were repeated a second time and errors thus discovered have been eliminated from the report. The explanation for such differences need not be sought further than in the variations which actually occur from time to time in the resistance itself. Variations in such components of train resistance as flange friction and wind resistance are probably sufficiently great to account for the differences discussed above. The data do not permit the influences of such components of resistance to be differentiated.

The curve drawn for each test has been accepted as representing the average values of net train resistance with a degree of accuracy sufficient for the purpose of rating locomotives. Such temporary excess of resistance as may be expected to occur will generally be absorbed in that reserve in the tractive effort of the locomotive which must be allowed in any system of tonnage rating.

19. *Results of All the Tests.*—The resistance curves for the individual tests have all been brought together on one sheet, a reproduction of which is shown as Fig. 2. The curves there drawn are duplicates of those separately shown in Appendix 5.* Figure 2 displays the immediate results of the whole research. The lower curves give values of resistance varying from 3 lb. to 5½ lb. per ton, while the upper curves show resistance values varying from 7 lb. to 14 lb. per ton. Resistance values at the lower speeds differ by 100 per cent, and values at higher speeds differ by as much as 200 per cent. If further analysis had not revealed the cause of the great variation in resistance here shown, Fig. 2 would have remained a useless exhibit.

The explanation of this variation has been sought in the test conditions enumerated below, each of which, it was conceived, might have contributed in some degree to bring about the differences disclosed in Fig. 2:

(*a*) Weather and temperature conditions.
(*b*) Wind velocity and direction.
(*c*) Kind of cars composing the train.
(*d*) Position of the loaded cars in the train.
(*e*) Defects in train equipment.
(*f*) Average weight of the cars in the train.

*The numbers shown on the curves are the last two figures of the test numbers. The curve marked 43 is derived from test S-1043.

TABLE 2

VALUES OF RESISTANCE AT VARIOUS SPEEDS, DERIVED FROM THE CURVES FOR THE INDIVIDUAL TESTS.

This table provides the coördinates of the points plotted in Figs. 3 to 9.

Test No.	Aver. Weight per Car tons.	Train Resistance—pounds per ton.						
		5 m.p.h.	10 m.p.h.	15 m.p.h.	20 m.p.h.	25 m.p.h.	30 m.p.h.	35 m.p.h.
S-1016	16.12	7.35	7.40	7.62	8.37	9.91	12.22	
S-1034	16.56	8.10	8.70	9.92	11.90	14.30		
S-1074	16.56	6.92	8.23	10.10	12.32	14.70		
S-1043	16.92	8.50	8.61	8.85	9.30	10.00	10.95	12.04
S-1019	17.72	7.30	7.47	7.90	8.85	10.32		
S-1063	20.04	6.98	7.13	7.43	7.90	8.63	9.63	
S-1031	20.72		6.24	6.30	6.40	6.73	7.60	8.94
S-1080	21.40	4.40	5.57	6.75	7.94	9.15	10.35	11.55
S-1070	24.60	5.93	6.63	7.47	8.57	9.90		
S-1052	24.80	7.55	7.63	7.80	8.10	8.55	9.20	10.05
S-1018	25.40	5.80	5.95	6.20	6.63	7.22	8.26	10.02
S-1077	28.40	4.32	4.91	5.58	6.34	7.15	8.01	8.96
S-1079	33.04	3.66	4.30	4.92	5.60	6.22	6.89	7.55
S-1015	36.08	5.20	5.36	5.52	5.70	6.02	6.71	7.95
S-1036	37.72	4.98	5.03	5.12	5.15	5.31	5.88	7.15
S-1013	38.04		5.40	5.65	5.95	6.32	6.90	7.68
S-1017	38.44	5.90	5.95	6.02	6.20	6.48	7.01	8.03
S-1023	38.72	4.16	4.80	5.56	6.40	7.30	8.25	
S-1050	40.44		5.10	5.25	5.40	5.62	5.90	6.33
S-1057	41.32	3.40	3.88	4.35	4.83	5.31	5.80	6.30
S-1048	45.24	4.05	4.35	4.80	5.48	6.30	7.23	
S-1040	45.76	4.22	4.30	4.40	4.58	4.90	5.52	6.53
S-1021	46.16	4.21	4.41	4.72	5.29	6.15	7.20	8.40
S-1027	47.44	4.31	4.48	4.67	4.90	5.22	5.79	6.55
S-1061	51.20	3.50	4.00	4.51	5.01	5.51	6.01	6.53
S-1033	51.72	4.10	4.15	4.20	4.25	4.32	4.40	4.65
S-1038	52.28	3.30	3.50	3.71	3.95	4.25	4.60	5.08
S-1030B	57.12	3.73	3.80	3.82	3.90	4.10	4.50	
S-1030A	59.88	3.84	3.88	3.92	4.10	4.45	4.95	
S-1072	66.40	3.40	3.50	3.70	4.10	4.61	5.27	6.00
S-1073	67.16	2.52	2.90	3.30	3.70	4.10	4.50	4.90
S-1076	69.92	2.97	3.13	3.37	3.70	4.04	4.49	4.95

The first five conditions are either uncontrollable or were purposely not controlled during these experiments. Attempts to explain the differences between the curves of Fig. 2 by reference to one or the other of these five factors have been altogether unsuccessful. While it is true that difference in wind velocity, for example, might be accepted as a plausible explanation of the differences between two or three curves selected at random from Fig. 2, such explanation will not hold when applied to two or three other curves similarly chosen; and it fails altogether to explain such differences when it is applied to the whole group. The same remarks apply to attempts to explain the differences between the curves of Fig. 2 by referring them to any other of the first five items cited above.

Item *f*, however, has furnished the clue whereby the apparent confusion in the results of the tests, as exhibited in Fig. 2, has been explained. It may be stated at once that the difference in train resistance

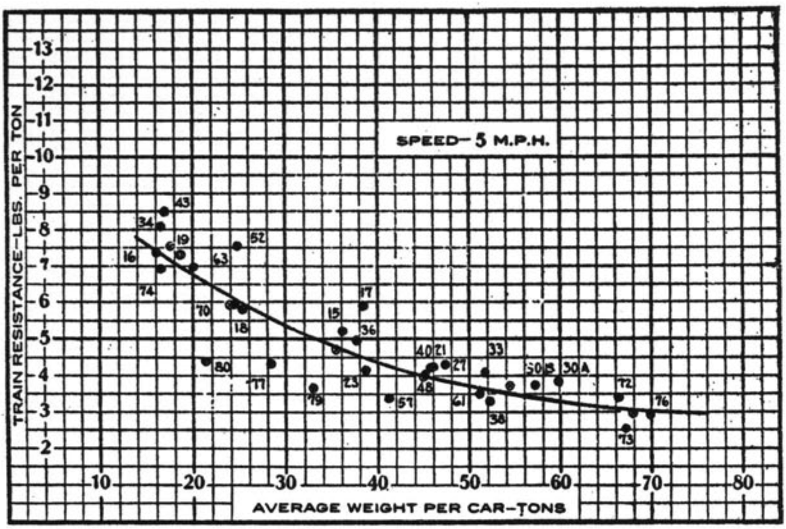


FIG. 3. THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 5 MILES PER HOUR

for various tests is believed to be due chiefly to differences in the average gross car weights existing during the tests. An explanation of the process which led to this opinion follows immediately below. As was stated at the outset, this conclusion was anticipated when the work was begun, and the average car weight was therefore controlled during the experiments, and made to vary through the widest possible range.

20. *The Effects of Car Weight on Resistance.*—The four upper curves of Fig. 2 are derived from trains in which the average weight per car was about 16 or 17 tons. The lowest curves are those derived from trains in which the car weight was nearly 70 tons. These facts serve as a rough indication of the part played by car weight in effecting changes in train resistance. This influence is more definitely brought out in the following discussion.

If from each of the curves of Fig. 2 the value of resistance is determined at one speed, say 5 miles per hour, these values of resistance may then be plotted with respect to their corresponding values of car weight; and, since the speed is common, its influence is eliminated and the resulting diagram may be expected to reveal the relation existing between train resistance and average weight per car. Table 2 was prepared to facilitate this process. In it the tests are arranged in the

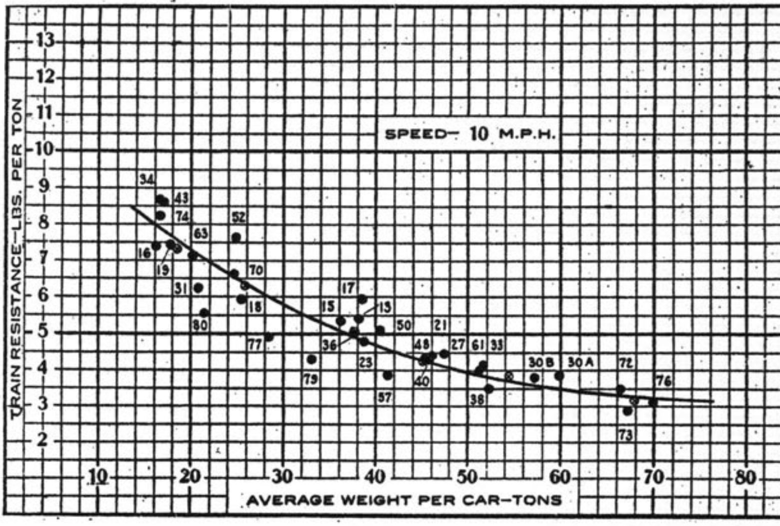


FIG. 4. THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 10 MILES PER HOUR

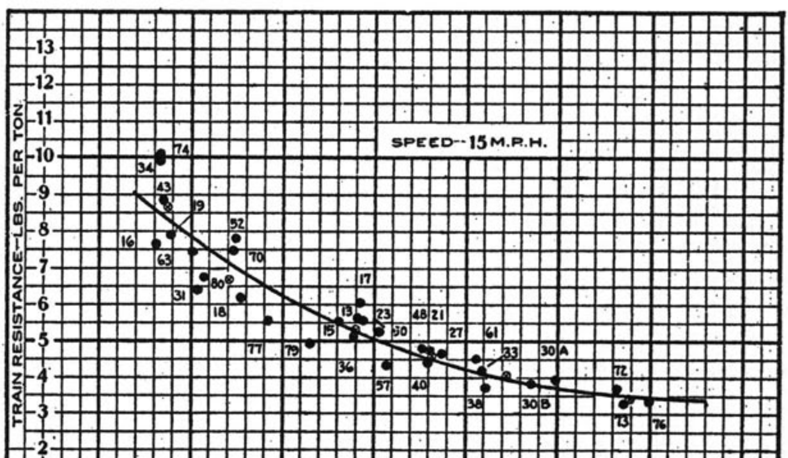


FIG. 5. THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 15 MILES PER HOUR

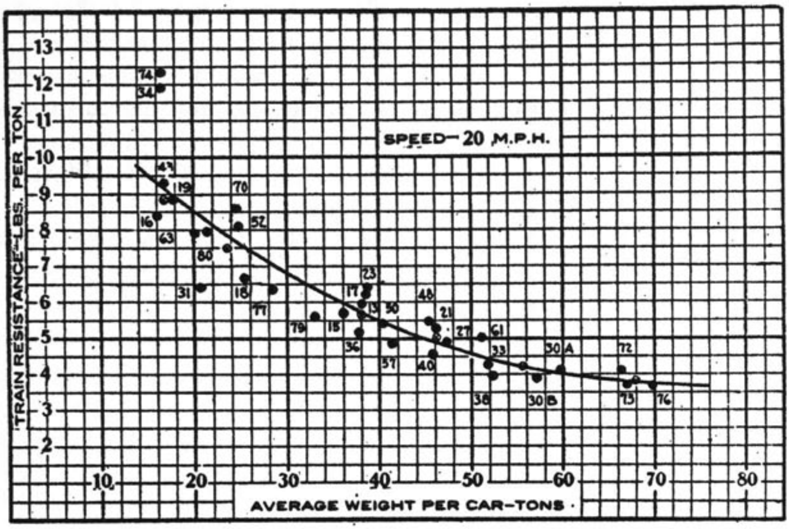


FIG. 6. THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 20 MILES PER HOUR

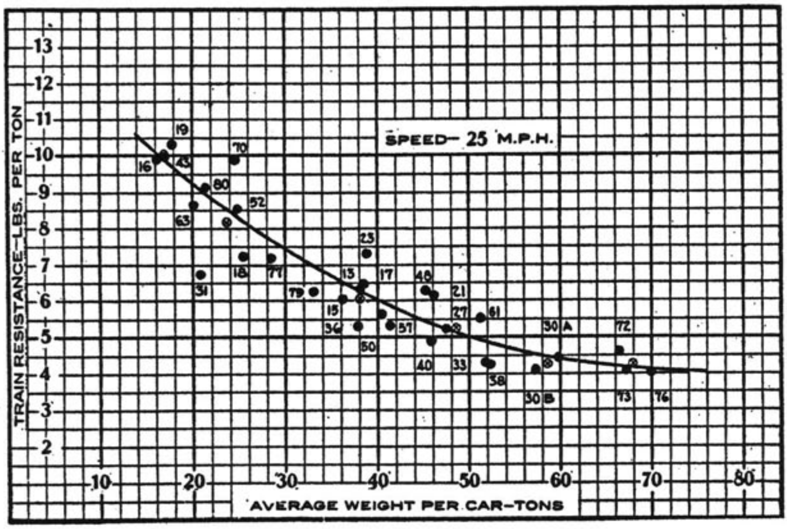


FIG. 7. THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 25 MILES PER HOUR

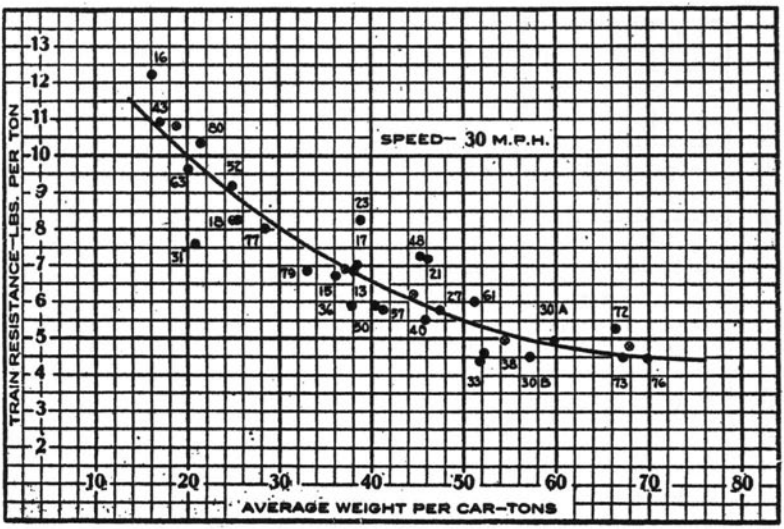


FIG. 8. THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 30 MILES PER HOUR

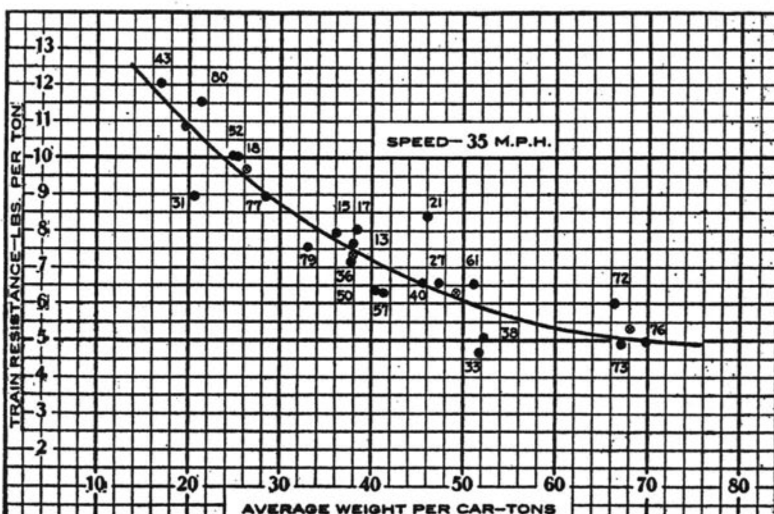


FIG. 9. THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 35 MILES PER HOUR

order of the average car weights. These weights are given in the second column and in the succeeding columns are set down the resistance values obtained from the *curves* of the individual tests, for each of seven different speeds. Table 2 therefore presents the values of the coördinates of seven points on each of the curves of Fig. 2 and hence, like Fig. 2, summarizes the immediate results of all tests.*

In Table 2 the second and third columns present a series of values of average car weight and of train resistance at 5 miles per hour. Each pair of these values represents the results of one of the 32 tests. Using these pairs of values as coördinates, a series of points has been plotted to form a new diagram, Fig. 3. For example, the point marked 21 in Fig. 3 is derived from the curve of test S-1021. The curve of resistance for this test (see Fig. 1 or Fig. 2) shows that at 5 miles per hour the mean resistance is 4.21 lb. per ton. During this test the average weight of the cars in the train was 46.16 tons. Table 2 also exhibits both of these values which, when plotted in Fig. 3, determine the point there marked 21. The other points of Fig. 3 were similarly determined. Each point represents the value of resistance at 5 miles per hour derived from a particular test train.

