DISCUSSION ON "FROM STEAM TO ELECTRICITY ON A SINGLE-TRACK ROAD." ATLANTIC CITY, N. J., JULY 1, 1908

J. B. Whitehead: This paper was suggested by some of the questions arising in undertaking to change a 30-mile, single-track road from steam to electricity. It is understood, of course, that every project of this nature must be considered in the light of the particular conditions involved, so that it is rather to the methods which have been followed in the present case than to the actual results and values which were finally adopted, that I ask attention.

W. I. Slichter: In the equipment of a single-phase railway system one of the most important points is the design of the conductor system, since there is not the synchronous converter to fall back upon as a booster to make up for any line losses by its compounding.

The drop in voltage in the rails with alternating current has been investigated by various persons, but as Mr. Whitehead has pointed out, there seems to be considerable difference in the results obtained. It is probable that these results differ because of the numerous conditions which enter with important effects into the phenomenon.

The drop in the rail varies with the perimeter of the rail, because it is a skin effect; it also varies with the chemical composition of the rail, which affects the permeability; with the bonding which affects the true or ohmic resistance of the circuit, and with the quantity of current in the rail, as this affects the permeability; and with the leakage of current to ground.

While the results of experimental tests will differ greatly on this account, conditions found in practice do not vary so greatly and we do get quite reliable and uniform values.

The general results of a series of tests made under operating conditions show that at 25 cycles the impedance drop in the rail itself is approximately eight times as great as the ohmic drop with direct current, that the power-factor of this drop is about 80 per cent. The impedance drop in the trolley is approximately 50 per cent greater than that with direct current. The result is that the total drop with alternating current is approximately twice as great per ampere as the drop with direct current.

An interesting feature of this voltage drop is that it has a power-factor greater than the power-factor of the input to the car at free running and less than that at starting, but more closely approximating the power-factor of free running. Thus under free-running conditions this drop is almost algebraically subtracted from the sub-station voltage.

At starting, when the input to the car has a value about twice that of free running, the drop is out of phase with the line voltage and is subtracted geometrically at a large angle, so that at starting there is a loss of voltage only about 50 per cent greater than that at free running, although the ratio of line current and actual voltage drops is as two to one.

Wm. McClellan: In regard to the choice of systems. Of the various systems proposed for electrification, none of us knows which one is going to be the best, if there is a best. I am perfectly willing to grant that there may be a heavy grade at some place where a 1200-volt, direct-current system may seem the best; there may be a long grade, perhaps, where a three-phase system may seem very advantageous; there are other places where the 11,000-volt, single-phase system may seem the right one; and still other places where the 650-volt system may seem best; and so on.

But we are not electrifying heavy grades or tunnels. We are not electrifying small portions of systems. We are beginning to electrify whole systems. Therefore, while we cannot at present choose any one system and electrify by means of that system, yet we must constantly realize that the great problem we have is the electrification of the large system. If we are called upon to work with a tunnel or grade, or something which needs immediate electrification, let us keep in mind the whole problem of the general electrification of the whole road at some future day.

I know of one place where they want to make a forty-mile extension on a part of the system, where a certain system of electrification is used on the original part of the road. There is no question whatever that another system of electric propulsion is more advisable for the extension; the problem is to know what to do, whether to throw away the part now in use, and remake it, or go ahead with the old system and install that on the extension, which is the easier thing to do, and trust to the future.

It is fortunate that one large system decided to solve their problem on a general basis. As a result they have been subjected to criticism, because some one can show where a few dollars might have been saved now by adopting some other system. They have done wisely, however, in keeping in mind the electrification of the whole system rather than to adopt the method that is perhaps more immediately applicable.

A. H. Babcock: The method given herein is not the only accepted one to be followed in discussing problems of this character. If it were the only method, in at least one case with which I have to deal, we would be hopelessly at sea. That particular case involves the electrification of about 135 miles of trans-continental railroad over the Sierra Nevadas, with a grade rising 7,000 ft. in 83 miles.

Have there been any tests made on the road, as in operation, to show how much drop was encountered in the rails and in the overhead system, as compared with the calculated figures?

J. B. Whitehead: There have been no tests of these figures. The best I was able to do was to take the literature as I found it in the matter and lay the system out. The starting conditions are excellent, so far as I can observe. As for actual figures of drop, I have not been able to get any.

A. W. Copley (by letter): The subject of the constants of alternating-current railway circuits is one to which I have given considerable attention. During the last few years I have had opportunity to make a number of tests for the determination of such constants, the most important of which were made on the New York, New Haven & Hartford Railroad, under the general direction of C. F. Scott and W. S. Murray. The data obtained in these tests is summarized in the following tables. The values given for double-track and single-track are calculated from the data obtained on the four-track road; the values obtained in this manner for single-track check closely with the results of tests made elsewhere on single-track roads.

The impedances given in the table are the electromotive forces required for sending current through the circuit, and are practically equal to the difference between the electromotive forces at the power house and at the load. The values in the table are the volts required per mile per hundred amperes in the trolley.

