Please read and send in as full a discussion as possible at earliest date.

The Canadian Society of Civil Engineers.

INCORPORATED 1887.

ADVANCE PROOF*—(Subject to revision.)*

SOME POSSIBILITIES OF THE ALTERNATING CURRENT SINGLE PHASE RAILWAY MOTOR.

By A. H. Armstrong.

Read before the Electrical Section, Nov. 19th, 1903.

The electric railway motor has replaced the horse and cable on our city streets, the steam locomotive on overhead and underground rapid transit lines, and has conclusively proved its exclusive right to operate suburban cars over distances reaching more than fifty miles from the outskirts of larger cities. All this has been accomplished with the direct current series motor operating at a potential approximating six hundred volts and with alternating current distribution to suitably located rotary converter sub-stations. There are isolated cases where the electric motor has replaced the steam locomotive on steam lines, and where this has been done the increase in the dividend earning power of the road has been sufficiently great to warrant the extension of the electric service and the changing over of more steam operated lines. With the commercial development of the alternating current railway motor, new possibilities are introduced in electric railroading, owing to the much higher voltages for which the motor itself can be wound, and due also to the fact that alternating current is used directly as motive power without the expensive transforming apparatus required for the direct current series motor.

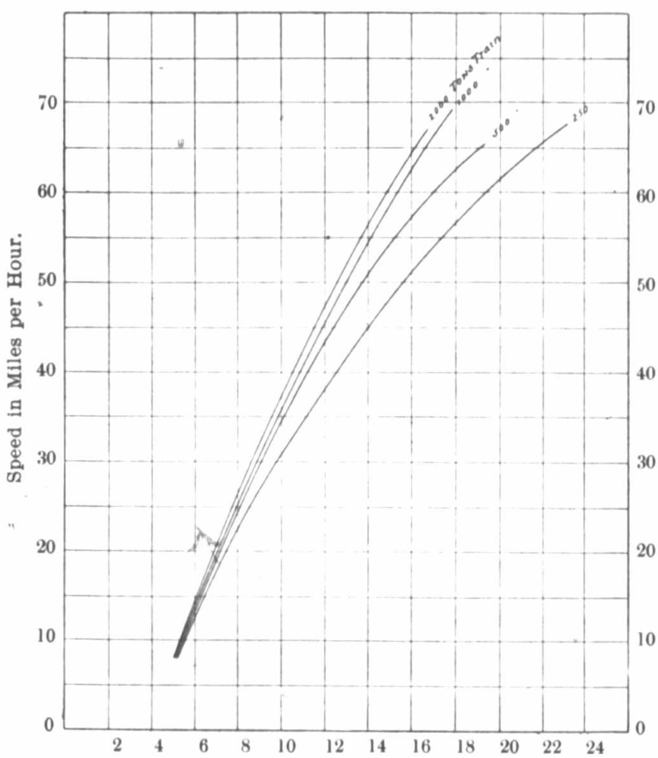
The alternating three phase induction motor has been applied to traction work with doubtful success, owing to its practically synchronous characteristic, its limited output making it sensitive to the heavy voltage drops liable to occur in railway work, and due, furthermore, to the complication of double overhead trolley required for this type of motor.

During the past few years there have been developed several types of single phase alternating current motors having speed-torque characteristics even better adapted for railway work than that of the direct current series motor, and, furthermore, providing ample starting torque with any voltage variation liable to occur in practical electric railway operation. As these motors can be operated with a single trolley and ground return, and can, furthermore, be operated satisfactorily on either direct or alternating current, it makes their field of usefulness much greater than their direct current series competitor.

Having such a motor with practically no restriction as to voltage, it is possible to break away from the exclusive field of electric traction with frequent service and small units and consider the operation of freight and passenger trains over our regular steam lines. In order to arrive at some general conclusions not limited by the local considerations of a specific case, this paper is devoted to a somewhat brief and general discussion of the operation of our steam lines by the alternating current railway motor.