Although there is considerable variation among the points of Fig. 3, they indicate clearly a decrease in the resistance as the car weight increases. The curve drawn in Fig. 3 represents, for the trains tested, the mean relation which existed between resistance at 5 miles per hour and the average car weight.† For higher speeds this relation between resistance and car weight is shown by Figs. 4 to 9, which were derived by the same methods employed in producing Fig. 3.

The variation in resistance represented by the points in Figs. 3 to 9 is sufficient to warrant further discussion. Such discussion will, however, be postponed until later in the report. The conclusion reached is that these variations are largely caused by factors which are uncontrollable in ordinary train operation. If this be admitted, it is clear that the discussion of such variations may enter into the solution of tonnage rating problems only as an argument for reserve tractive effort in the locomotive. An estimate of the desirable amount of such reserve appears beyond.

The curves of Figs. 3 to 9 have been accepted as representing, for

*Table 2 has been prepared from the original curves of the individual tests, only one of which is separately presented in Part I (see Fig. 1). It gives no information not obtainable from Fig. 2, but presents the information in more convenient form, since the number of curves drawn in the figure makes it confusing.

†As has been previously explained, the curve is drawn by finding the "centers of gravity" of several groups of points. These centers are defined in Figs. 3 to 9 by the crosses within circles. Points 34 and 74 were virtually ignored in drawing the curves of Figs. 6 and 7. The numbers at the points are the last two figures of the test numbers.

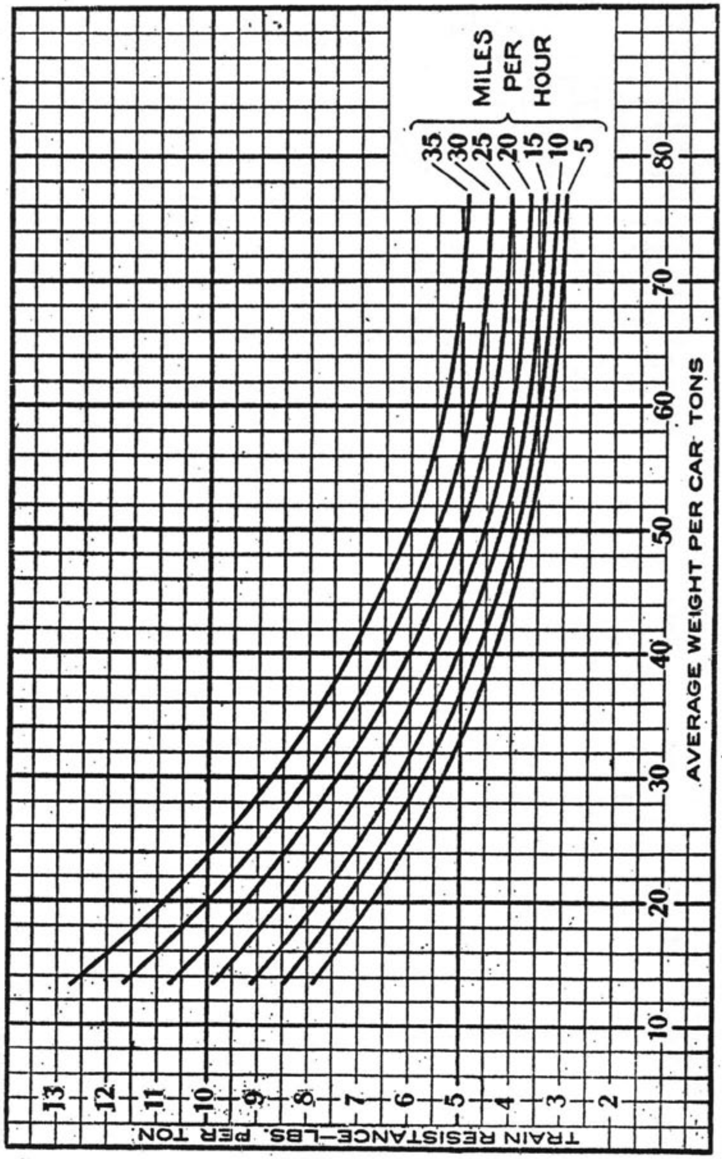


FIG. 10. THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT VARIOUS SPEEDS

these tests, the mean relation which existed between train resistance and the average gross weight of the cars composing the trains. These curves exhibit this relation at seven different speeds, 5, 10, 15, 20, 25, 30 and 35 miles per hour. For convenience in use and to make comparison easier, these seven curves have been brought together in one diagram which is reproduced in Fig. 10.

Figure 10 presents the final results of the whole research. Each of the curves there drawn shows the mean relation, which existed during the tests, between car weight and resistance at a definite speed.

It is believed that the curves of Fig. 10 are generally applicable to ordinary American freight trains, provided the conditions surrounding their operation are like those which prevailed during these tests. The curves of Fig. 10 enable one to determine the probable mean resistance of any such train, at speeds between 5 and 35 miles per hour, provided the average weight of the cars composing the train be known.

21. *The Results Expressed as Resistance-Speed Curves.*—While Fig. 10 presents the main results of the experiments, the form in which these results are there expressed is unusual. Ordinarily, train resistance is expressed either as a curve or equation which defines the relation between resistance and speed, instead of the relation between resistance and car weight as in Fig. 10. Obviously, to express the results of these experiments in the usual form, a single curve will not suffice, since the influence of car weight cannot be thereby made evident. A number of curves will be required for this purpose each of which will apply only to a definite average car weight. Figure 11 presents such a group of resistance-speed curves, which have been derived directly from the curves of Fig. 10. Figure 11 therefore exhibits in different form only such information as is obtainable from Fig. 10.

The relation between the two figures may be made clear by explaining the derivation of the upper curve in Fig. 11—the one applying to a car weight of 15 tons. In Fig. 10 the ordinate corresponding to an average car weight of 15 tons cuts the seven curves there drawn at 7 points, at which the mean resistance values are 7.62, 8.20, 8.81, 9.56, 10.37, 11.24 and 12.25 lb. per ton, corresponding to speeds of 5, 10, 15, 20, 25, 30 and 35 miles per hour, respectively. These values are the coördinates of 7 points on a resistance-speed curve applying to a car weight of 15 tons. These 7 points have been plotted in Fig. 11 and the upper curve there shown has been passed through them and extended to 40 miles per hour. The other curves of Fig. 11 were derived by a like process. In the original diagram three additional

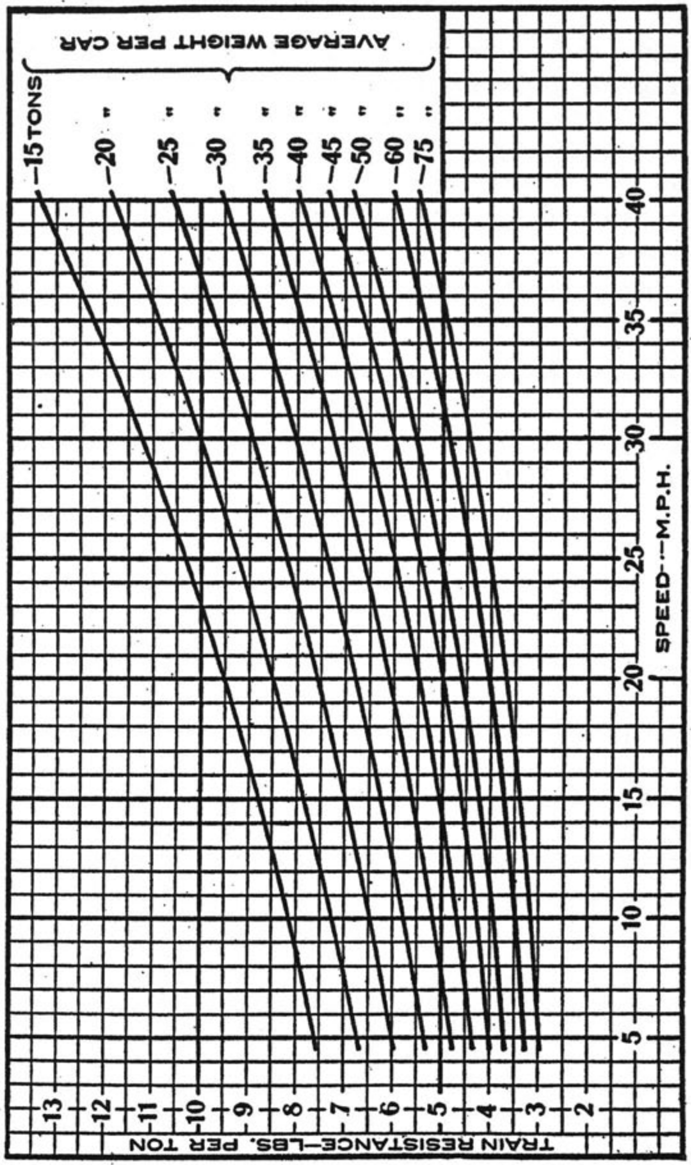


FIG. 11. THE RELATION BETWEEN RESISTANCE AND SPEED, FOR VARIOUS AVERAGE WEIGHTS PER CAR

TABLE 3

VALUES OF RESISTANCE AT VARIOUS SPEEDS FOR TRAINS OF DIFFERENT AVERAGE WEIGHTS PER CAR

The values are derived directly from the curves of Fig. 11 and represent the final results of the tests.

Speed miles per hour	Train Resistance—pounds per ton													Speed miles per hour
	Column Headings Indicate the Average Weights Per Car													
	15 tons	20 tons	25 tons	30 tons	35 tons	40 tons	45 tons	50 tons	55 tons	60 tons	65 tons	70 tons	75 tons	
5	7.6	6.8	6.0	5.4	4.8	4.4	4.0	3.7	3.5	3.3	3.2	3.1	3.0	5
6	7.7	6.9	6.1	5.5	4.9	4.4	4.1	3.8	3.5	3.3	3.2	3.1	3.0	6
7	7.8	7.0	6.2	5.5	5.0	4.5	4.1	3.8	3.6	3.4	3.2	3.1	3.1	7
8	8.0	7.1	6.3	5.6	5.0	4.6	4.2	3.9	3.6	3.4	3.3	3.2	3.1	8
9	8.1	7.2	6.4	5.7	5.1	4.6	4.2	3.9	3.6	3.4	3.3	3.2	3.1	9
10	8.2	7.3	6.5	5.8	5.2	4.7	4.3	4.0	3.7	3.5	3.3	3.2	3.2	10
11	8.3	7.4	6.6	5.9	5.3	4.8	4.3	4.0	3.7	3.5	3.4	3.3	3.2	11
12	8.4	7.5	6.7	6.0	5.4	4.8	4.4	4.0	3.8	3.6	3.4	3.3	3.3	12
13	8.6	7.6	6.8	6.1	5.5	4.9	4.5	4.1	3.8	3.6	3.5	3.4	3.3	13
14	8.7	7.8	6.9	6.2	5.5	5.0	4.5	4.2	3.9	3.7	3.5	3.4	3.4	14
15	8.8	7.9	7.0	6.3	5.6	5.1	4.6	4.2	3.9	3.7	3.6	3.5	3.4	15
16	9.0	8.0	7.1	6.4	5.7	5.1	4.7	4.3	4.0	3.8	3.6	3.5	3.5	16
17	9.1	8.1	7.2	6.5	5.8	5.2	4.8	4.4	4.1	3.9	3.7	3.6	3.5	17
18	9.3	8.3	7.4	6.6	5.9	5.3	4.8	4.5	4.1	3.9	3.7	3.7	3.6	18
19	9.4	8.4	7.5	6.7	6.0	5.4	4.9	4.5	4.2	4.0	3.8	3.7	3.6	19
20	9.6	8.5	7.6	6.8	6.1	5.5	5.0	4.6	4.3	4.0	3.9	3.8	3.7	20
21	9.7	8.7	7.7	6.9	6.2	5.6	5.1	4.7	4.3	4.1	3.9	3.9	3.8	21
22	9.9	8.8	7.9	7.0	6.3	5.7	5.2	4.8	4.4	4.2	4.0	3.9	3.8	22
23	10.0	9.0	8.0	7.1	6.4	5.8	5.3	4.9	4.5	4.3	4.1	4.0	3.9	23
24	10.2	9.1	8.1	7.3	6.6	5.9	5.4	4.9	4.6	4.3	4.2	4.1	4.0	24
25	10.4	9.3	8.3	7.4	6.7	6.0	5.5	5.0	4.7	4.4	4.2	4.1	4.0	25
26	10.5	9.4	8.4	7.5	6.8	6.1	5.6	5.1	4.8	4.5	4.3	4.2	4.1	26
27	10.7	9.6	8.5	7.7	6.9	6.2	5.7	5.2	4.8	4.6	4.4	4.3	4.2	27
28	10.9	9.7	8.7	7.8	7.0	6.3	5.8	5.3	4.9	4.7	4.5	4.4	4.3	28
29	11.1	9.9	8.8	7.9	7.1	6.5	5.9	5.4	5.0	4.8	4.6	4.5	4.4	29
30	11.3	10.0	9.0	8.0	7.3	6.6	6.0	5.5	5.1	4.9	4.7	4.5	4.5	30
31	11.4	10.2	9.1	8.2	7.4	6.7	6.1	5.6	5.2	5.0	4.8	4.6	4.5	31
32	11.6	10.4	9.3	8.3	7.5	6.8	6.2	5.8	5.3	5.0	4.9	4.7	4.6	32
33	11.8	10.5	9.4	8.5	7.6	7.0	6.3	5.9	5.4	5.2	5.0	4.8	4.7	33
34	12.0	10.7	9.6	8.6	7.8	7.1	6.5	6.0	5.5	5.3	5.1	4.9	4.8	34
35	12.3	10.9	9.7	8.8	7.9	7.2	6.6	6.1	5.7	5.4	5.2	5.0	4.9	35
36	12.5	11.1	9.9	8.9	8.0	7.4	6.7	6.2	5.8	5.5	5.3	5.1	5.0	36
37	12.7	11.2	10.0	9.0	8.2	7.5	6.9	6.4	5.9	5.6	5.4	5.2	5.1	37
38	12.9	11.4	10.2	9.2	8.3	7.6	7.0	6.5	6.0	5.7	5.5	5.3	5.2	38
39	13.1	11.6	10.4	9.4	8.5	7.8	7.1	6.6	6.2	5.8	5.6	5.4	5.3	39
40	13.4	11.8	10.6	9.5	8.6	7.9	7.3	6.8	6.3	6.0	5.7	5.6	5.5	40

curves, corresponding to 55, 65, and 70 tons per car, were drawn. These three curves have been omitted from the figure to avoid confusion. Figure 11 reproduces quite exactly the facts presented in Fig. 10,* and presents the final results of the experiments.

22. *The Results Expressed in Tabular Form.*—From each of the curves of Fig. 11 the values of resistance at various speeds have been determined and set down in Table 3. Table 3 also includes the co-

*The points derived from Fig. 10 have been omitted from the tracing from which Fig. 11 was reproduced. All such points lie very close to the curves drawn in Fig. 11, the maximum deviation amounting to but ¾ of one per cent of the corresponding curve ordinate. In Appendix 6 there are presented tables of coördinates, by means of which Figs. 10 and 11 may be exactly reproduced.

ordinates of the resistance curves corresponding to 55, 65, and 70 tons per car, which are omitted from Fig. 11.

23. *The Results Expressed As Equations.*—The relation between resistance and speed shown by each of the curves of Fig. 11 may also be expressed in the form of an equation. Formulas (1) to (13) below are such equations, by means of which resistance may be calculated for any speed and for various car weights. In the formulas, R is the resistance expressed in pounds per ton, S is the speed expressed in miles per hour, and W is the average weight of the cars in the train expressed in tons. The formulas are purely empirical, and are simply equations of parabolas so selected as to correspond very closely with the curves of Fig. 11. The correspondence between the formulas and the curves is such that the maximum difference between any value of resistance obtained by the formulas and the corresponding value obtained from the curves of Fig. 11 is ½ of one per cent. Since these are empirical equations, their use should not be extended beyond the speed limits shown on Fig. 11.

Train Resistance Formulas

$$\text{When } W = 15 \text{ tons}; R = 7.15 + 0.085\,S + 0.00175\,S^2 \qquad (1)$$
$$\text{When } W = 20 \text{ tons}; R = 6.30 + 0.087\,S + 0.00126\,S^2 \qquad (2)$$
$$\text{When } W = 25 \text{ tons}; R = 5.60 + 0.077\,S + 0.00116\,S^2 \qquad (3)$$
$$\text{When } W = 30 \text{ tons}; R = 5.02 + 0.066\,S + 0.00116\,S^2 \qquad (4)$$
$$\text{When } W = 35 \text{ tons}; R = 4.49 + 0.060\,S + 0.00108\,S^2 \qquad (5)$$
$$\text{When } W = 40 \text{ tons}; R = 4.15 + 0.041\,S + 0.00134\,S^2 \qquad (6)$$
$$\text{When } W = 45 \text{ tons}; R = 3.82 + 0.031\,S + 0.00140\,S^2 \qquad (7)$$
$$\text{When } W = 50 \text{ tons}; R = 3.56 + 0.024\,S + 0.00140\,S^2 \qquad (8)$$
$$\text{When } W = 55 \text{ tons}; R = 3.38 + 0.016\,S + 0.00142\,S^2 \qquad (9)$$
$$\text{When } W = 60 \text{ tons}; R = 3.19 + 0.016\,S + 0.00132\,S^2 \qquad (10)$$
$$\text{When } W = 65 \text{ tons}; R = 3.06 + 0.014\,S + 0.00130\,S^2 \qquad (11)$$
$$\text{When } W = 70 \text{ tons}; R = 2.92 + 0.021\,S + 0.00111\,S^2 \qquad (12)$$
$$\text{When } W = 75 \text{ tons}; R = 2.87 + 0.019\,S + 0.00113\,S^2 \qquad (13)$$

The results of the tests may also be approximately expressed by the following single empirical equation in which R is expressed in terms of both S and W.

$$R = \frac{S + 39.6 - 0.031\,W}{4.08 + 0.152\,W} \qquad (14)$$

When compared with the results of the tests as shown in Fig. 11, or in Table 69 in Appendix 6, this equation results in a maximum error of 9.5 per cent. This error occurs when $S = 21$ and $W = 55$. For all other values of S and W the error resulting from the use of the equation is 9.0 per cent or less.