The figures showing the division of current between the track and the earth refer to intermediate portions of long sections; the division is different near the power house and near the load.

The figures in the tables apply to average practical conditions and are suitable for the calculation of commercial circuits.

FOUR-TRACK ROAD

Four 0000 trolley wires......... Eight 100-lb. rails.

Electromotive force	25 cycles	15 cycles
Resistance		
Trolley	6.8 volts	6.7 volts
Rail	1.8 "	1.5 "
Total	8.6 "	8.2 "
Reactance		
Trolley wires (internal)	0.35	0.2
Rails (internal)	0.85	0.5
Between trolley and return circuit	15.6	9.4
Total	16.8	10.1
Impedance, total	18.9	13.
Division of current		
Each outside trolley wire	26.6 amperes	26.3 amperes
Each inside trolley wire	23.4 "	23.7 "
Rails	75 "	
Earth	25 "	

FOUR TRACK WITH AUXILIARY FEEDERS

Four 0000 trolley wires	Two 00 feeders	Eight 100-lb. rails
Electromotive force	25 cycles	15 cycles
Resistance		
Overhead wires	5.7 volts	5.6 volts
Rail	1.8 "	1.5 "
Total	7.5 "	7.1 "

Reactance		
Overhead wires (internal)	0.2	0.1
Rails (internal)	0.9	0.6
Between overhead wires and return circuit	13.3	8.0
Total	14.4 volts	8.7 volts
Impedance, total	16.5 "	11.2 "
Division of current		
Each feeder wire	14.2 amperes	
Each outside trolley	18.8 "	
Each inside trolley	17. "	
Rails	75 "	
Earth	25 "	

DOUBLE-TRACK ROAD

Two 0000 trolley wires	Four 100-lb. rails	
Electromotive force	25 cycles	15 cycles
Resistance		
Trolley	13 volts	13 volts
Rail	2.5 "	2 "
Total	15.5 "	15 "
Reactance		
Trolley wires (internal)	0.6	0.4
Rails (internal)	1.2	0.7
Between trolley wires and return circuit	25.1	15
Total	26.9	16.1
Impedance, total	31.	22.
Division of current		
Rails	58 amperes	
Earth	42 "	

SINGLE-TRACK ROAD

One 0000 trolley wire	Two 100-lb. rails	
Electromotive force	25 cycles	15 cycles
Resistance		
Trolley	26 volts	26 volts
Rail	3 "	2 "
Total	29 "	28 "
Reactance		
Trolley wire (internal)	1.3 volts	.8 volts
Rails (internal)	1.5 "	.9 "
Between trolley and return circuit	44.2 "	26.5 "
Total	47. "	28.2 "
Impedance, total	55.3 "	39.6 "
Division of current		
Rails	40 amperes	
Earth	60 "	

NOTE.—With 000 trolley wire instead of 0000 for single-track the total impedance in volts per 100 amperes per mile is 60.

The earth losses are left out of the above tables. Such losses are comparatively small and are not easily measured; moreover they undoubtedly vary greatly with different kinds of soil and the ballast of the roadbed, the largest part of the loss occurring in the region where the current is leaking from the rails and going into the earth.

Mr. Whitehead has given figures for various losses in railway circuits published by Parshall & Hobart and by the Railway Test Commission and has made calculations of such constants from theoretical considerations. A comparison of the values given in his paper with values obtained from the tests on the New Haven road brings out several interesting points.

Rail impedance. The values for the ratio between the impedance of the rails at 25 cycles and the direct-current resistance, are given from Parshall & Hobart as 8.1 and from the Test Commission Report as 5.5. These ratios are presumably for an 80-lb. rail. Measurements made on the New York, New Haven & Hartford Railroad with 100-lb. rails with 0000 bonds gave a value of between 2.5 and 3 for the ratio. This ratio was obtained with current densities of from 40 to 200 amperes per rail, and the results show only a very slight increase in the ratio with increased density. The resistance of the rail showed no noticeable change with the density, but the impedance rose slightly as the density increased.

Rail resistance. The resistance of the rails to alternating current at 25 cycles as measured on the New Haven road was 0.16 ohm per mile of single rails. Multiplying this by the rail current gives the ohmic drop of voltage in the rails. With 100 amperes per rail, this would amount to 16 volts. This value is little more than half of the value given by the Railway Test Commission (28.8 volts for 80-lb. rail) which is used in Mr. Whitehead's calculations.

Rail reactance. The reactance within the rail was found in the New Haven tests to be about 8 volts per 100 amperes per mile for a single rail. The value used by Mr. Whitehead (21 volts for 80-lb. rail) in his calculations is that taken from the Railway Test Commission's tests and is over double the value given above for a 100-lb. rail.

Rail current. The proportion of the trolley current which returns by rails is seen from the tables to vary according to the number of tracks. A single-track road has only 40 per cent of the current returning by the rails while a four-track road has 75 per cent.