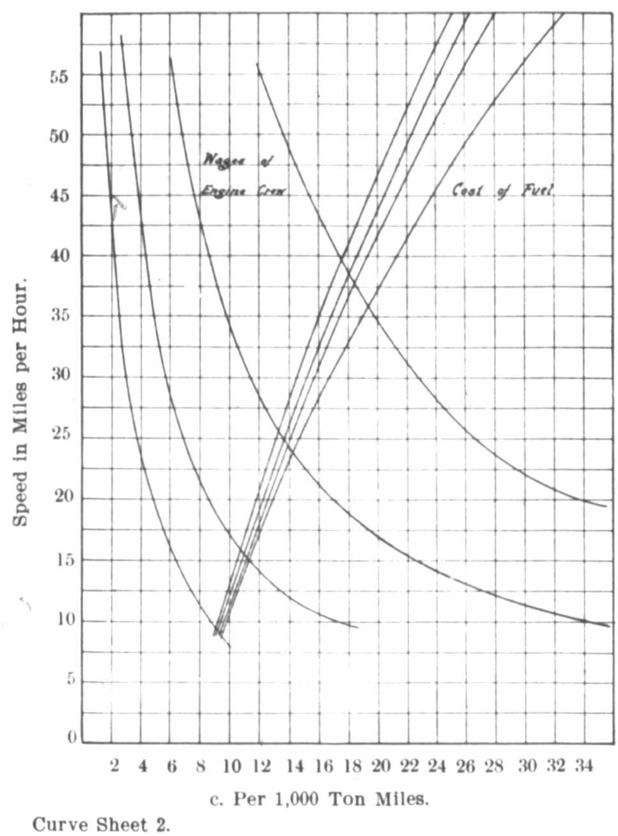
To make the conclusions general, trains of different weight have been taken, operating at different speeds and varying headway over a level track. As being typical, train weights of 2,000, 1,000, 500 and 250 tons of 2,000 lbs. have been selected. As the investigation of the operation of these trains will be carried to maximum speeds of 60 to 70 m.p.h., the total friction of the train expressed in pounds per ton is given in curve sheet 1. This friction is not that of the trailing load, but includes the running and wind friction of the locomotive itself.

From a number of tests a steam consumption of approximately 30 lbs. per I.H.P. hour is taken as the basis of all locomotive work. It is assumed that locomotives are compound, as this steam consumption could hardly be expected with simple engines under average conditions. To make all results comparable further assumptions are made of an evaporation of 7 lbs. of water per pound of coal, an engine efficiency of 85%, and cost of coal at $2.00 per ton of 2,240 lbs. The price of fuel will vary and this is considered later. As we are figuring upon actual performance of the locomotive, that is work done in overcoming train friction, it will be necessary to introduce a factor allowing for coal wasted in making up and damping fires, and general waste incident to locomotive practice when standing idle for a large part of the twenty-four hours. Furthermore, a steam locomotive is called upon to operate throughout the year at varying temperatures of the surrounding air, and coal consumption during the winter months is in excess of that during the summer. This excess may reach 20% as an average during the cold



Curve Sheet 1. Lbs. per Ton.

Train Friction Curves.



Curve Sheet 2.

Cost of Steam Operation.—Coal, $2.00 per 2,240 lbs.

weather, and hence 10% additional fuel is charged to the locomotive for the work assumed, to take care of the different conditions of operation which the electric locomotive does not have to contend with.

On the basis of the above assumptions, all of which are the result of practical tests, curve sheet 2 is obtained :—

These figures check up reasonably close with the locomotive performance sheets for steam roads after superfluous mileage has been deducted from the total mileage given. As an example the shifting locomotives and pushers are charged with so many miles per hour and often do not make one-third the mileage charged to them, so that locomotive performance sheets, as published, some times indicate too low a coal consumption per 1,000 ton mile of actual work done.

The next item of considerable expense in steam operation is the labour account. As it is immaterial to the train crew whether steam or electric locomotives are supplied, this item will not be entered into. The engineer and fireman, however, are greatly influenced by the character of the motive power. In steam operation a crew working ten hours a day average for the railroad company will not be in actual service on the road more than forty or fifty per cent. of the time, the remainder of the time being taken up in caring for the locomotive. In electrical operation the full time of the crew can be utilized for active duty, and hence a considerable saving effected in this item. In steam operation a crew costing $8.50 for ten hours labour has been assumed to be in active commission for five hours per day, while in electric service the crew is assumed to be in commission 8.3 hours per day out of the ten. For shorter hours of labor the same proportion would hold true, and the crew for the electric locomotive will cost but sixty per cent. of that for the steam locomotive. The cost of wages per thousand ton mile is given in curve sheet 2.

In order to approximate the repairs on steam locomotives of different capacities, it is assumed that the locomotive will have its weight proportioned to the trains which it is to handle and as a basis of the repair item, the following values are assumed, agreeing closely with the results of compound locomotive in actual service.

STEAM OPERATION— REPAIRS, CENTS PER 1,000 TON MILE.