24. *Final Results.*—The final results of the research are presented in Fig. 11, in Table 3, and in Formulas (1) to (13). It is believed that by means of the figure, or the table, or the formulas, the resistance of ordinary freight trains may be fairly accurately predicted; provided the conditions surrounding their operation are similar to those which prevailed during these tests. These conditions have been fully stated and are restated in the conclusions. It is sufficient to repeat at this point that the results apply to trains running at uniform speed, on tangent and level track of good construction, during weather when the temperature is not lower than 30° F., and when the wind velocity does not exceed about 20 miles per hour.

VII. Discussion of the Results

25. *Variation in Resistance of Different Trains.*—Reference has been made to the variations among the points of Figs. 3 to 9. In each figure about one-half of the points lie above the curve there drawn, and their resistance values vary from those of the curve by different amounts. It should be borne in mind that, in these figures, each point represents the average resistance which prevailed throughout a particular test, and differences among the points represent, therefore, differences in the mean resistance of the different trains.

Among those trains which are regarded as normal there are two or three whose resistance at some speed varies from the mean, as expressed in the curves, by as much as 23 per cent. The great majority, however, vary from this mean by about 10 per cent or less. In Fig. 4, for example, there are 19 points which lie above the curve, among which the maximum deviation from the mean is 23 per cent, while the average of the deviations for all 19 points is 8 per cent. The following table presents similar average deviations above and below the mean for each of Figs. 3 to 9.

Average Deviation of All Points in Figs. 3 to 9, from the Mean as Shown by the Curves There Drawn—Expressed as Percentages of the Curve Ordinates

	Fig. 3 5 m.p.h.	Fig. 4 10 m.p.h.	Fig. 5 15 m.p.h.	Fig. 6 20 m.p.h.	Fig. 7 25 m.p.h.	Fig. 8 30 m.p.h.	Fig. 9 35 m.p.h.
Points above the curve	11	8	8	11	13	8	7
Points below the curve	13	10	9	8	9	9	9

The data present no satisfactory general explanation for these differences in the resistance of different trains of like average weight per car. They may be due to difference in external conditions or to difference in train condition and make-up. Whatever may be the explanation for these differences it is significant that about one-half of the trains experimented upon developed a resistance about 9 per cent in excess of the mean resistance which would be predicted by the use of Figs. 3 to 9 and Figs. 10 and 11. Obviously a similar excess may be expected with any train, and it is suggested therefore that, in determining the resistance of trains on *level tangent track* for the purpose of rating locomotives under operating conditions which demand conservative ratings, 9 per cent be added to the resistance values obtained from the curves, tables, and equations presented. Such considerations are of little practical importance in rating locomotives for speeds above 15 miles per hour. In such cases an excess in resistance over that expected can result in nothing more serious than failure to realize the expected train speed.

It should be understood that this 9 per cent allowance is intended to cover probable variations in the resistance of different trains under normal operating conditions. It in no way takes the place of that additional reserve which must be allowed to cover unusual variations in resistance due to low temperatures or high winds, or of that reserve in tractive effort of the locomotive which is necessitated by operating conditions which reduce the efficiency of the locomotive itself.

26. *Tests Which Present Abnormal Resistance Values.*—There are four points in Figs. 3 to 9 whose deviation from the curves is so great as to demand special examination. These are the points corresponding to tests S–1034, S–1074, S–1080, and S–1031 (points 34, 74, 80, and 31). These tests show a persistent and great variation from the mean at various speeds. The trains of tests 1034, 1074, and 1080 were alike in having average car weights less than 23 tons and in containing a large proportion of empty gondolas, 99, 98, and 84 per cent, respectively. Any explanation based on the train composition is however nullified by the fact that the trains of tests No. 1016, 1043, and 1063, which show close correspondence with the curves, had similar average car weights and contained almost equally large proportions of empty gondolas. Weather and wind conditions likewise offer no explanation of the divergences presented by these three tests. Explanations are rendered more difficult by the fact that, while the trains of tests 1034 and 1074 show unusually high resistance, the resistance in test 1080

is exceptionally low. The abnormalities presented by these three trains have therefore been accepted as unexplained by the data at hand.

The resistance of the trains of the fourth test mentioned above (S–1031) is low at all speeds. This train had an average car weight of 20.7 tons, contained 94 per cent of box cars, and was only 1425 ft. long. Other test trains of similar average car weight differ from this in having generally less than 60 per cent of box cars and in being all 2400 ft. or more in length. Taking into consideration all the data, neither fact seems, however, to offer an adequate explanation of the variations exhibited by this train.

27. *Car Weight as a Basis of Expression.*—Objection may be made to the form of expression adopted in Figs. 3 to 9 and 10, in which the resistance is expressed solely in terms of average car weight, to the apparent neglect of the influence of those elements of resistance, such as air resistance, which are independent of weight and which probably vary only with the number of cars in the train. The neglect is only apparent, however, for the process by which Fig. 10 was derived involves, although indirectly, the recognition of the influence of the number of cars. It is quite likely that, if Fig. 10 were applied to determine the total resistance of a single car, the result would be in error.

Whatever objection may be urged against the form of expression adopted, it remains true that Fig. 10 rests upon experimental results obtained with trains of usual length and that in practice one is not likely to encounter trains which present in this respect any extreme variation from the test data. The form of expression will not lead to error unless misapplied and it was chosen because it permits the results to be conveniently used in establishing tonnage ratings.

It might likewise have been more rational to express the resistance in terms of load per axle instead of load per car, since the latter can operate to cause variations in resistance only in so far as it affects the former. Since, however, all American freight cars have four axles, the expression in either form would be identical. Convenience in application warrants the choice made in this respect also.

28. *Effect of Variety in Car Weight upon Total Train Resistance.*—In Fig. 10 those portions of the curves which apply to average car weights below 20 tons were derived from trains which were quite homogeneous in their make-up as regards weight per car. These trains were necessarily composed almost exclusively of empty cars, since an average car weight of 20 tons or less cannot be obtained with cars of current design unless they are empty or nearly so, and being empty

they will be uniform in weight. Similarly for average car weights above 55 or 60 tons, the test trains were necessarily uniform in make-up. For trains of average car weights below 20 and above 60 tons, the curves of Fig. 10 are accepted, therefore, as valid and applicable to any train to be met with in practice.

In Fig. 10, those portions of the curves corresponding to car weights of from 20 to 60 tons were, on the other hand, derived from trains which presented considerable diversity in make-up as regards weight per car. Some of these trains were composed almost entirely of loaded cars, others contained large proportions of both empty and loaded cars. In presenting the results in the form adopted in Fig. 10 (and Fig. 11) the assumption is that the curves there drawn will be used throughout their entire range of average car weight to determine the total resistance of both homogeneous and mixed trains, and that, when so applied, they will lead to no material error. In view of the facts just stated it is pertinent to inquire whether this assumption is justifiable.

Assume two trains of equal tonnage, and of the same average weight per car. Assume further that one is composed of cars uniform in weight, and that the other is composed of cars of different individual weights. Now if such trains are to have equal total resistance, it can be shown that the variation in the resistance *per car* of the individual cars must be directly proportional to their weight. This implies that the curve showing the relation between *total car resistance* and car weight at a given speed must be a straight line, if homogeneous and mixed trains are to have equal total resistances at this speed. From Fig. 10 there have been derived curves showing this relation between car resistance and car weight. These curves (not shown in the report) correspond quite closely, but not exactly, with straight lines; and the correspondence is especially close for those portions of the curves which apply to car weights between 20 and 60 tons. From these facts we may conclude that the curves of Fig. 10 are not quite, but are nearly equally applicable to mixed and homogeneous trains, and that, if the curves are applied to both kinds of trains, we may expect a slight error in the resulting total train resistance. The amount of such error is indicated by the following examination of a specific case.

Assume two trains, A and B, the first homogeneous, the second mixed, as regards car weight. Train A is composed of 60 cars, each weighing 45 tons, and its total weight is 2700 tons. Train B is composed of 30 cars of 70 tons each, and 30 cars of 20 tons each; its total weight is 2700 tons and its average car weight is 45 tons. Train B presents about as great a diversity in car weight as may be encountered in current practice. Both trains have equal tonnage and the same average weight per car. Assume that the total resistance of these two trains at a speed of 5 miles per hour is to be determined. By the procedure, which it is intended shall usually be followed in using Fig. 10, the resistance for an average car weight of 45 tons, at 5 miles per hour, is found to be 4.0 lb. per ton; and the total resistance of either train A or train B is $2700 \times 4.0 = 10\ 800$ lb.

Train B, however, may be considered as made up of two shorter homogeneous trains of average car weights of 20 and 70 tons respectively and the resistance of each may be determined from those portions of the curves of Fig. 10, about whose validity no question is raised. From Fig. 10, the resistance at 5 miles per hour for a car weight of 20 tons is found to be 6.8 lb. per ton and for a car weight of 70 tons, 3.1 lb. per ton. By the use, therefore, of these portions of the curves of Fig. 10, the total resistance of train B is found to be $30 \times 20 \times 6.8 + 30 \times 70 \times 3.1 = 10\ 590$ lb., which differs from the resistance previously found by 2 per cent. If a similar analysis be made for a speed of 40 miles per hour, the corresponding difference is found to be 4 per cent. If these differences be accepted as a measure of the maximum error likely to result from the indiscriminate application of the curves of Fig. 10 to mixed and homogeneous trains, we may conclude that for purposes of rating locomotives the results of the tests as expressed in Figs. 10 and 11 and Table 3 may be so applied without material error.

29. *The Influence of Speed on Resistance.*—Within the last two years the opinion has been expressed in some quarters that train resistance between speeds of 5 and 35 miles per hour is constant. It is proper to point out that there is nothing in the data here presented to support such a conclusion.

30. *The Influence of Wind Velocity on Resistance.*—The wind velocities prevailing during the tests were generally less than 20 miles per hour. The data do not permit the influence of such winds to be differentiated from the other elements affecting resistance; but they do warrant the conclusion that this influence is small. In the introduction, train resistance was defined as the resistance in still air, whereas throughout the report the term is used to apply to the test results from which the influence of wind has not been eliminated. This inconsistency has been deliberately incurred to avoid unwieldy expression and is partially justified by the facts just stated.

31. *Comparison with Other Experiments.*—There is no point in comparing the results of these tests with formulas in which the influence of car weight is given no consideration, nor with those which are not derived from tests with American cars of recent design. The results obtained on the Chicago, Burlington and Quincy Railroad and on the Pennsylvania Railroad, and recently published by Mr. F. J. Cole,* take into consideration the influence of car weight and they apply to cars of recent design. They are therefore selected for comparison.

The results obtained on the Chicago, Burlington and Quincy road (curve No. 1, for temperatures above 30° F. and no wind) apply to a speed of 20 miles per hour. Compared with the curve for 20 miles per hour in Fig. 10, they show resistance values which are from 35 to 60 per cent lower than the corresponding results of these tests. The Pennsylvania Railroad results are claimed to be equally applicable at all speeds between 5 and 30 miles. When plotted on Fig. 10 of this report they show very close correspondence with the curve there drawn for 10 miles per hour, for car weights from 25 to 70 tons; while for car weights below 25 tons they indicate resistance values as much as 20 per cent in excess of the results obtained during these tests.

*Railway Age Gazette, August 27 to October 1, 1909.

PART II

APPENDIX 1

Railway Test Car No. 17

The dynamometer car by means of which these tests were made was built in 1900. Under the arrangements perfected at that time, the car was built and has since been maintained by the Illinois Central Railroad, while the University has supplied all apparatus, and has manned and operated the car. Both the car body and the apparatus were remodeled in 1907.*

The car body was especially designed for its purpose. It is 40 ft. long over the end sills, and 8 ft. 4 in. wide inside. The central sills and the platforms are of steel, while the remainder of the construction is of wood. The general design of the car is shown in Fig. 12, and an interior view is shown in Fig. 13. The working space occupies about two-thirds of the length of the car, and in it are placed the recording apparatus, the auxiliary instruments, the storage batteries, work-bench, etc.

During the tests, the test car apparatus made continuous autographic records of draw-bar pull, speed, time, mile post positions, air-brake cylinder pressure, wind velocity with respect to the car, and wind direction with respect to the longitudinal axis of the car. These records are made upon a chart 36 in. wide, drawn across the table of the recording apparatus. This chart was driven by gearing from the axle of the central truck below the car, so that its travel was proportional to the travel of the car itself. In all tests a car travel of one mile produced a paper travel of 13.2 in. A view of the recording apparatus is shown in Fig. 14.

Figure 15 is reproduced from a tracing of a portion of the chart made during test S–1057 of this series. The only lines there shown which do not appear on the original record are the profile and the transverse lines which mark the limits of one of the sections selected for calculation. These lines and some of the explanatory lettering have been added to the tracing, in order to make clearer the significance of the various records.

The total pull which comes upon the measuring draw-bar of the car is transmitted to oil contained in the receiving cylinder, the design

*A more detailed description of the present equipment is contained in an article by F. W. Marquis, in the Railway Age Gazette, February 19, 1909.

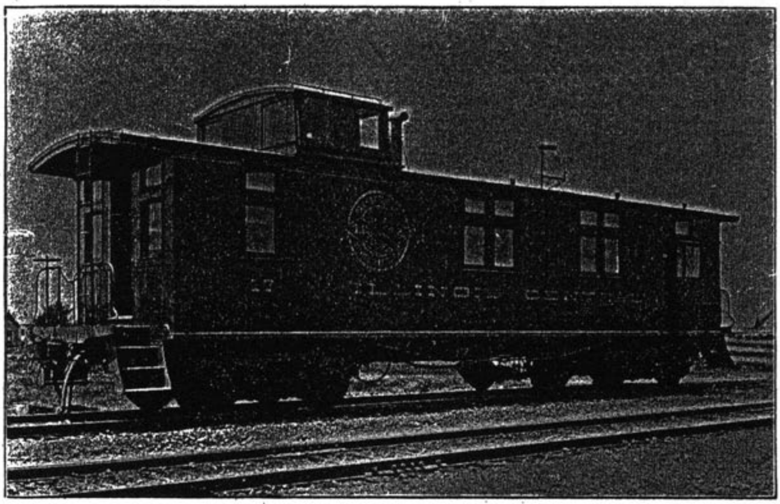


Fig. 12. Railway Test Car No. 17

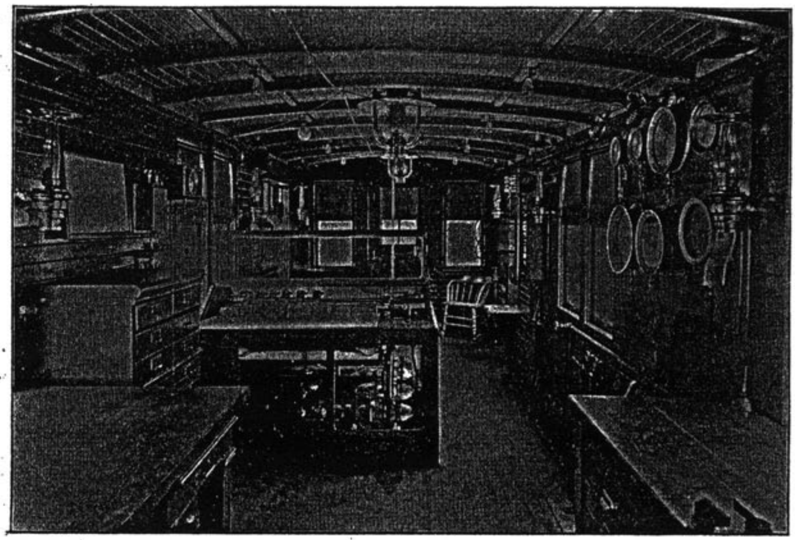


Fig. 13. Interior of Test Car No. 17

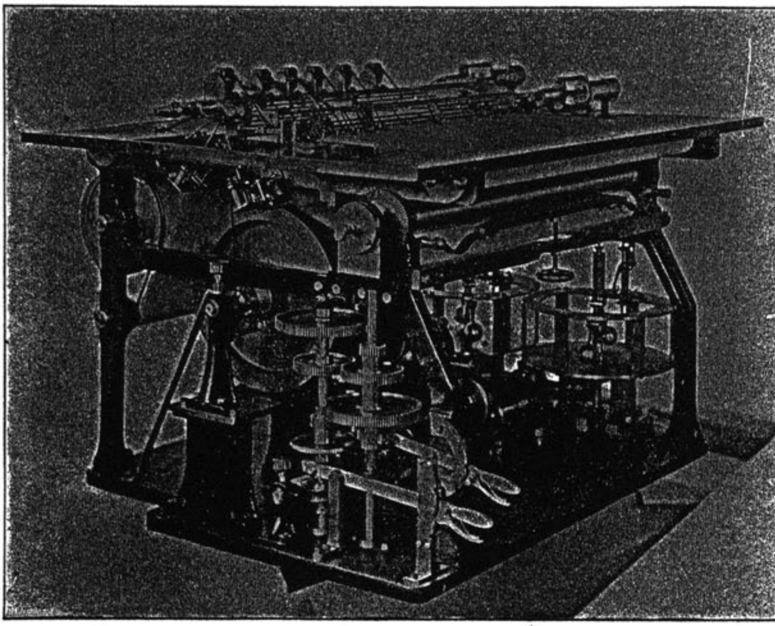


FIG. 14. THE RECORDING APPARATUS

of which is shown in Fig. 16. This cylinder is hung from the center sills, immediately behind the draw-bar yoke. Its inside diameter is 10 in., and its piston is 7½ in. long. Both cylinder and piston are carefully ground to an exact fit and no piston packing is used. The pull is transmitted from the draw-bar yoke to the piston through a roller-borne yoke; and the whole device is practically frictionless. Such leakage of oil as takes place proceeds so slowly as to prove no inconvenience, even when operating under maximum pull. The cylinder may be refilled with oil by means of a pump within the car, and this is done while the car is in operation and without impairing the accuracy of the record. The pressure of the oil in this receiving cylinder is transmitted to the cylinder of an indicator located upon the table within the car. This indicator is identical, in its design, with one of the modern types of steam engine indicators, although it is larger and heavier throughout. During its ten years of service this type of dynamometer has demonstrated its reliability and accuracy.