At the point where current enters the rails on a single-track road 70 per cent of the current starts toward the power house and 30 per cent in the opposite direction. The 30 per cent leaks from the rails into the earth in from two to three miles. Coming toward the power house the 70 per cent decreases to 40 per cent in about the same distance, and the rail current then stays at this value until near the power house. Similar results were found on the four-track road, 87 per cent starting toward the power house and decreasing to 75 per cent in two miles.

Position of earth current. The position of the earth current varies, no doubt, under different conditions of soil etc. On the New Haven road it was found that if the earth conductor was assumed as 1000 ft. in diameter and tangent to the surface at the rails, the constants of the circuit calculated theoretically would be substantially the same as those determined experimentally. For a single-track road an assumed diameter of 600 ft. gave theoretical constants the same as the measured values.

Impedance volts due to trolley current. In the calculation given for the division of current between a 000 copper trolley wire and a $\frac{7}{16}$ in. steel messenger wire, it does not appear that any allowance has been made in the value of R_1 (the resistance of the messenger wire) for the fact that the current is alternating. The value 3.7 ohms is about the value of the resistance to direct current, but 9 or 10 ohms is probably nearer the value for the resistance at 25 cycles. By making this change from 3.7 to 10, the values of i_2 and i_1 (the currents in the trolley wire and messenger respectively) become 97 and 3.5 amperes, respectively and E (the impedance voltage in the circuit due to the trolley current) becomes 47.2 instead of 44.75. This value of E (47.2 volts) is close to the value found by neglecting the messenger wire as a conductor.

Impedance volts due to rail current. The resistance voltage due to rail current as given above is 16.2 per 100 amperes in each rail per mile of 8.1 volts per 100 amperes in a pair of rails per mile.

The reactance volts due to the field inside the rails is 4 volts per mile of single track (two rails). The reactance voltage in the trolley-rail circuit due to rail current is calculated from the distance between rails and trolley wire, the rail current, and the diameter of the rails. If this last is taken as 2.5 in., the value of reactance volts is about 32 as is given by Mr. Whitehead for 100 amperes in each rail or 16 for 100 amperes in the track. The total impedance due to track current of 100 amperes is then $8.1 - j\,20$. Adding this to the value deduced for the impedance due to the trolley current, gives E_0, the total impedance, as 67.8 volts per mile per 100 amperes for 000 trolley wire and 100 lb. rails. Taking into account that the rail current is only 40 per cent of the trolley current drops the value of E_0 to about 60 volts.

Chas. F. Scott: Mr. Copley is, I believe, substantially correct in his measurements, and what he has contributed is a valuable addition to our knowledge on this subject. I might add that the height of the trolley wire is 22 ft.

J. B. Whitehead: I am particularly glad to see these figures. This is one of the objects which I had in mind in bringing the calculation of the impedance volts into the paper. I have only seen Mr. Copley's figures for the first time, in the last few minutes, and am not prepared to make specific comments upon them.

The value of the impedance volts for the single-track road is what I was most concerned with in my paper. I notice that the total impedance in Mr. Copley's discussion at 100 amperes per mile, is 60 volts as against 65 volts given in my paper.

The difference between 80 and 100 lb. rails at 100 amperes per mile is appreciable; maybe it will make up for the difference in impedance values.

I did not mention the matter of rail impedance at the time I was abstracting the paper, but I called attention at the time to the difference in the ratios of impedance of rails and direct-current resistances, as given by the several authorities which I quoted. I brought out in the substance of the paper the point which Mr. Copley has reported here. He has touched on the subject of rail resistance, and I would be glad to see more figures on that particular point. They are all over the place, if one looks up the measurements which have been taken, and doubtless the variations are caused by the different conditions of track under which the measurements are taken; that is the only way I can account for them.

As to the matter of rail current, these are the first figures I have seen bearing on the subject. I should like to ask Mr. Scott whether there were any single-track measurements taken at the time of these tests? Do I understand these figures for single-track are calculated from the results of four-track tests?

Chas. F. Scott: Yes; calculated, and also the result of direct measurement. The figures relating to three single-track measurements taken at three places are from actual tests.

J. B. Whitehead: I should like to see the record of these single-track tests, because there are remarkably few at present available in the literature. The resistance of the catenary cable at 25 cycles is placed here at from 9 to 10 ohms, but by conjecture only. The value appears excessive.

S. H. Clarkson: In figuring out the cost per car-mile, I should like to know whether Mr. Whitehead took the locomotive into consideration, and if so to what extent? It seems to me that the cost per ton-mile would be a much more equitable basis for comparison, not only in the present instance where a steam and a single-phase road are being considered, but in all cases where it may be necessary to compare trains having different equipment or motive power.

J. B. Whitehead: I shall answer the question last asked. The figures given at the end of the paper on the relative costs of operation are based entirely on the passenger traffic of the road. The freight traffic will be handled by steam, certainly for the present. The comparison here given is entirely on the basis of passenger traffic, and it has been estimated that a certain car mileage was necessary to handle the passenger traffic. That is the reason for the basis of car-mileage.

As to the maintenance of locomotives, the figures for the cost of maintenance are at once available from the company's books, and it was a simple matter to put them on the car-mileage basis.