250 tons..	25	cents.
500 tons..	13.8	"
1,000 tons..	7.7	"
2,000 tons..	3.3	"

The items of oil, waste and water are not determined here at length, but are introduced in the final values obtained for operating expense. Combining the figures obtained above for steam operation, including fuel at $2.00 per 2,240 lbs., engine crew at $8.50 per ten hours (five of which are in actual service), repairs, oil, waste, water, etc. the results in curve sheet 3 are obtained.

It is evident from the curves that each weight train can be run at a certain speed with a minimum expense for operation, this speed varying with the weight of the train. This economical speed will, of course, vary with any variation of the constants assumed above, such as the price of coal, labor, etc. but the values obtained are instructive and are given below :—

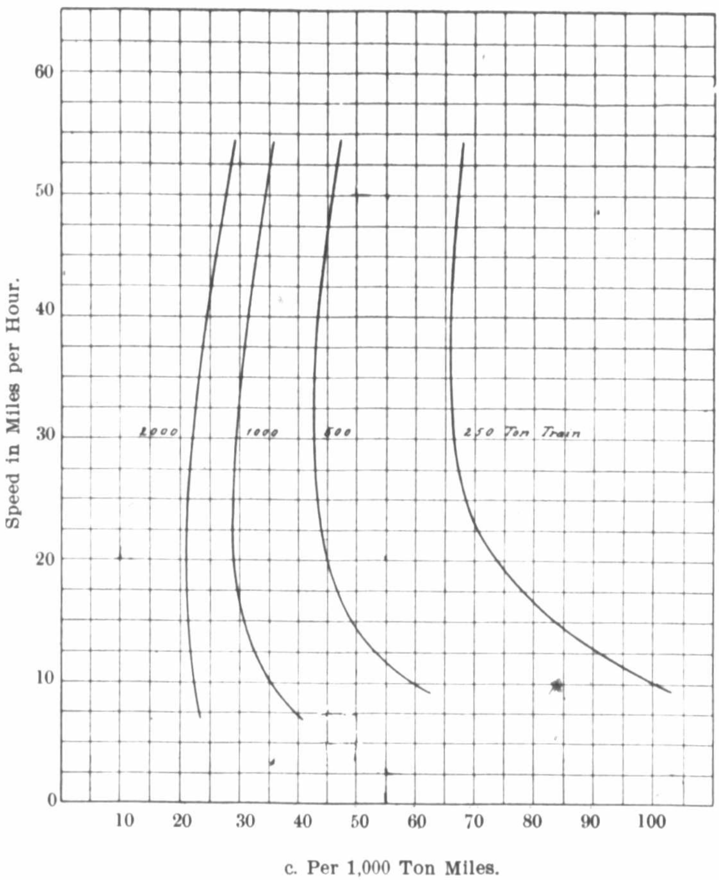
SPEEDS OF ECONOMICAL OPERATION.

250 tons..	38 m.p.h.
500 tons..	28 "
1,000 tons..	23 "
2,000 tons..	19 "

Considerable latitude is given above and below these speeds without greatly increasing expense per 1,000 ton mile for operation.

Coming now to the determination of the cost of operating an electrically propelled train under the same conditions, we arrive at some very interesting results due to the low first cost of electrically equipping the proposed steam line afforded by the alternating current single phase motor.

The same friction values are used as given in curve sheet 1 for steam operation. From these values the kilowatt capacity of each train is determined for the different speeds and varying weights of trains. From these values the cost of trolley copper, step down line transformers and generating station are determined. The electrical system consists, in brief, of a generating station controlling one hundred miles of track, that is, feeding fifty miles in either direction. At intervals of approximately twelve miles are installed step down transformers reducing the transmission potential to 3,000 volts or more for the trolley potential. This trolley potential is assumed at 3,000 volts for a good majority of the results, but for heavy work, that is 1,000 and 2,000 ton miles the voltage is somewhat increased, but nowhere exceeds a safe operating value. The transmission potentials also are kept entirely within practical limits. The generating station does not get excessively large and the electrical system throughout presents no features of unusual interest, but



Curve Sheet 3.

Cost of Steam Operation—Coal. $2.00 per 2,240 lbs.

rather duplicates work that is being done throughout the country. By keeping all values within conservative limits, the results obtained become of practical application and not of theoretical interest.