Two speed records are shown on the chart, and both are used. The one is obtained from a speed recorder which resembles in design a "fly-ball" engine governor. This instrument is used in measuring

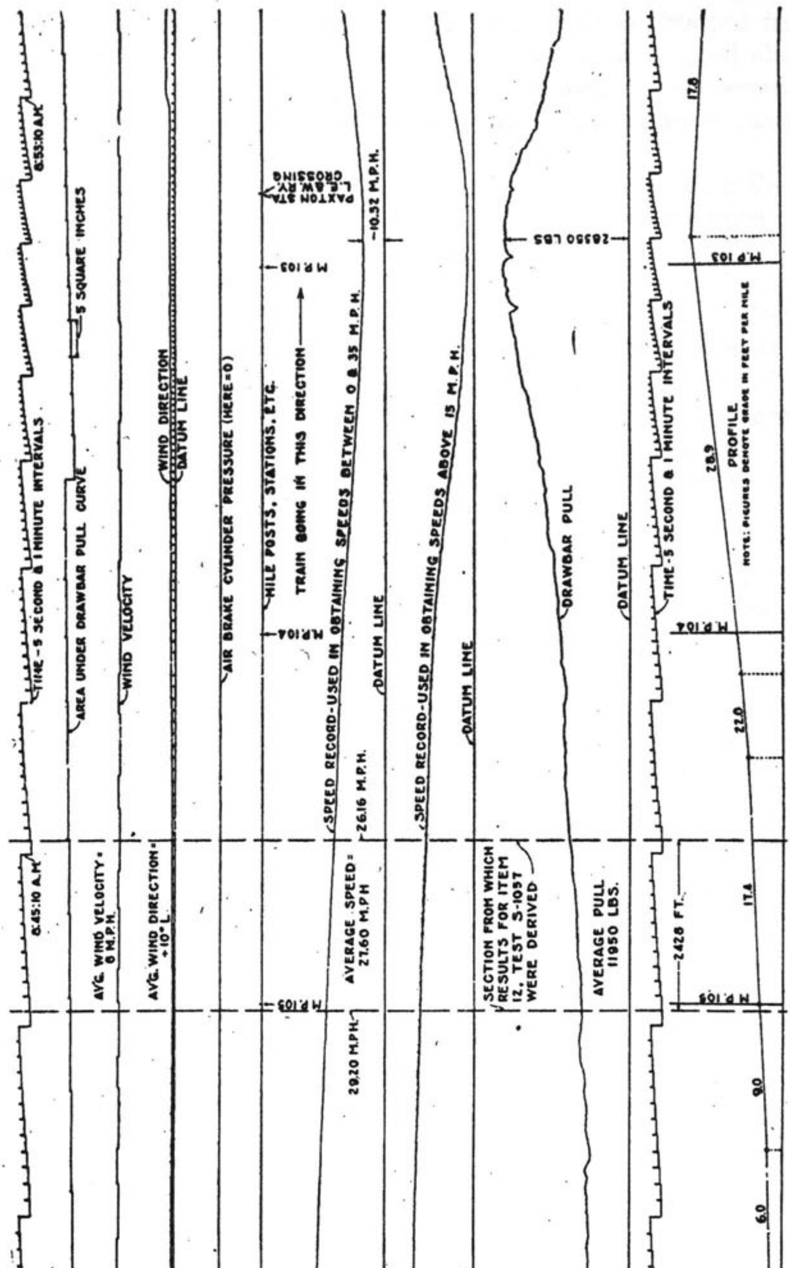


Fig. 15. A Portion of the Chart from Test S-1057

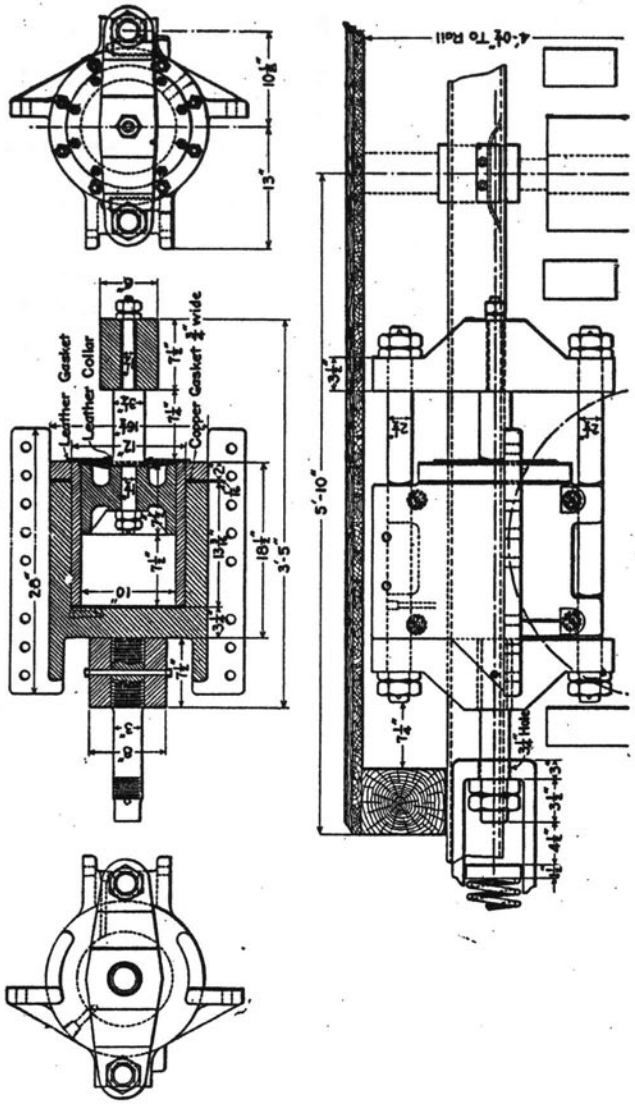


FIG. 16. THE RECEIVING CYLINDER OF THE DYNAMOMETER

speeds above 15 miles per hour. The second record is obtained from a chain-driven Boyer speed recorder, geared to run at a speed about three times as great as is usual with these instruments. This record is used for speeds up to 35 miles per hour. Within their respective ranges, both instruments produce accurate speed curves.

The air-brake cylinder of the test car is connected to the cylinder of an ordinary steam engine indicator, which is mounted upon the table and which draws a curve of air-brake cylinder pressure.

The velocity of the wind with respect to the car is obtained by means of a Robinson cup-anemometer of the standard United States Weather Bureau type, which is so mounted that the cups revolve 32 in. above the car roof. This instrument controls an electric circuit, which operates an electro-magnet connected to the recording pen. By means of this magnet offsets are made in the line drawn by the pen. During the time which elapses between two successive offsets, the travel of the air past the cups amounts to 0.2 of a mile.

The direction of the wind with respect to the longitudinal axis of the car is derived from a wind vane mounted 3 ft. above the car roof. The spindle of the vane extends downward to a point above the recording apparatus and terminates there in a crank, parallel to the vane. This crank is connected to the recording pen through a rod with a yoke end. The ordinate of the curve drawn by this pen is proportional to the sine of the angle made by the vane with the car axis. The offsets in the datum line for this curve, which appear in Fig. 15, indicate that the vane, at the moment, was pointed toward the front end of the car. While the vane points toward the rear end no offsets are made in the datum line.

Figure 15 shows a record of "area under the curve of pull" which is made by means of a recording planimeter mounted on the table. This record is inaccurate and was not used in these calculations.

APPENDIX 2*

The Tonnage Records of the Trains

Tables 4 to 35 present the records of make-up and tonnage of the trains. The car numbers are arranged in the tables in the order in which the cars were placed in the train, beginning at the head end.

With the few exceptions cited in Part I, the weights given in the last column of the tables were obtained by weighing the train on the track scales. In all tests the dynamometer car was coupled immediately behind the locomotive tender. In the tonnage records for those tests in which the test car ran with its measuring drawbar pointed toward the rear of the train, the test car weight is excluded, since in such cases its own resistance is not included in the pull recorded on the chart.

**Note on reprint. The tables in Appendix 2 of the original bulletin showed the following information for each car of each of the test trains: Kind of car, loaded or empty, car number, initials of owning line, stenciled light weight, capacity, and gross weight. Each table corresponded to a single test train. It is considered that these tables of train make-up are only of use to the investigator of the general subject of train resistance, and, since they are available in the copies of the original bulletin remaining in circulation and have been extant in printed form for many years, it is not deemed necessary to reproduce them in this reprint.*

APPENDIX 3

The Track

All tests, except No. S–1030A, were made over the 91 miles of Illinois Central main line track lying between Gilman (mile 81.12) and Mattoon (mile 172.38), Illinois.

Roadbed.—This track, formerly a part of one of the oldest single track lines in the State, was converted about ten years ago into a double track road; and the roadbed is now well settled and in good condition. In construction the roadbed has been made to conform as closely as practicable to the standard Illinois Central section for class A double track. This section has a 34-ft. crown with a slope of 1½ to 1 for embankments, and a 46½-ft. base with slopes of 1 to 1 or 1½ to 1 for cuts. The drainage of the track is, in general, excellent.

Ballast and Ties.—Except on a few short stretches through station grounds where screenings are used for ballast, both tracks are ballasted with broken limestone throughout this distance. There is not less than 12 in. of ballast beneath the ties, and the ballast shoulder extends 12 in. beyond the ties whence it runs off to the subgrade on a slope of 1¾ to 1. The cross ties are of either untreated white oak or treated red oak, and are 6 in. by 8 in. by 8 ft. long. They are spaced about 20 in. from center to center.

Rail.—The south-bound or west track between mile 161 + 3500 ft. and mile 171 is laid with rail weighing 75 lb. per yard. The remainder of the west track and all of the east track are laid with rail weighing 85 lb. per yard. The 75-lb. rail is of the standard American Society of Civil Engineers' section, rolled by the Illinois Steel Company, and is further designated as Illinois Steel Company's section No. 7506. All 85-lb. rail is of standard A. S. C. E. section, and Illinois Steel Company's section No. 8504.

Rail Joints and Fastenings.—All rails are laid with square joints, supported on three ties. The 75-lb. rails are joined with Illinois Central Standard 40-in. angle-bar splices, weighing 76 lb. per pair; and the 85-lb. rails are joined with similar splices weighing 80 lb. per pair. In each joint six track bolts are used, which are ¾ by 4⅛ in. for the 75-lb. rails, and ⅞ by 4½ in. for the 85-lb. rails. Four 9/16 by 5½ in.

track spikes are used in each cross tie. No tie plates or rail braces are used, except through switches.

Maintenance.—During eight months of the year there is employed in maintaining this portion of the road a force of men averaging one man per mile of track; during the remaining four months this force is reduced to one man for each two miles.

APPENDIX 4

Methods Employed in Calculating the Results

This appendix presents a detailed explanation of the processes used throughout this investigation in deriving the results of the tests. Two methods of calculation have been employed. By one method resistance was determined at a point on the road; by the other, the average resistance was determined for the period during which the test car passed over a certain track section. The former is termed Method 1, the latter, Method 2. A general statement and comparison of the two methods and an explanation of the general limitations imposed upon the selection of points and sections have been given in Part I. Whatever is said under "Methods Employed in Calculating the Results" in Part I is to be considered as supplementary to the contents of this Appendix.

The Elements of Gross Resistance

The various elements which make up gross train resistance are:

1. Net resistance on straight, level track, at uniform speed, in still air.
2. Resistance due to wind, (as distinguished from still air resistance).
3. Resistance due to grade.
4. Resistance due to acceleration.
5. Resistance due to track curvature.

Item 1 is always in operation to retard a moving train. One or more (or none) of the others may also be acting with item 1 to form gross resistance.

The dynamometer car records directly the gross resistance or drawbar pull as here defined. The purpose of the calculations has been to determine net resistance (item 1); or more strictly speaking, the purpose, by force of circumstances, has been to determine the sum of net resistance (item 1), and wind resistance (item 2), since it has been impossible to differentiate the latter from the other elements. Curve resistance has been entirely eliminated from consideration by selecting for calculation only those points and sections where the train was on tangent track. Grade resistance and acceleration resistance may always be determined by calculation; and in order to find the net resistance, it is necessary only to subtract these two items (3 and 4) from the gross resistance recorded on the test car chart.

Since the process employed implies the ability to calculate the grade and acceleration resistances, their determination will be explained before proceeding with the explanation of the two methods by which net resistance was derived.

The following general notation is used throughout. Other special notation needed in the development of the analysis is given as the necessity arises.

NOTATION:

P = Total gross resistance = draw-bar pull,—pounds.
R = Net resistance on tangent, level track, at uniform speed,—pounds per ton.
R_g = Resistance due to grade,—pounds per ton.
R_a = Resistance due to acceleration,—pounds per ton.
W = Total train weight,—tons.
V, V_1, etc. = Train speed,—miles per hour.
G = Grade,—feet per mile.
A = Acceleration of the train speed,—miles per hour per second.
a = Acceleration of the train speed,—feet per second per second.
E_1 and E_2 = Elevations of the center of mass of the train,—feet.
S = Length of track section used in Method 2,—feet.
N = Number of cars in the train.

Grade Resistance

If the train be on a uniform grade of G feet per mile, the grade resistance in pounds per ton is at the moment

$$R_g = 0.379 \times G \tag{15}$$

If it be desired to find the average grade resistance during the period in which the test car passes a certain section of track, we must determine the elevations of the center of mass of the train at the moments the car enters and leaves the section. If we call these elevations E_1 and E_2 respectively, and the length of the section S (in feet), then the average grade in feet per mile is

$$G = (E_2 - E_1) \times \frac{5280}{S}$$

and

$$R_g = 0.379 \times (E_2 - E_1) \times \frac{5280}{S} = \frac{2000\,(E_2 - E_1)}{S} \tag{16}$$

G and $(E_2 - E_1)$ in these equations may be found directly from the profile; and S may be calculated from the profile or from the dynamometer chart. To give correct results, the entire train must be on uniform grade at the moments for which G, E_1 and E_2 are determined.

Acceleration Resistance

The total force needed to produce acceleration is made up of two parts. The first is the force needed to produce acceleration in the motion of translation of the train as a whole; and the second is the force needed to produce acceleration in the rotation of the wheels and axles. This total force is the total acceleration resistance R_a.

Let R_a = Acceleration resistance due to both translation and rotation,—pounds per ton.
F = Total draw-bar pull needed to produce the acceleration,—pounds.
T = Draw-bar pull needed to produce acceleration in the translation of the whole train,—pounds.
f = Draw-bar pull needed to produce acceleration in the rotation of all wheels and axles,—pounds.