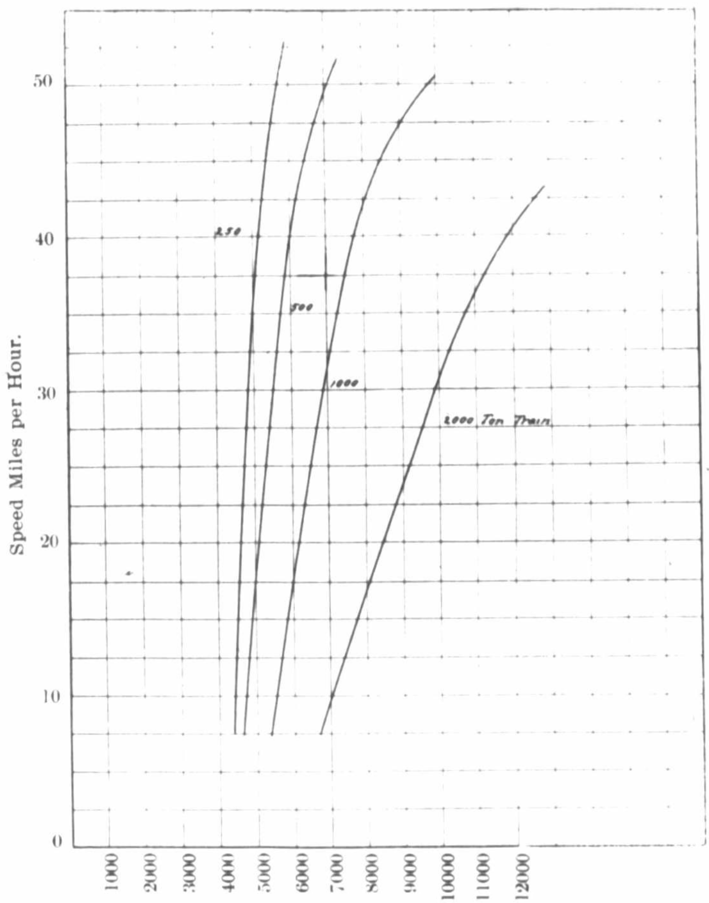
The cost of installing the electric system complete, including generating station, transformer sub-stations, transmission line, poles, bonding of track, etc. is given in the following table :—

COST OF ELECTRICAL INSTALLATION.—COST PER MILE SINGLE TRACK.

M.P.H.	5 trains each way.	10 trains each way.	20 trains each way.
	2,000 ton train.		
10	5,600	7,020	9,860
20	6,520	8,490	12,430
30	8,510	9,840	14,580
40	11,690	11,910	16,770
	1,000 ton train.		
10	4,800	5,500	6,920
20	5,200	6,200	8,100
30	6,250	6,900	9,400
40	7,600	7,700	10,600
50	9,820	9,820	12,700
	500 ton train.		
10	4,400	4,700	5,400
20	4,500	5,100	6,000
30	5,100	5,500	6,800
40	5,900	6,000	7,500
50	7,100	7,100	8,600
	250 ton train.		
10	4,200	4,400	4,800
20	4,300	4,600	5,000
30	4,600	4,800	5,400
40	5,100	5,200	6,000
50	5,700	5,700	6,600

The above tables are given at length as they form very interesting reading, showing how the cost increases with the size of the unit rather than by the frequency of the trains. Also it is very necessary to arrive at an initial cost of electrical installation somewhat accurately as this constitutes a funded debt upon which the saving, if any, between electrical and steam operation must pay dividends.

In determining the cost of electrical operation it has been necessary to consider the cost of producing power, and a sliding scale has been taken for the different kilowatt outputs, ranging from four mills per KW. hour to nine or more, with coal at $2.00 per ton.



Cost per Mile Single Track.

Curve Sheet 4.

Cost of Electrical Installation, Ten Trains Each Way per Day.

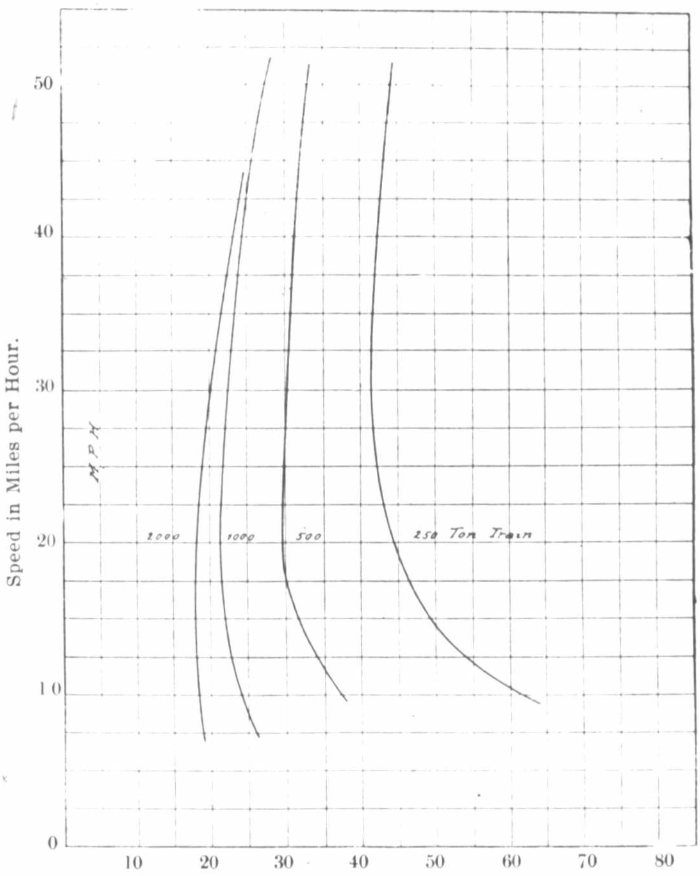
depending upon the KW. capacity of the generating station. It is assumed that steam turbines and modern methods of generating station construction are used, looking to the greatest economy of operation. Wages of engine crew, as stated, are taken at sixty per cent. of those for steam operation. Repairs for electrical locomotives are given in the following table.

ELECTRICAL LOCOMOTIVE REPAIRS.

250 tons..	8	cents per 1,000 ton mile.
500 tons..	4.8	" " " " "
1,000 tons..	2.3	" " " " "
2,000 tons..	1	" " " " "

These repairs, in common with that given for steam operation, include all running repairs, overhauling and renewals. The cost of electrical operation is given complete in curve sheet 5, which are directly comparable to the cost of operation for steam previously given. It is obvious that as there is a fixed charge of five per cent. depreciation and repair account on the entire electrical installation, it is necessary to consider the frequency of travel over our proposed route. In order to make it as general as possible, it has been assumed that there will be five, ten and twenty trains per day each way. The cost of operation expressed in cents per 1,000 ton mile does not vary greatly with the different frequency of trains, but the dividend account must be based upon a selected train frequency. For convenience, a train frequency of ten per day each way is taken, and the cost of electrical operation given. For other frequency of trains, the cost of operation per 1,000 ton mile will not vary more than one or two cents either way from the results given in the curves and they are, therefore, of fairly general application.

By comparing this curve with that given for steam operation, a considerable saving is shown, giving varying dividends depending upon the frequency of travel, weight of train, maximum speed, etc. In fact, frequency of travel and weight of train are the determining features in considering the adoption of electric transportation. In order to show the dividend earning power, that is the saving in electric operation over steam as the percentage of the cost for electrical installation, the three following tables have been prepared for a frequency of train service of five, ten and twenty trains each way per day.



Curve Sheet 5.

Cost of Steam Operation.—Coal, $2.00 per 2,240 lbs.

INTEREST ON ELECTRICAL INVESTMENT, FIVE TRAINS PER DAY EACH WAY.

M.P.H.	2.000 tons.	1,000 tons.	500 tons.	250 tons.
10	5.75%	8.17%	9.25%	9.22%
20	3.88	4.92	5.73	6.02
30	1.81	3.82	4.1	4.85
40	....	3.47	3.68	4.07
50	....	....	3.36	3.74