Then

$$R_a = \frac{F}{W}$$

and

$$F = T + f$$

therefore

$$R_a = \frac{T + f}{W} \tag{17}$$

T and f in this equation are found as follows:

$$T = \text{mass} \times \text{acceleration} = \frac{W \times 2000}{32.2} \times a$$

but

$$a = A \times \frac{5280}{60 \times 60} = 1.466\,A$$

hence

$$T = \frac{W \times 2000 \times 1.466\,A}{32.2} = 91.09\,A\,W \tag{18}$$

To find f:

Let p = Draw-bar pull required to produce the acceleration in the rotation of one pair of wheels and their axle,—pounds. This is to be considered as a force applied at the wheel rim.

p_1 = Force which, applied at the end of the "radius of gyration," would produce the acceleration in rotation produced by p.

r = Wheel radius,—any unit.

k = Radius of gyration of one pair of wheels and axle,—same unit as r.

w = Weight of one pair of wheels and their axle,—pounds.

a = Acceleration in the linear velocity of a point on the wheel rim,—feet per second per second. This equals the acceleration of the train.

b = Acceleration in the linear velocity of a point at the end of the radius of gyration,—feet per second per second.

w is taken as equal to 1950 lb.,* which is the approximate mean between the weight of a 4¼ by 8 axle and its wheels and the weight of a 5 x 9 axle and its wheels. $\frac{k}{r}$ is found to be about 0.64 for various axles and wheels.*

Since cars have 4 axles, we have:

$$f = 4\,N \times p$$

$$p = \frac{k}{r} \times p_1$$

$$p_1 = \frac{w}{32.2} \times b = \frac{1950}{32.2} \times b = 60.56\,b$$

$$b = a\frac{k}{r} = 1.466\,A \times \frac{k}{r}$$

$$p_1 = 60.56 \times 1.466\,A \times \frac{k}{r} = 88.82\,A \times \frac{k}{r}$$

$$p = 88.82\,A \times \frac{k^2}{r^2} = 88.82 \times (0.64)^2 \times A = 36.38\,A$$

and

$$f = 4 \times N \times 36.38\,A = 145.5\,A\,N \qquad (19)$$

From Equations (17), (18), and (19)

$$R_a = \frac{T}{W} + \frac{f}{W}$$

Hence

$$R_a = \left(91.09 + 145.5\frac{N}{W}\right) \times A \qquad (20)$$

---

*The maximum error in R_a which may result from possible variations in w and $\frac{k}{r}$ under current standards of car design is 1.1 per cent. R_a in the calculations seldom exceeds R, and the maximum probable error in R due to such variations is therefore about one per cent. It would occur with a train of *empty* gondolas equipped with 5½ x 10 journals and wheels weighing 725 lb. each.

Formula (20) may be applied to find the momentary acceleration resistance at a point on the road, or to determine its average value while the train passes a certain section. In the former case A denotes the momentary acceleration, and in the latter case A denotes the average acceleration over the section. N and W are derived from the train data. In either case A may be found as explained below.

The determination of acceleration.—In determining the net resistance by Method 1—at a point on the road—the momentary value of A in Equation (20) has been determined as follows. In this discussion it should be remembered that all curves on the dynamometer chart are drawn on a distance base, i.e., to some scale their abscissas represent distances, in feet.

On the speed curve in Fig. 17, let B represent the point on the road which is under consideration. At B draw the tangent $O\ D$ to this curve, and select on this tangent the points C and D *equidistant* from B. This tangent may be considered as a speed curve which at B represents the same acceleration as the actual speed curve. By direct measurement the ordinates of the tangent at C and D are determined as v_1 and v_2, respectively. Similarly the distance S may be determined. The speed at B is called v. The acceleration A at the point B is then determined thus:

Let v, v_1, v_2 = Speed,—feet per second.
V_1, V_2 = Speed,—miles per hour.
t = Time,—seconds.
l = Distance,—feet.
a = Acceleration,—feet per second per second.

Then

$$a = \frac{d\,v}{d\,t}$$

and

$$d\,t = \frac{d\,l}{v}$$

hence

$$a = \frac{vdv}{dl}$$

The equation of the tangent referred to the axes Ov and Ol is

$$v = ml$$

$$m = \frac{v_2 - v_1}{S}$$

$$v = \frac{v_2 - v_1}{S} \times l$$

whence

$$d\,v = \frac{v_2 - v_1}{S}\,d\,l$$

and

$$\frac{d\,v}{dl} = \frac{v_2 - v_1}{S}$$

also, since v is the mean between v_1 and v_2,

$$v = \frac{v_2 + v_1}{2}$$

therefore

$$a = \frac{vdv}{d\,l} = \frac{v_2 + v_1}{2} \times \frac{v_2 - v_1}{S} = \frac{v_2^2 - v_1^2}{2\,S}$$

but

$$a = 1.466\,A$$

and

$$v = 1.466\,V,$$

hence

$$A = \frac{(1.466)^2 \times (V_2^2 - V_1^2)}{1.466 \times 2\,S} = 0.733\,\frac{V_2^2 - V_1^2}{S} \qquad (21)$$

Formula (21) is used to determine the momentary acceleration at a point B on the speed curve. V_1 and V_2 are ordinates at the two points, C and D, located on the tangent drawn at B and equidistant from B. To draw this tangent with sufficient accuracy, the speed curve must be nearly a straight line for a small distance on either side of B.

In determining the net resistance by Method 2—while the test car passes a certain track section—the average value of A in Equation (20) has been determined as follows. The conditions are represented in Fig. 18.

Let a = the *uniform* acceleration which, acting during the passage of the car through the section, would have caused a speed change the same as that actually produced,—feet per second per second.

A = The same, expressed in miles per hour per second.

v_1 and v_2 = Speeds at entrance and exit,—feet per second.

V_1 and V_2 = Speeds at entrance and exit,—miles per hour.

S = The length of the section,—feet.

t = The time elapsed in transit over the section,—seconds.

Then

$$v_2 = v_1 + a\,t$$

and

$$S = v_1\,t + \frac{a\,t^2}{2}$$

whence, by the elimination of t,

$$a = \frac{v_2^2 - v_1^2}{2\,S}$$

and, since

$$a = 1.466\,A$$

and

$$v = 1.466\,V,$$

$$A = 0.733\,\frac{V_2^2 - V_1^2}{S} \qquad (22)$$

This equation is identical in form with Equation (21). It is used to determine the average acceleration over a given track section. In it A is to be understood as that hypothetical uniform acceleration which, acting during transit over the section, would have caused the absorption of the same energy as was actually expended to produce acceleration under the prevailing speed changes. V_1 is the speed at the moment the head of the train enters the section. V_2 is the speed at the moment the head of the train leaves the section. S is the length of the section.

Formula (22) is correct for all cases, regardless of the shape or variations of the speed curve. However, for reasons which are entirely unrelated to the accuracy of the acceleration determination and which have been explained in Part I, the sections were so chosen that V_1 and V_2 varied but slightly, and that the speed curve between the section limits presented no great speed variations.

The Determination of Net Resistance

Net resistance on straight, level track, at uniform speed is termed R, and is expressed in pounds per ton. In both methods of calculation its value was derived from the equation

$$R = \frac{P}{W} - R_g - R_a \qquad (23)$$

In which P is determined from the test car chart, W from train data, and R_g and R_a as previously explained.

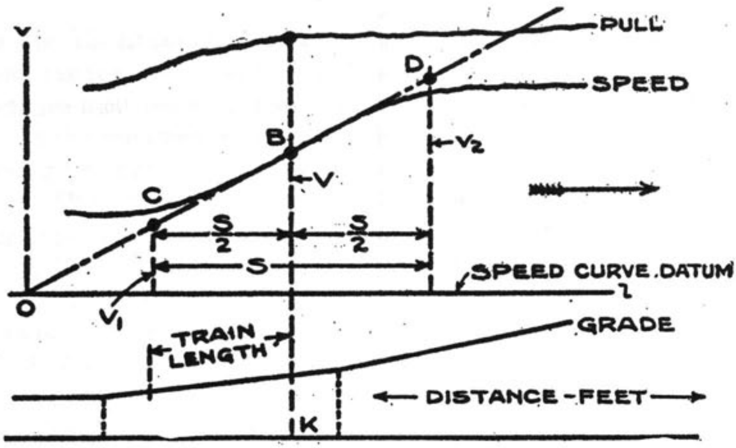


FIG. 17. DIAGRAM USED IN THE EXPLANATION OF METHOD I

Method No. 1.—To determine R at a point on the track, Equations (23), (15), and (20) may be used; these when combined give us

$$R = \frac{P}{W} - 0.379G - \left(91.09 + 145.5\frac{N}{W}\right) \times A \qquad (24)$$

If the train is on a down grade the sign of the second term should be changed to plus. The value of A should be found by means of Equation (21), and, as there explained, by drawing a tangent to the speed curve. The other quantities in the equation,—W, N, P, S, and G, may be found directly from the train data, or the dynamometer chart, or the profile. Figure 17 represents the conditions which prevailed at points chosen for the calculations by this method. In Fig. 17 the line $K\ B$ represents the point on the road which is under consideration. All values of momentary resistance included in this report have been found by means of Equation (24).

In the selection of points for the application of Method 1, the following precautions must be and have been observed:

1. The entire train must be on tangent track and on a uniform grade.

2. The speed curve must be nearly straight for a certain distance either side of the point chosen, in order to permit the tangent to be accurately drawn.

3. The acceleration should preferably be low. The maximum acceleration at any point chosen for the calculation of values included in this report was 0.106 miles per hour per second.

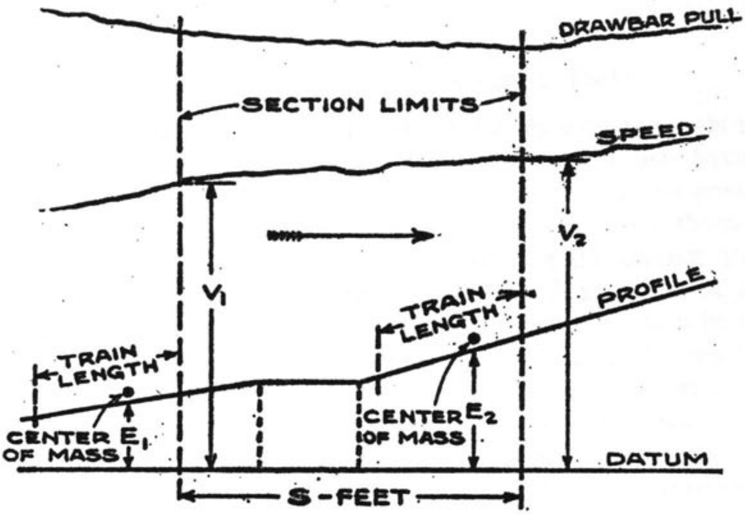


FIG. 18. DIAGRAM USED IN THE EXPLANATION OF METHOD II

Method No. 2. To determine the mean value of R over a certain track section, Equations (23), (16), and (20) may be used; these when combined give

$$R = \frac{P}{W} - \frac{2000 \times (E_2 - E_1)}{S} - \left(91.09 + 145.5\frac{N}{W}\right) \times A \quad (25)$$

In this case the value of A should be found by means of Equation (22). The quantities to be determined in order to use Equation (25) are W, N, P, S, V_1, V_2 and $(E_2 - E_1)$. W and N are derived from the train data. P is the mean draw-bar pull over the section, and is found by determining by the use of a planimeter the mean height of the pull curve between the section limits. S is the section length and may be found directly from the dynamometer chart. V_1 is the speed as the train enters the section. V_2 is the speed as the train leaves the section. V_1 and V_2 are determined directly from the dynamometer chart. E_1 is the elevation of the center of mass of the train at the moment its head end enters the section. E_2 is the corresponding elevation at the moment the head end of the train leaves the section. The quantity $(E_2 - E_1)$ is found from the profile. R in this case corresponds to the mean speed over the section. This mean speed is determined by means of the records of time and distance. Figure 18 represents the conditions which prevailed at sections chosen for the calculations by this method.

In Fig. 15, Appendix 1, is represented the section from which the results for item 12 of test S–1057 were derived. All values of mean resistance included in this report have been found by Equation (25).

In the selection of points for the application of Method 2, the following precautions must be and have been observed:

1. The track must be straight over the section and also for a distance (equal to the train length) before the entrance to the section.

2. The entire train must be on a uniform grade at the moment its head end enters the section, and again at the moment it leaves the section. These grades need not, however, be alike.

3. For reasons which have been explained in Part I, the speed curve between the section limits should not present great speed variations nor should the difference between V_1 and V_2 be greater than ten or twelve miles per hour.

APPENDIX 5*

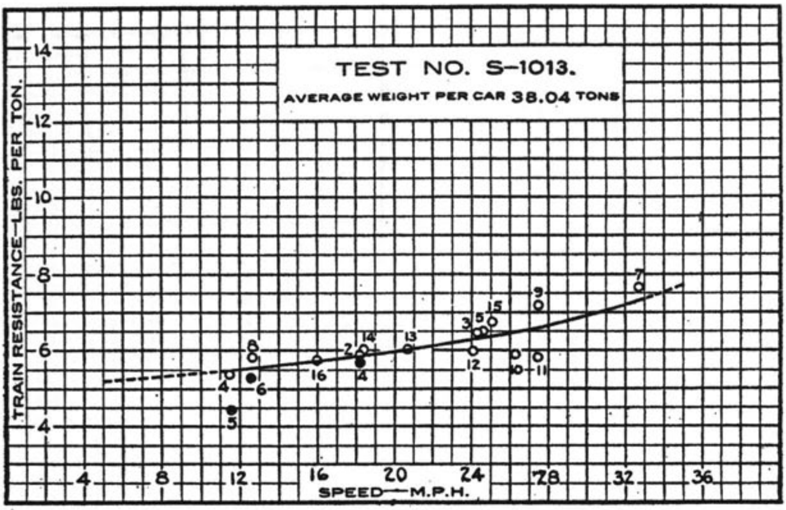
The Results of the Individual Tests

Appendix 5 exhibits for each test a table showing the main results of the calculations. Where both methods of calculation have been employed, the tables show two groups of items. The one group displays the results obtained by Method 1, and the other shows those obtained by Method 2. The notation following the column headings is the same as that used in Appendix 4. The final values of net resistance on tangent, level track, at uniform speed are given in column 13, and the corresponding values of speed are given in column 12.

Following the table of results for each test is a figure which shows the relation between speed and resistance for the same test. The coordinates of the points plotted in these diagrams are the values of speed and resistance given in columns 12 and 13 of the corresponding table. The points represented in the diagrams by circles are plotted from values of momentary speed and momentary resistance obtained by Method 1. The points represented by circular black spots are plotted from values of average speed and average resistance obtained by Method 2. The numbers shown at the points are the corresponding item numbers given in column 2 in the table.

The curves represent for each test the mean relation between resistance and speed. In order to draw these curves, the plotted points were assumed to be arranged in a number of groups for each of which the "center of gravity" was determined and plotted on the diagram. The curve was then drawn by confining attention to the few points thus determined. The groups of points were arbitrarily selected so that the resulting "centers of gravity" were almost equidistantly distributed throughout the speed range.

**Note on reprint.—For reasons identical with those stated on p. 52, the tables originally presented in Appendix 5 have been omitted from the reprint. Table 1 in the body of the report presents a summary of the main conditions for each test.*



FIGS. 19 TO 50. CURVES SHOWING THE RELATION BETWEEN RESISTANCE AND SPEED FOR EACH OF THE 32 TESTS

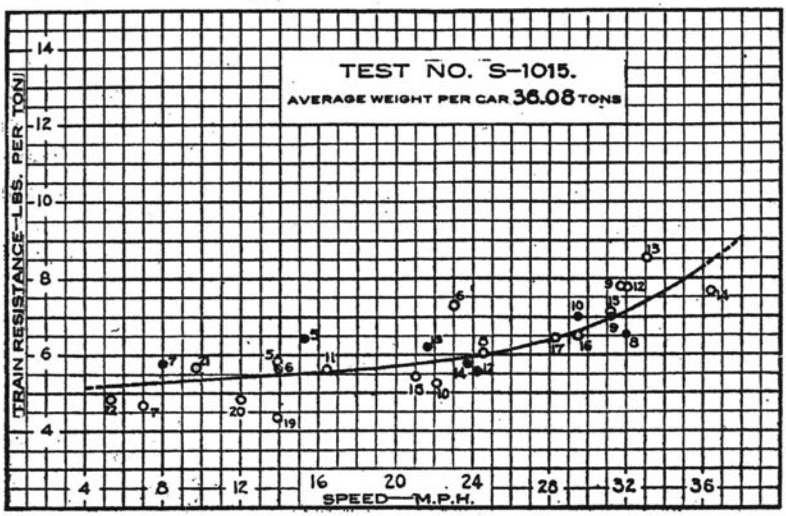


FIG. 20

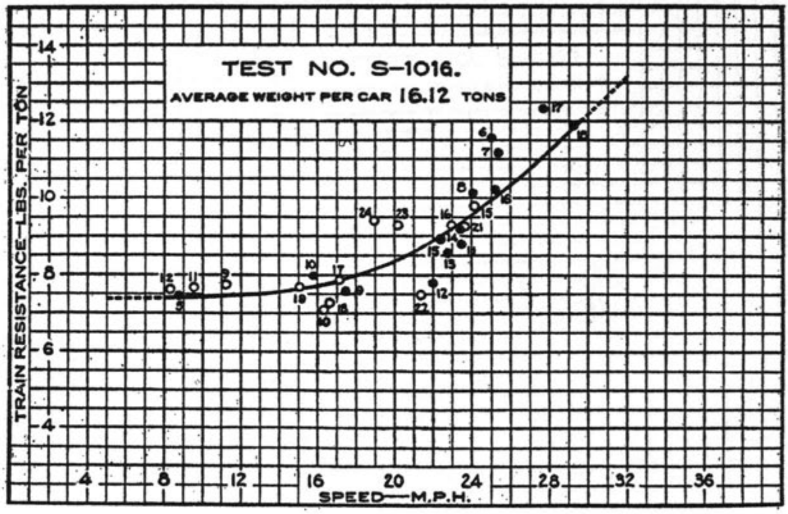

TEST NO. S–1016.
AVERAGE WEIGHT PER CAR 16.12 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

Fig. 21

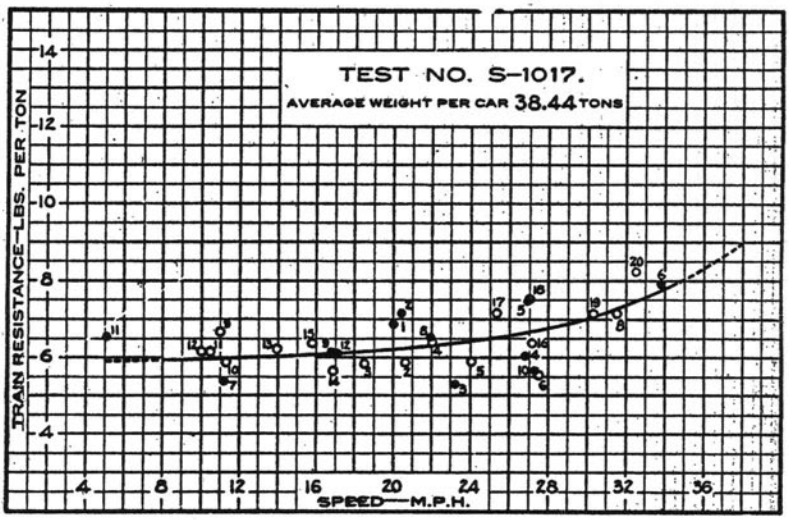

TEST NO. S–1017.
AVERAGE WEIGHT PER CAR 38.44 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

Fig. 22

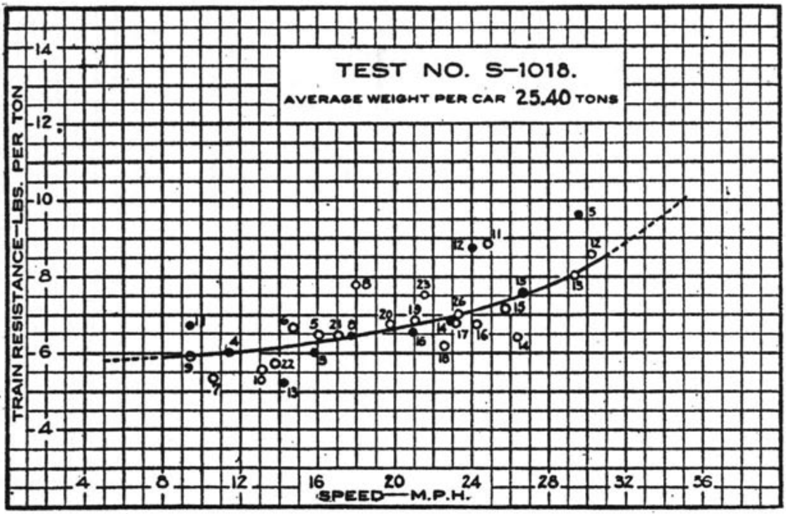

TEST NO. S-1018.
AVERAGE WEIGHT PER CAR 25.40 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 23

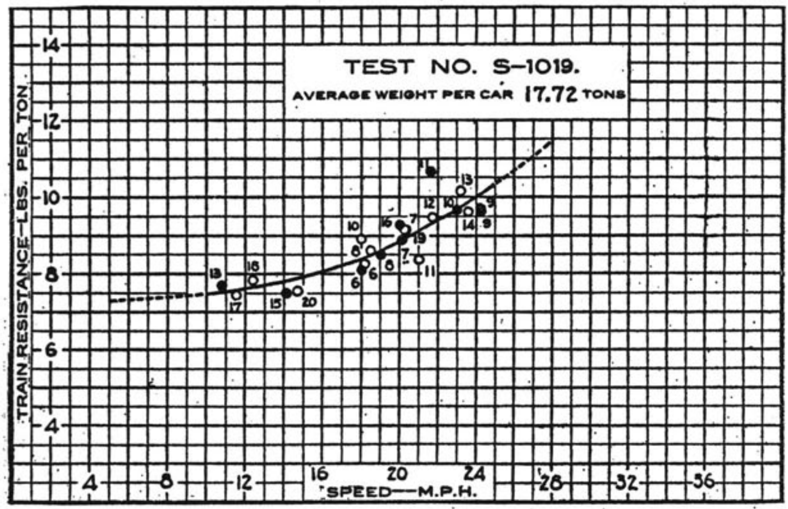

TEST NO. S-1019.
AVERAGE WEIGHT PER CAR 17.72 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 24

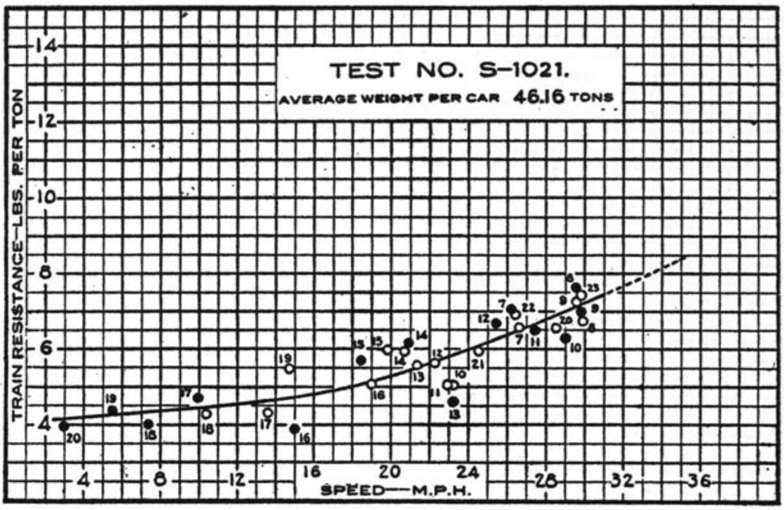

TEST NO. S–1021.
AVERAGE WEIGHT PER CAR 46.16 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED—M.P.H.

Fig. 25

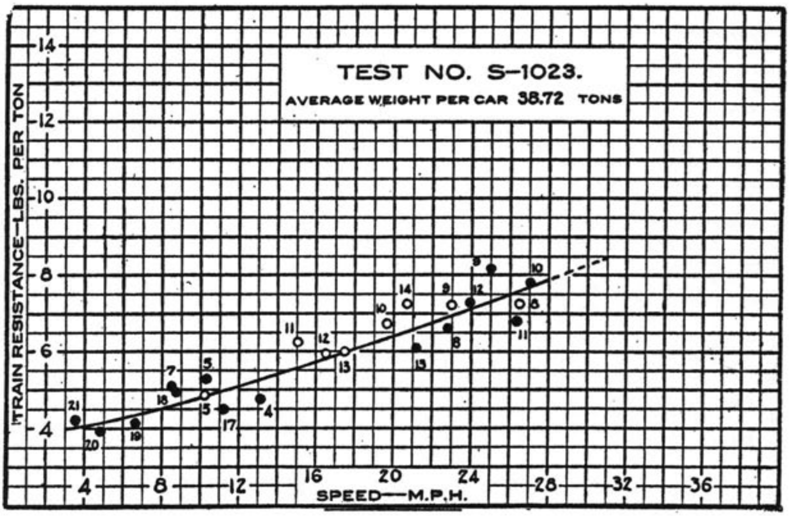

TEST NO. S–1023.
AVERAGE WEIGHT PER CAR 38.72 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED—M.P.H.

Fig. 26

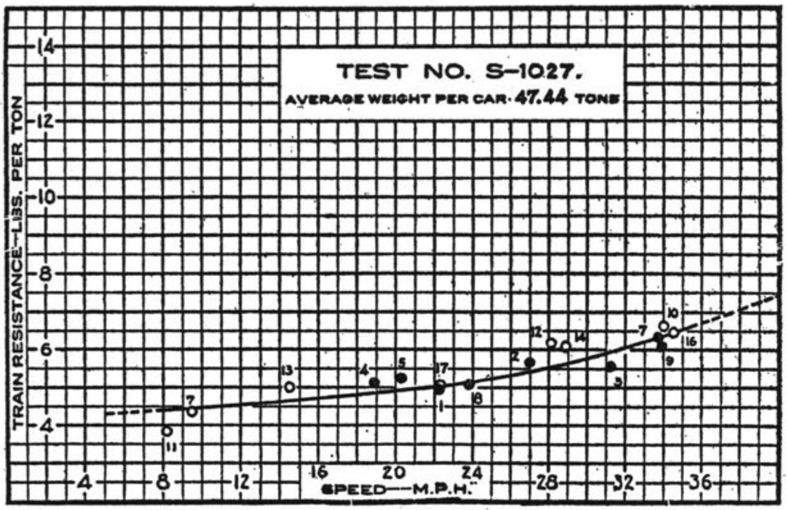

TEST NO. S-1027.
AVERAGE WEIGHT PER CAR 47.44 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

Fig. 27

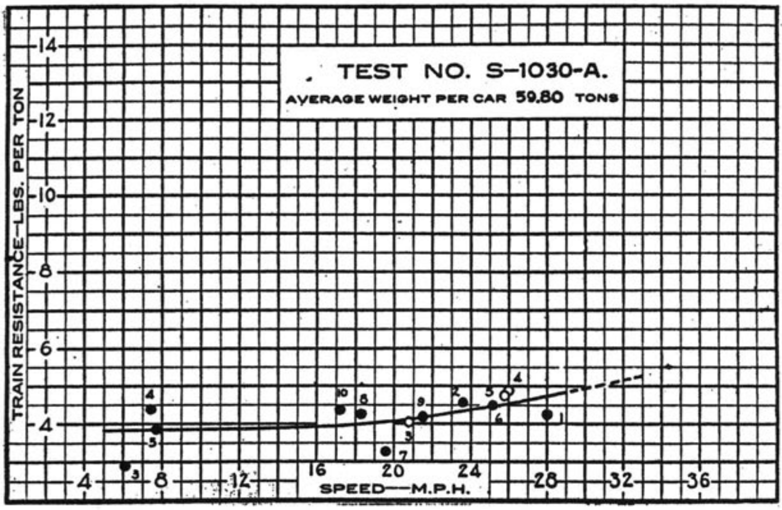

TEST NO. S-1030-A.
AVERAGE WEIGHT PER CAR 59.80 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

Fig. 28

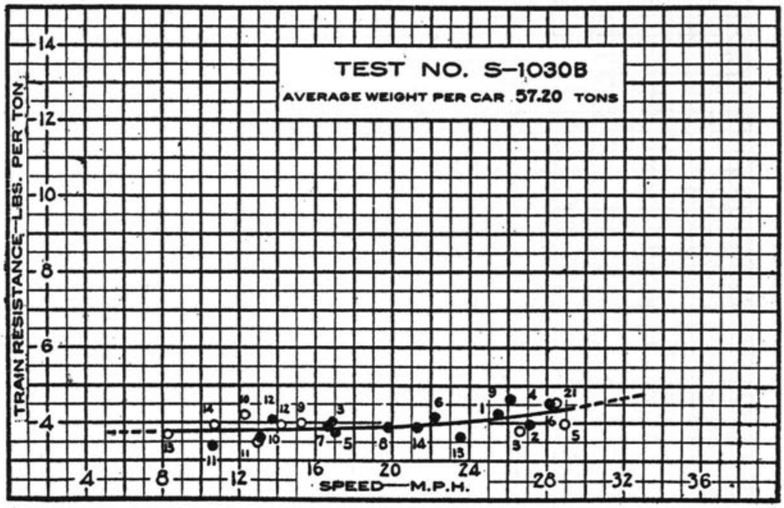

TEST NO. S–1030B
AVERAGE WEIGHT PER CAR 57.20 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 29

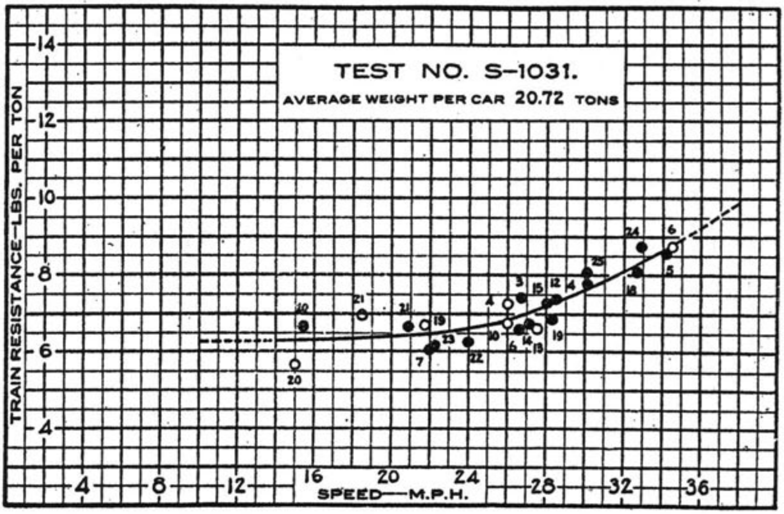

TEST NO. S–1031.
AVERAGE WEIGHT PER CAR 20.72 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 30

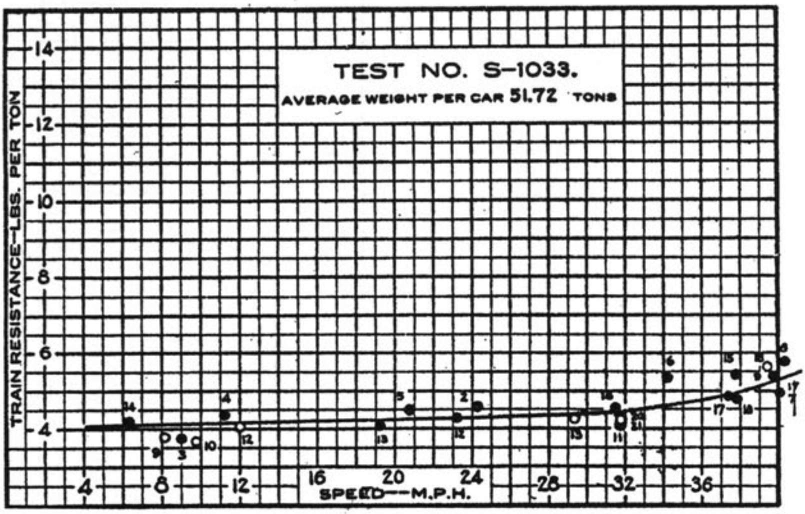

TEST NO. S–1033.
AVERAGE WEIGHT PER CAR 51.72 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 31

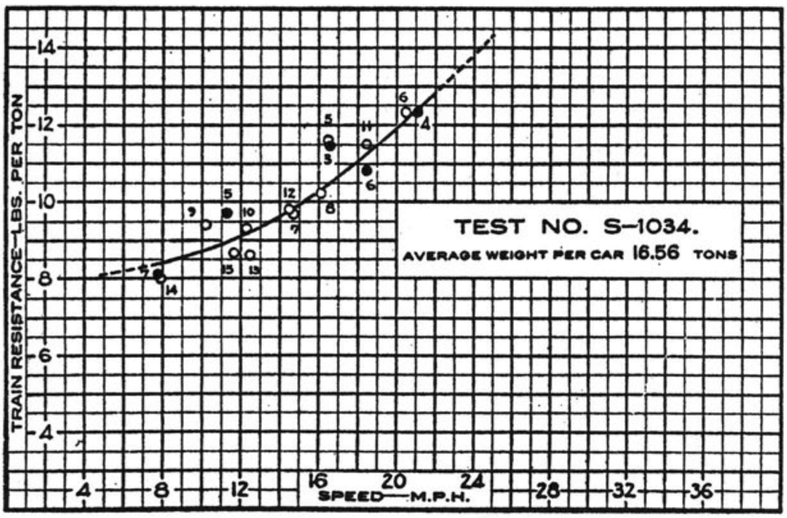

TEST NO. S–1034.
AVERAGE WEIGHT PER CAR 16.56 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 32

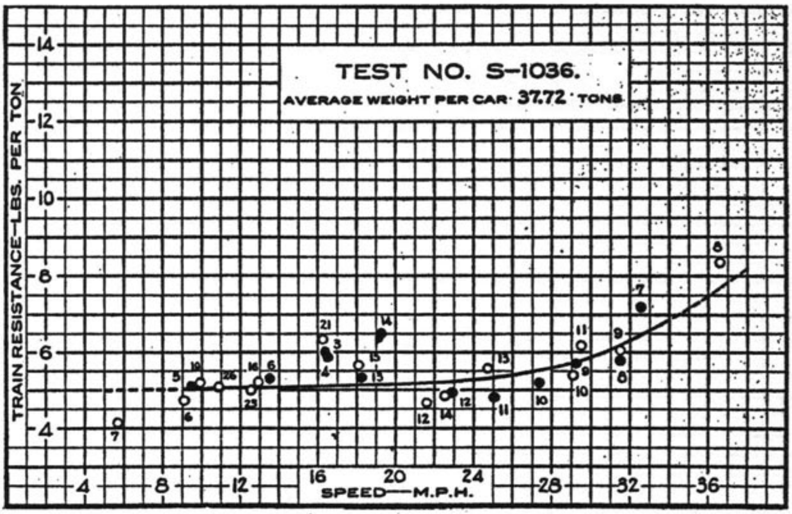

TEST NO. S–1036.
AVERAGE WEIGHT PER CAR 37.72 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