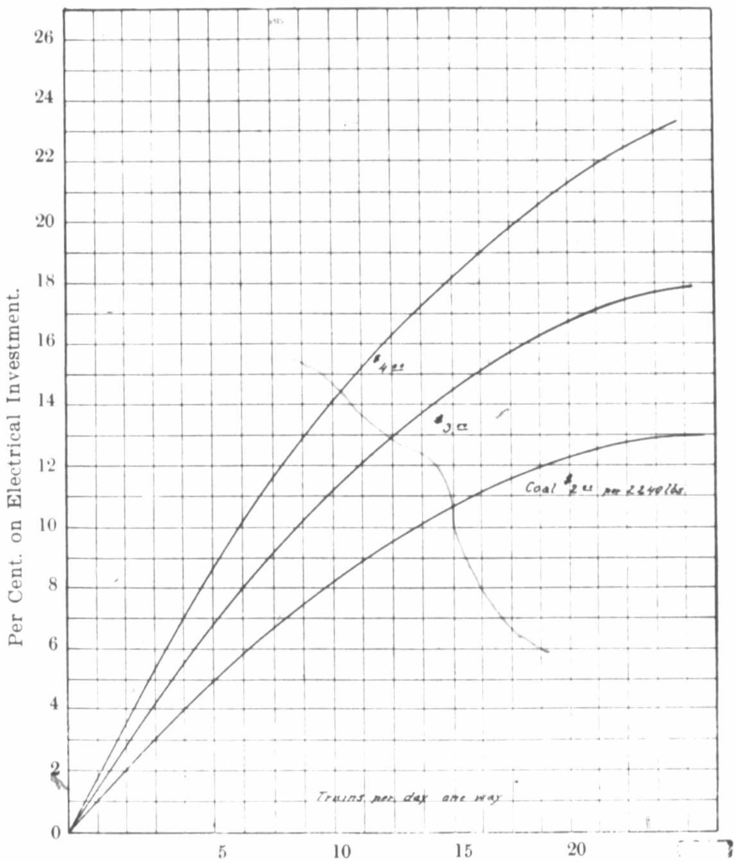
TEN TRAINS PER DAY EACH WAY.

M.P.H.	2.000 tons.	1,000 tons.	500 tons.	250 tons.
10	8.48%	14.8%	17.5%	18.3%
20	4.68	8.87	11.05	11.9
30	1.31	7.2	8.1	9.65
40	....	6.8	7.62	8.14
50	....	....	6.72	7.48

TWENTY TRAINS PER DAY EACH WAY.

10	8.92%	23.1%	31.4%	34.5%
20	2.6	12.9	19.1	22.1
30	....	9.8	13.65	17.8
40	....	9.73	12.8	15.0
50	....	.....	11.25	13.7

As shown by the above tables, electric locomotives cannot compete with steam for trains of 2,000 tons at higher speeds, owing to the enormous cost of equipping the road electrically with the constants chosen. Should such heavy railroading be contemplated electrically, it would be necessary to adopt longer transmissions than the fifty miles either way from the power house assumed, and which is very conservative, also the use of higher voltages on the trolley than the 5,000 or 6,000 volts maximum assumed in arriving at the tables. The scope of the paper has been limited, however, to the use of standard apparatus and voltages met with in every day practice. The results given thus represent the practice of today and not what electrical engineers may be able to do sometime in the future. The consideration of the operation of 2,000 ton trains at speeds of 50 or 60 m.p.h. is hypothetical as no steam locomotive could be constructed that would furnish sufficient power to haul a train of this weight at the speeds considered. The problem is feasible from an electrical standpoint as the weight of the locomotive could be distributed among a number of units distributed throughout the train to lessen the draw bar pull without exceeding a permissible weight per axle.



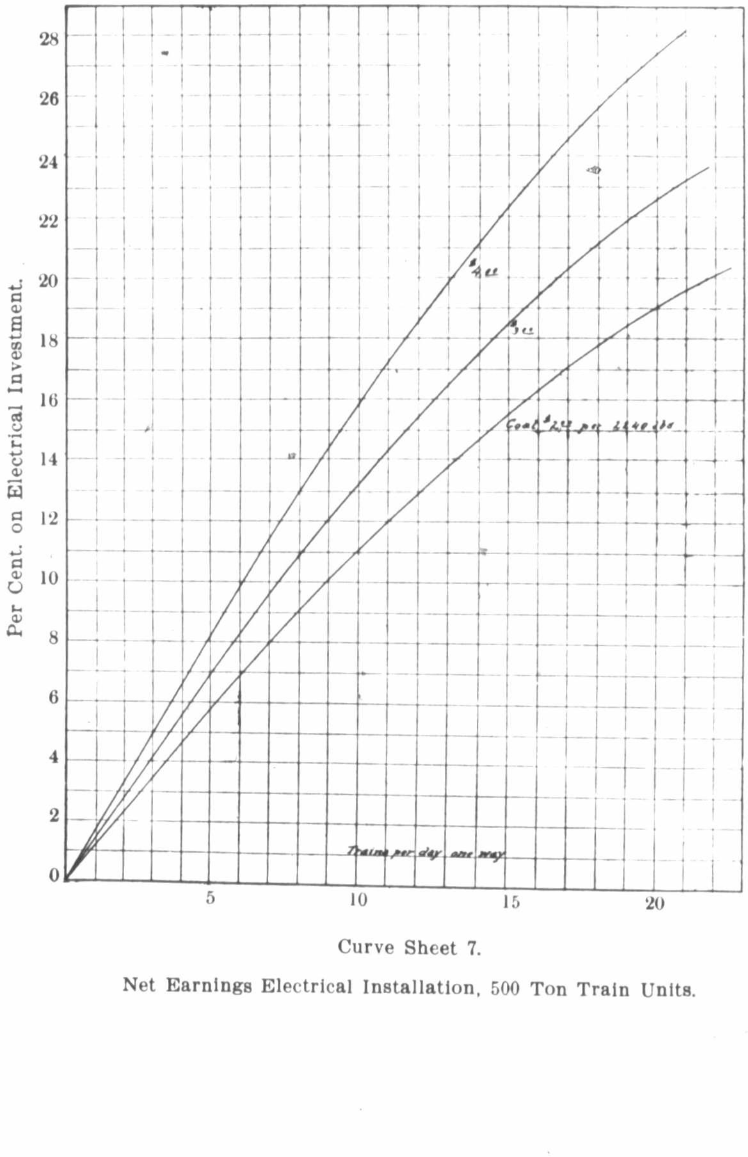
Curve Sheet 6.