Fig. 33

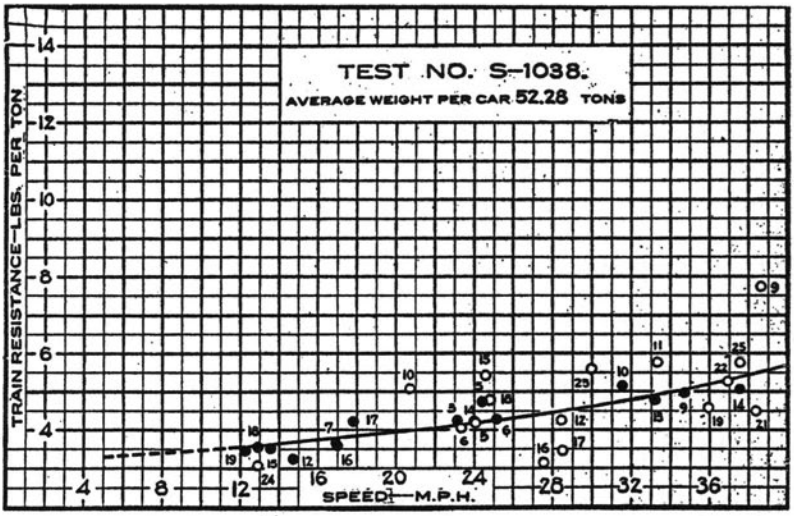

TEST NO. S–1038.
AVERAGE WEIGHT PER CAR 52.28 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

Fig. 34

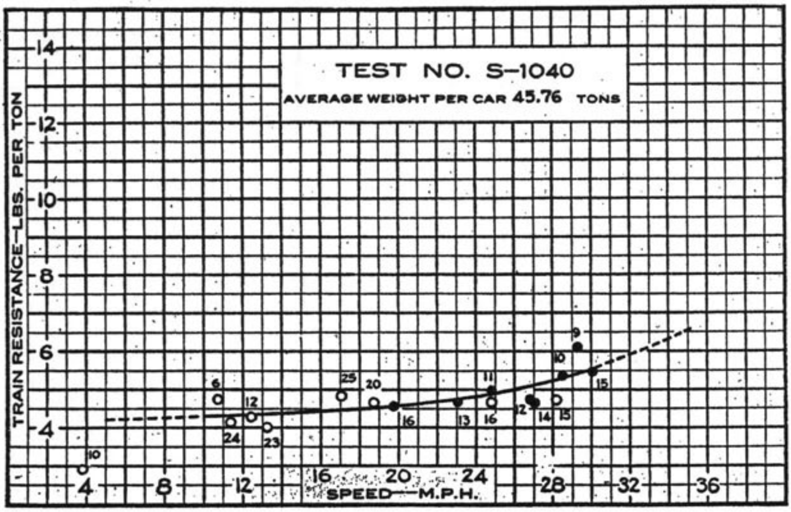

TEST NO. S–1040
AVERAGE WEIGHT PER CAR 45.76 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED—M.P.H.

FIG. 35

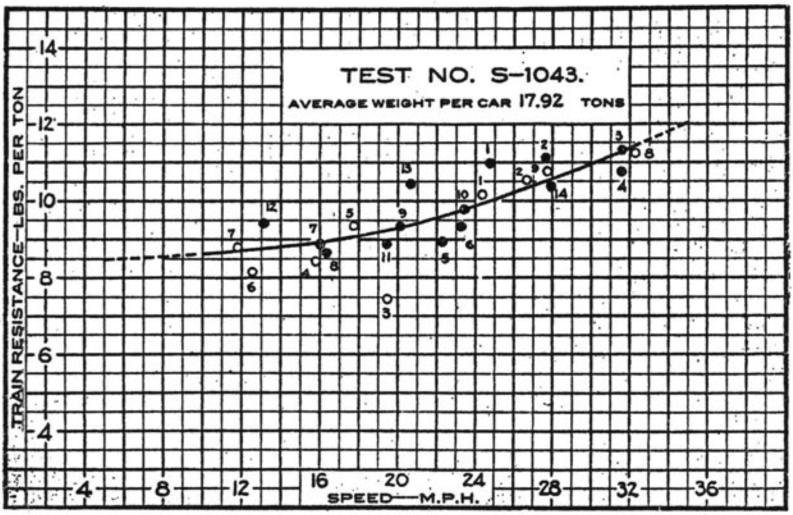

TEST NO. S–1043.
AVERAGE WEIGHT PER CAR 17.92 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED—M.P.H.

FIG. 36

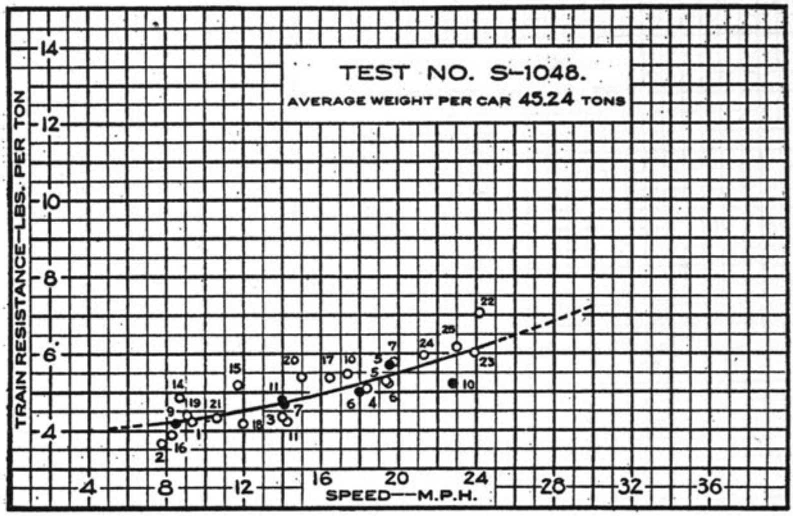

TEST NO. S-1048.
AVERAGE WEIGHT PER CAR 45.24 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 37

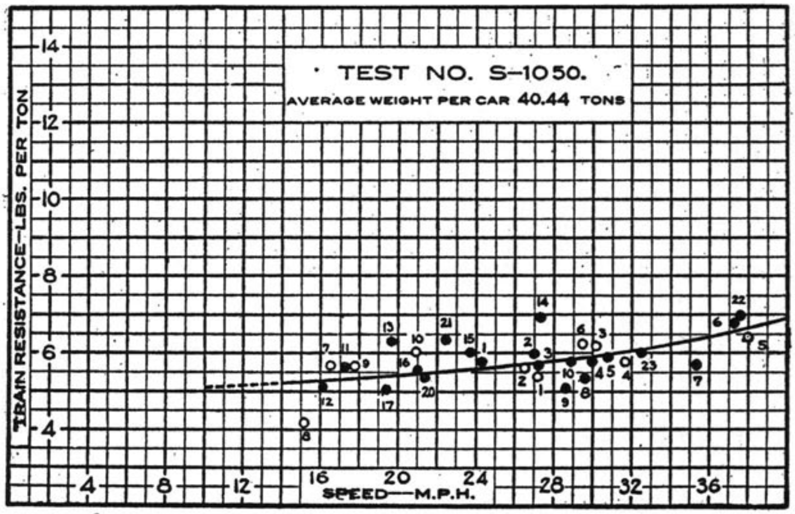

TEST NO. S-1050.
AVERAGE WEIGHT PER CAR 40.44 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 38

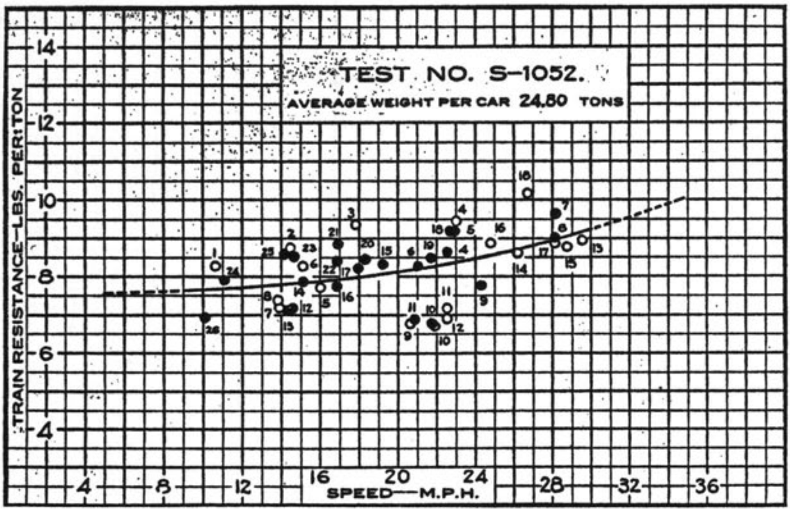

TEST NO. S-1052.
AVERAGE WEIGHT PER CAR 24.80 TONS
TRAIN RESISTANCE-LBS. PER TON
SPEED—M.P.H.

FIG. 39

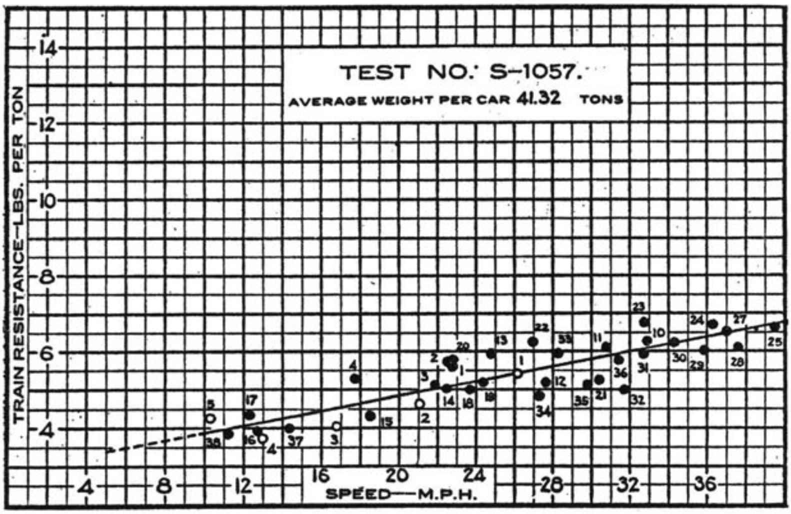

TEST NO. S-1057.
AVERAGE WEIGHT PER CAR 41.32 TONS
TRAIN RESISTANCE-LBS. PER TON
SPEED—M.P.H.

FIG. 40

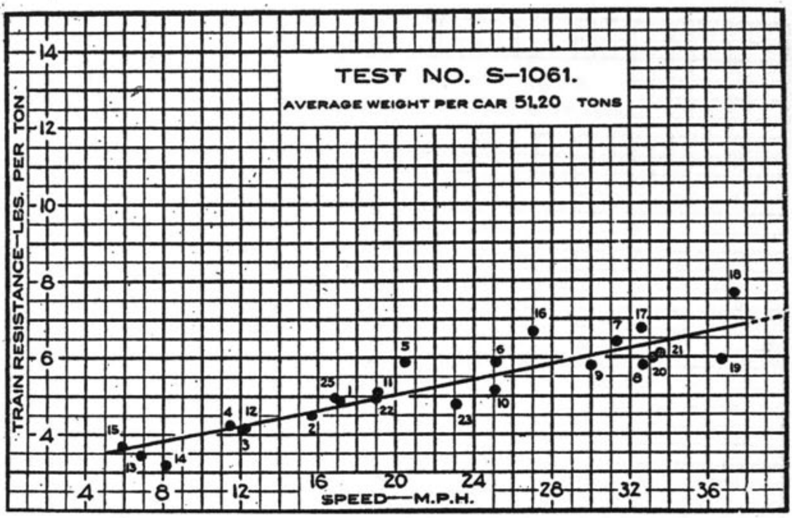

TEST NO. S–1061.
AVERAGE WEIGHT PER CAR 51.20 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 41

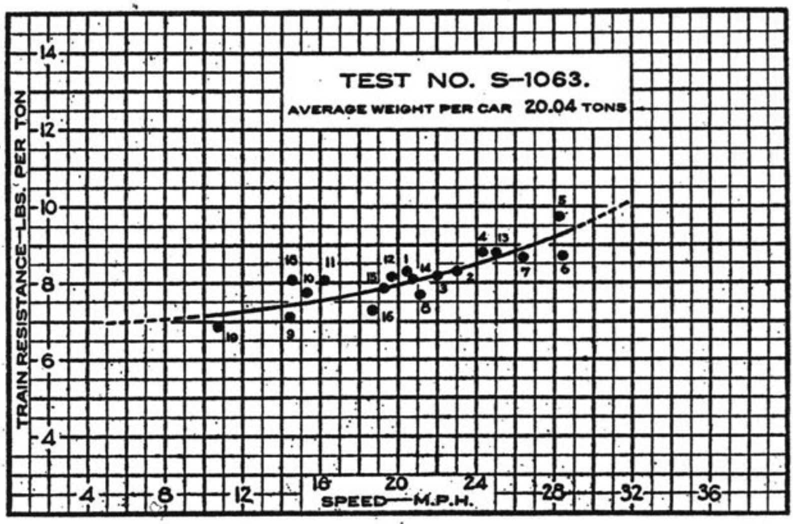

TEST NO. S–1063.
AVERAGE WEIGHT PER CAR 20.04 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 42

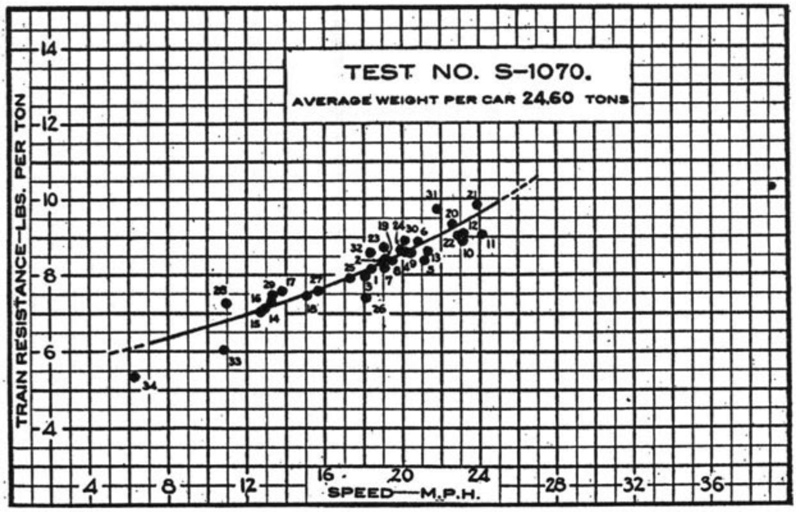

TEST NO. S–1070.
AVERAGE WEIGHT PER CAR 24.60 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 43

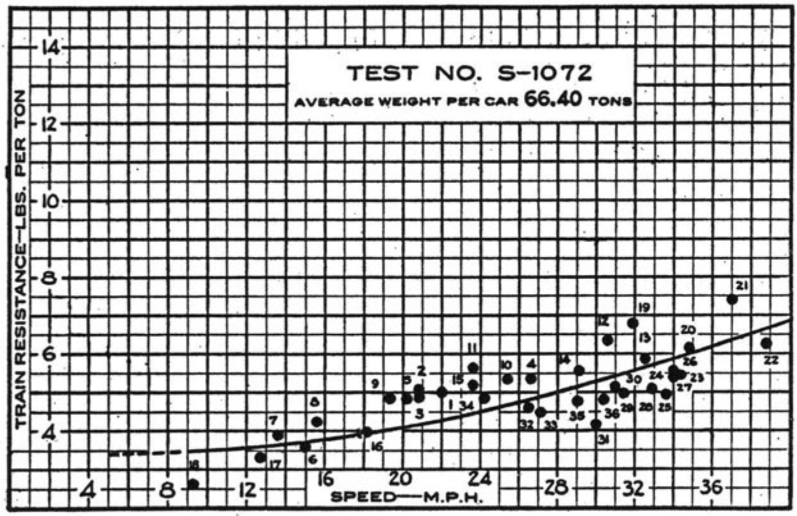

TEST NO. S–1072
AVERAGE WEIGHT PER CAR 66.40 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 44

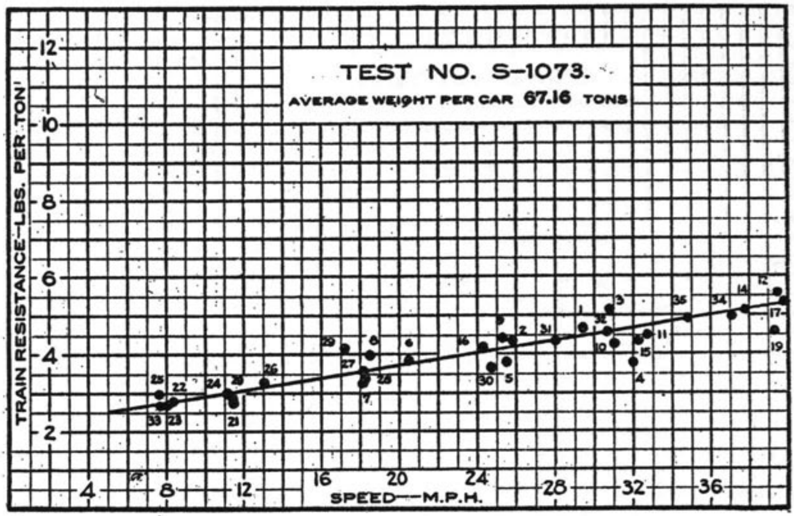

TEST NO. S-1073.
AVERAGE WEIGHT PER CAR 67.16 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 45