Net Earnings Electrical Installation, 1,000 Ton Train Units.

The discussion of the paper has been limited thus far to the use of coal costing $2.00 per ton for both steam and electric locomotive work. It is a well known fact that generating stations can use cheaper coal than it is economical to use on steam locomotives, and hence it is interesting to follow through the results with varying prices of coal. In figuring the cost of coal, it is assumed that coal will be charged to operation at the price for which it could be sold in the wholesale market at the locality used. Coal at $2.00 per ton is somewhat cheap, especially for some of the western roads, and the same method of figuring has been used in determining the earning capacity of the electrical installation for $3.00 and $4.00 coal as well. As the saving in electrical operation and its percentage of the cost of installing the electrical system are of fundamental importance, the tables for interest earning capacity expressed as percentage of the electrical installation is given in the following tables both for $3.00 and $4.00 coal.

COAL AT $3.00 PER 2,240 LBS.—INTEREST ON ELECTRICAL INVESTMENT.

M.P.H.	2,000 tons.	1,000 tons.	500 tons.	250 tons.
	Five Trains per Day Each Way.			
10	8.35%	10.6%	10.8%	9.6%
20	6.77	6.8	6.9	6.4
30	4.35	5.8	4.85	5.02
40	8.12	5.5	4.94	5.0
50	....	....	4.7	4.67
	Ten Trains per Day Each Way.			
10	12.8%	17.7%	19.5%	19.4%
20	8.77	12.1	13.2	13.
30	7.3	10.75	10.	11.1
40	6.	10.75	10.47	10.3
50	....	....	9.4	9.34
	Twenty Trains per Day Each Way.			
10	14.9%	27.8%	38.4%	36.3%
20	8.2	17.7	22.6	23.8
30	7.9	15.	17.	20.1
40	6.25	15.2	17.3	18.1
50	....	....	20.4	16.9



Curve Sheet 7.

Net Earnings Electrical Installation, 500 Ton Train Units.

COAL AT $4.00 PER 2,240 LBS.—INTEREST ON ELECTRICAL INVESTMENT.

Five Trains per Day Each Way.

M.P.H.	2,000 tons.	1,000 tons.	500 tons.	250 tons.
10	11.0%	11.65%	11.6%	10.2%
20	9.65	8.65	8.15	7.19
30	7.04	7.74	6.35	5.72
40	5.64	7.54	6.2	5.75
50	....	....	6.13	5.6

Ten Trains per Day Each Way.

M.P.H.	2,000 tons.	1,000 tons.	500 tons.	250 tons.
10	16.8%	20.8%	21.4%	20.4%
20	13.4	15.2	15.8	14.7
30	12.0	14.3	12.2	12.7
40	10.72	15.	12.8	11.8
50	....	....	12.2	11.2

Twenty Trains per Day Each Way.

10	21.1%	33.2%	38.4%	38.0%
20	14.8	22.9	27.4	25.6
30	16.8	20.3	20.3	22.6
40	12.4	20.9	21.1	20.7
50	....	....	20.4	20.1

A study of the above tables brings out the fact that for very infrequent service, that is five trains per day each way or less, it would hardly pay to equip the road electrically, there being a dividend of from four to seven per cent. on the capital invested. With more frequent service, however, the saving in electrical operation becomes more marked until at from fifteen to twenty trains per day each way, the interest earning power of the electrical investment is worthy of very careful consderation. It should be borne in mind that all these figures do not contemplate increase in the present traffic of the road, and, therefore, do not take into consideration one of the chief characteristics of electric traction, that is developing short haul local traffic and thus increasing the dividends by increasing the receipts rather than by cutting down operating expenses. The well known ability of electric roads to greatly increase previous steam traffic has lead them to be installed, in many cases, without too close an investigation into their economical installation. Taking into account therefore that the electrically equipped road, while caring for the heavy through freight traffic with an earning capacity of from four to seven per cent. on the investment, can also build up a local traffic both freight and passenger, with practically no additional cost and showing very large returns.

Taking up the possibilities of the alternating motor in general haul work, the problem had to be treated in a very general way in order not to lose sight of the scope of the problem in considering local details. The average specific problem has its local conditions, which must be carefully considered in detail, and, in many cases, would show a greater return for the money invested than indicated in this paper. For instance, all power is supposed to be generated from coal from power house devoted to the interests of railroading alone. Along many of our roads exist water power facilities which could be advantageously developed and furnish power much cheaper than the figures assumed from coal generation. Furthermore, the cost of power in the smaller generating station capacity has been assumed as high as one cent per kilowatt hour or more, and should a generating station supply other industries, such as mining, lighting, general power distribution, etc. the cost of purchasing power would be consideraby decreased with a consequent reduction in cost of operating electrically. The results given in the table therefore are of general application only and may be considerably modified when considering the local aspect of a given proposition. It is believed, however, that the results as obtained are based upon conservative assumptions, in fact, most of these assumptions were obtained from operating conditions, and, with the figures given, outline somewhat briefly the possibilities of the alternating current single phase motor in the railway field.

The operating expenses considered include fuel, wages, repairs, oil, waste, water, and five per cent. depreciation on the electrical installation. No depreciation is charged off against the locomotives, as although the electric locomotives cost more than the steam, they will permit of a greater mileage, so that the total capital invested in locomotives should be practically the same in either case. There are a number of expenses incidental to steam operation other than those considered which must be done away with with the adoption of the electric locomotive. While each of these expenses is small they may amount to considerable in the aggregate. For example, the electric locomotive is double ended and requires no turn table. Two electric locomotives can be coupled together and operated by one engineer in the cab of the leading locomotive, each locomotive doing an equal share in hauling the train. In fact, it is not strictly necessary to consider the use of a fireman in electric propulsion, as his duties will be largely confined to ringing the bell, and waiting for the engineer to die of heart disease. His services can be dispensed with entirely if we consider that the electric locomotive cab can be made the caboose for the train, and the train crew serve as a reserve for the engineer in case of trouble. The cost of fuel has been assumed equal in both cases, but there is an added expense in handling the fuel for steam operation as the source of supply of the locomotives is distributed in small pockets over considerable track, each pocket requiring more or less outlay for its establishment and maintenance, all of which can be saved by electric locomotive fed from a central generating station. The increasing tendency towards the adoption of very heavy trains calls for heavier locomotives with consequent increase in weight of rail, cost of bridges, ballasting track, and general maintenance of the right of way. Indeed, the wear upon a light rail with a heavy reciprocating engine must be considerably more than that given to the rail by an electric locomotive of half the weight and having a perfectly uniform rotary impulse imparted to the drivers. Just how much money may be saved by the lessened maintenance of the track is conjectural and hence has not been entered into here, but the figure must reach a considerable size for heavy locomotive work. As the maintenance of electric locomotives is considerably less than its steam competitor it will reduce the size of repair shops required, the difference in the interest on which should appear as a fixed charge against steam operation. Furthermore, a steam locomotive including a tender has not more than fifty per cent. of its weight upon the drivers, which will constitute from seven to ten per cent. of the average train weight. As this is a dead weight, producing no revenue, it would be fair to compare the two systems by estimating upon a train for steam operation from seven to ten per cent. heavier than for electric operation. The comparative figures given in the table based upon 1,000 ton miles are not, therefore, entirely fair toward electric operation, but should be somewhat increased for haulage involving the use of the steam locomotive.

The earning capacity of the money invested in electric equipment can be looked upon, therefore, as exceeding the values given in the tables, but as stated above, local conditions will largely affect the application of the general figures to any given example. Should all the factors entering into the engineering expense of operating roads by steam and by electric locomotives be carefully considered, the possibilities opened up by the use of the alternating motor are sufficiently great to warrant its replacing the steam locomotive in many of our railway systems, either in part or for the complete system.