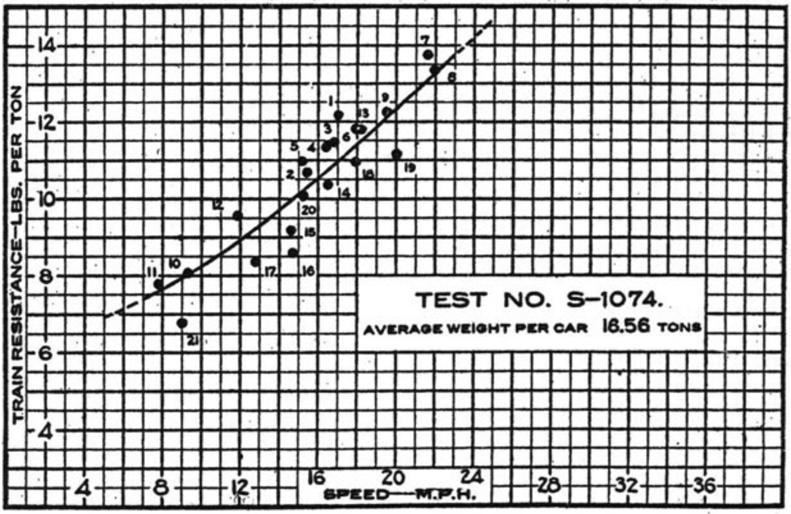

TEST NO. S-1074.
AVERAGE WEIGHT PER CAR 16.56 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 46

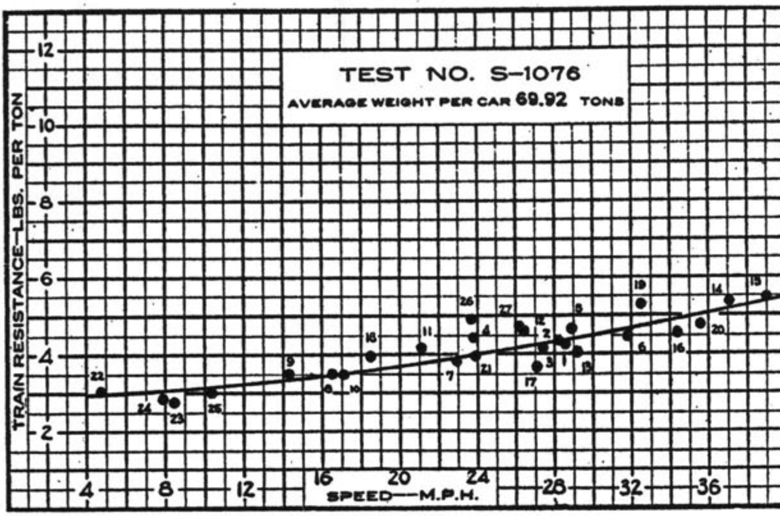

TEST NO. S-1076
AVERAGE WEIGHT PER CAR 69.92 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 47

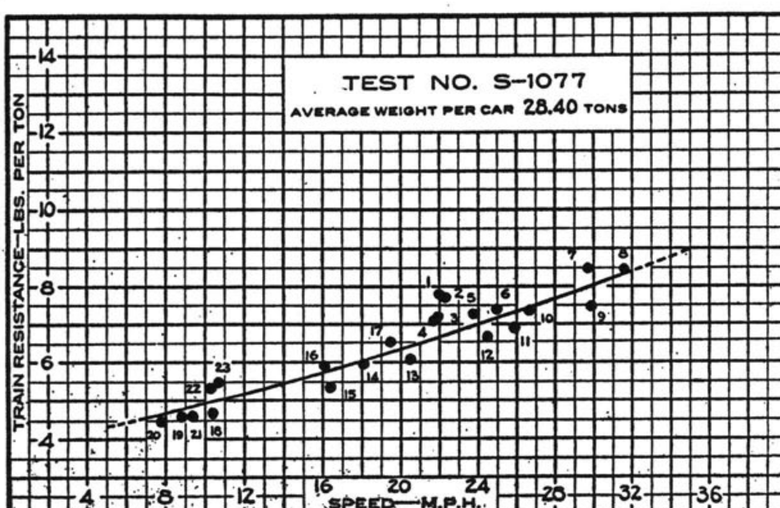

TEST NO. S-1077
AVERAGE WEIGHT PER CAR 28.40 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

FIG. 48

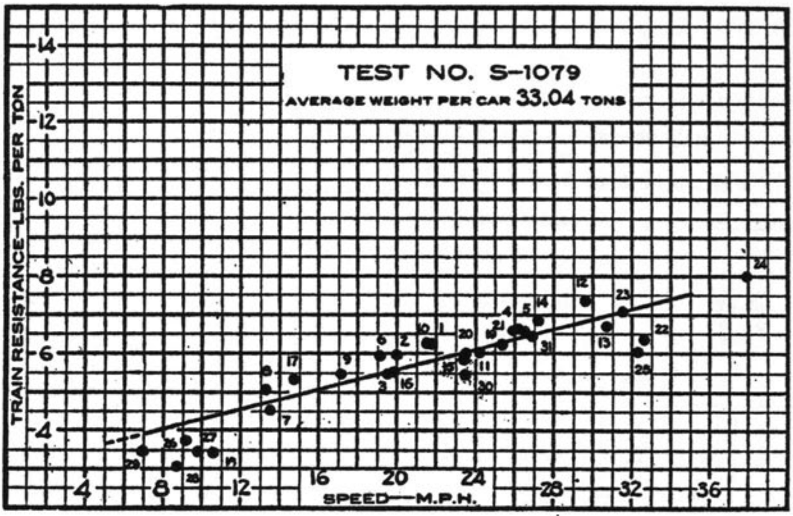

TEST NO. S-1079
AVERAGE WEIGHT PER CAR 33.04 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

Fig. 49

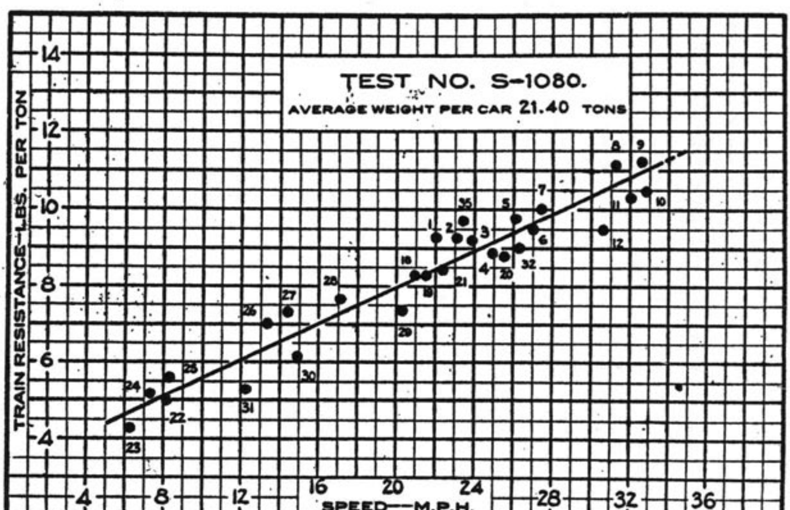

TEST NO. S-1080.
AVERAGE WEIGHT PER CAR 21.40 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.

Fig. 50

APPENDIX 6

Exact Coördinates for the Curves of Figs. 10 and 11

The original drawings from which Figs. 10 and 11 have been reproduced were drawn to a scale about twice as great as that of the cuts shown in the report. From these original drawings, the values of the coördinates of the various curves of both figures have been determined as accurately as possible; and these values are presented in Tables 68 and 69.

The curves of Fig. 10 (and of Figs. 3 to 9) may be accurately reproduced by the use of Table 68; the curves of Fig. 11 may be reproduced from the values given in Table 69. The tables are presented merely to permit the accurate reproduction, to any scale, of the curves of the report; they are not intended for use in determining values of resistance. For the latter purpose Table 3 is more convenient and sufficiently accurate.

Table 68

Values of Resistance for Trains of Various Average Car Weights and for Different Speeds

This table presents the coördinates of the original curves from which Figs. 3 to 9 and Fig. 10 were reproduced.

Average Weight Per Car tons	Train Resistance—pounds per ton							Average Weight Per Car tons
	Column Headings Indicate the Various Speeds							
	5 m.p.h.	10 m.p.h.	15 m.p.h.	20 m.p.h.	25 m.p.h.	30 m.p.h.	35 m.p.h.	
15	7.62	8.20	8.81	9.56	10.37	11.24	12.25	15
16	7.44	8.00	8.61	9.34	10.13	10.98	11.95	16
18	7.10	7.63	8.22	8.92	9.68	10.47	11.39	18
20	6.77	7.30	7.85	8.53	9.26	10.00	10.89	20
22	6.45	6.97	7.49	8.16	8.84	9.56	10.41	22
24	6.16	6.64	7.14	7.79	8.46	9.16	9.94	24
25	6.02	6.50	6.98	7.62	8.28	8.95	9.72	25
26	5.88	6.35	6.81	7.44	8.10	8.77	9.52	26
28	5.61	6.07	6.51	7.11	7.76	8.40	9.12	28
30	5.38	5.80	6.23	6.80	7.43	8.05	8.75	30
32	5.13	5.54	5.98	6.51	7.12	7.72	8.40	32
34	4.92	5.31	5.72	6.24	6.82	7.40	8.06	34
35	4.82	5.20	5.61	6.11	6.68	7.26	7.91	35
36	4.72	5.10	5.50	5.99	6.55	7.11	7.77	36
38	4.55	4.90	5.28	5.74	6.29	6.83	7.48	38
40	4.38	4.70	5.06	5.50	6.03	6.57	7.20	40
42	4.22	4.52	4.88	5.29	5.80	6.32	6.95	42
44	4.08	4.38	4.70	5.09	5.59	6.10	6.71	44
45	4.01	4.30	4.61	4.99	5.49	6.00	6.60	45
46	3.95	4.21	4.52	4.90	5.38	5.90	6.49	46
48	3.82	4.08	4.38	4.71	5.20	5.71	6.28	48
50	3.72	3.96	4.24	4.56	5.03	5.52	6.10	50
52	3.61	3.85	4.11	4.42	4.88	5.36	5.91	52
54	3.52	3.75	3.99	4.30	4.74	5.20	5.74	54
55	3.48	3.71	3.94	4.25	4.68	5.12	5.67	55
56	3.43	3.67	3.90	4.20	4.62	5.05	5.60	56
58	3.37	3.58	3.81	4.10	4.50	4.93	5.47	58
60	3.30	3.50	3.73	4.02	4.42	4.83	5.36	60
62	3.23	3.44	3.67	3.97	4.34	4.74	5.27	62
64	3.18	3.39	3.60	3.90	4.29	4.68	5.18	64
65	3.15	3.36	3.58	3.88	4.25	4.64	5.14	65
66	3.12	3.32	3.55	3.85	4.22	4.61	5.11	66
68	3.09	3.30	3.50	3.80	4.18	4.57	5.06	68
70	3.05	3.26	3.47	3.76	4.13	4.52	5.01	70
72	3.02	3.22	3.44	3.73	4.10	4.49	4.98	72
74	3.01	3.19	3.42	3.71	4.08	4.48	4.93	74
75	3.00	3.18	3.41	3.70	4.07	4.47	4.91	75

TABLE 69

VALUES OF RESISTANCE AT VARIOUS SPEEDS FOR TRAINS OF DIFFERENT AVERAGE WEIGHTS PER CAR

This table presents the coördinates of the original curves from which Fig. 11 is reproduced.

Speed miles per hour	Train Resistance—pounds per ton													Speed miles per hour
	Column Headings Indicate the Average Weights Per Car													
	15 tons	20 tons	25 tons	30 tons	35 tons	40 tons	45 tons	50 tons	55 tons	60 tons	65 tons	70 tons	75 tons	
5	7.62	6.77	6.02	5.38	4.82	4.39	4.01	3.72	3.49	3.30	3.16	3.05	3.00	5
6	7.73	6.86	6.12	5.46	4.90	4.43	4.07	3.77	3.52	3.33	3.19	3.08	3.03	6
7	7.83	6.97	6.21	5.53	4.98	4.50	4.12	3.81	3.56	3.37	3.23	3.12	3.07	7
8	7.96	7.06	6.31	5.62	5.04	4.57	4.18	3.86	3.60	3.40	3.26	3.16	3.10	8
9	8.07	7.18	6.40	5.71	5.11	4.62	4.22	3.90	3.64	3.44	3.30	3.20	3.13	9
10	8.19	7.29	6.50	5.80	5.20	4.69	4.28	3.96	3.69	3.49	3.34	3.24	3.18	10
11	8.30	7.40	6.60	5.90	5.29	4.76	4.33	4.00	3.73	3.52	3.38	3.29	3.21	11
12	8.42	7.51	6.71	5.98	5.37	4.83	4.40	4.04	3.78	3.58	3.42	3.33	3.26	12
13	8.56	7.63	6.81	6.08	5.46	4.90	4.47	4.11	3.83	3.62	3.47	3.38	3.31	13
14	8.70	7.76	6.92	6.18	5.53	4.98	4.53	4.18	3.89	3.68	3.52	3.43	3.36	14
15	8.82	7.88	7.01	6.28	5.64	5.06	4.60	4.24	3.94	3.73	3.57	3.48	3.41	15
16	8.98	8.00	7.12	6.39	5.73	5.13	4.68	4.31	4.00	3.80	3.62	3.53	3.47	16
17	9.10	8.13	7.24	6.49	5.82	5.23	4.75	4.38	4.05	3.86	3.68	3.60	3.52	17
18	9.25	8.27	7.37	6.60	5.92	5.32	4.83	4.45	4.12	3.92	3.74	3.66	3.58	18
19	9.40	8.40	7.49	6.71	6.01	5.41	4.91	4.52	4.19	3.98	3.81	3.72	3.64	19
20	9.56	8.53	7.60	6.82	6.11	5.50	5.00	4.60	4.27	4.04	3.88	3.79	3.71	20
21	9.71	8.69	7.72	6.93	6.22	5.60	5.08	4.69	4.32	4.11	3.94	3.85	3.78	21
22	9.88	8.82	7.86	7.03	6.33	5.70	5.17	4.78	4.41	4.18	4.00	3.92	3.84	22
23	10.02	8.97	7.99	7.14	6.44	5.80	5.27	4.86	4.49	4.25	4.07	3.99	3.92	23
24	10.20	9.11	8.11	7.27	6.55	5.90	5.37	4.94	4.58	4.33	4.15	4.06	3.98	24
25	10.37	9.26	8.25	7.40	6.67	6.01	5.46	5.03	4.66	4.41	4.23	4.13	4.04	25
26	10.52	9.42	8.38	7.52	6.79	6.11	5.57	5.12	4.75	4.50	4.31	4.21	4.12	26
27	10.71	9.57	8.51	7.65	6.91	6.21	5.67	5.22	4.83	4.58	4.40	4.29	4.20	27
28	10.89	9.72	8.67	7.78	7.01	6.33	5.78	5.32	4.92	4.67	4.48	4.38	4.29	28
29	11.06	9.89	8.81	7.91	7.12	6.45	5.88	5.43	5.01	4.76	4.57	4.46	4.36	29
30	11.25	10.03	8.96	8.04	7.26	6.58	5.99	5.53	5.11	4.86	4.66	4.53	4.45	30
31	11.43	10.20	9.10	8.18	7.39	6.71	6.10	5.64	5.21	4.95	4.75	4.63	4.53	31
32	11.63	10.37	9.26	8.31	7.51	6.83	6.21	5.76	5.32	5.04	4.85	4.73	4.62	32
33	11.84	10.53	9.41	8.46	7.63	6.96	6.33	5.87	5.43	5.15	4.95	4.83	4.72	33
34	12.04	10.71	9.57	8.60	7.78	7.08	6.47	5.99	5.54	5.26	5.05	4.92	4.82	34
35	12.25	10.89	9.72	8.75	7.91	7.20	6.60	6.10	5.67	5.36	5.16	5.01	4.92	35
36	12.47	11.07	9.89	8.90	8.04	7.35	6.73	6.23	5.78	5.48	5.27	5.12	5.01	36
37	12.69	11.23	10.04	9.04	8.19	7.49	6.87	6.36	5.90	5.59	5.38	5.22	5.12	37
38	12.91	11.42	10.21	9.20	8.33	7.64	7.00	6.49	6.02	5.71	5.48	5.33	5.22	38
39	13.12	11.61	10.39	9.36	8.48	7.79	7.13	6.63	6.15	5.83	5.60	5.44	5.33	39
40	13.35	11.80	10.55	9.51	8.62	7.93	7.29	6.78	6.28	5.95	5.72	5.55	5.45	40

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