A Study of the Various Experiments for the Determination of the Resistance of Electric Cars and Trains

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A STUDY OF THE VARIOUS EXPERIMENTS FOR THE DETERMINATION OF THE RESISTANCE OF ELECTRIC CARS AND TRAINS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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A STUDY OF THE VARIOUS EXPERIMENTS FOR THE DETERMINATION OF THE RESISTANCE OF ELECTRIC CARS AND TRAINS

INTRODUCTION

The most important factor in electric train operation is the power required to accelerate and keep in motion when brought up to speed. The power required to accelerate can easily be determined from the fundamental laws of mechanics. However the latter division of the total power, namely, the power required to overcome train resistance, can not be so easily determined. Numerous experiments have been performed and resulting formulae deduced for the determination of this resistance. Up to the present time, however, none have proved applicable to general conditions. This is due to the fact that little is known of the laws governing the variation of frictional and air resistance at high speeds, under different conditions, such as weight and length of trains, shape of cars and the condition of the track and weather. The experiments have shown conclusively that the above conditions have a marked effect on the value of the train resistance. It can thus easily be seen that with so many varying conditions all tending to change the value of the train resistance, no general formula can be expected to give reliable results for all classes of service.
COMPONENTS OF TRAIN RESISTANCE

The total resistance to be overcome by the movement of a train, on a straight and level track at constant speed, consists of the following separate components; the friction in the bearings, motor comutator and gears, the track resistance and the air resistance. A separation of these components by J.B. Blood is shown in Fig. I. The friction in the bearings is merely the rubbing of the journals on the sides of the bearings and has been assumed to be practically constant by all investigators up to the present time. With good lubrication it is a very small part of the total resistance, especially at high speeds. The frictional resistance of gears and motor commutators must be considered in dealing with geared motor cars. J.B. Blood, after a study of the laws of friction involved, has decided that this component is small at low speeds but increases appreciably with the speed. John Lundie in his tests on the South Side Elevated Railway of Chicago neglected this component. Therefore his formula gives too high results for trains composed of trailing cars drawn by locomotives.

The general attitude of most investigators towards track resistance, is summarized in an editorial in the Street Railway Journal of August 4, 1900, in which the total track resistance is divided as follows; pure rolling friction, which is small and fairly steady; joint friction, which consists of
Frictional Resistance - lb. per ton

Fig. 1

Separation of Elements of Train Resistance for Motor Cars by Blood

Speed - miles per hr.

5 10 15 20 25
the resistance due to the irregularities of rail joints, rather large and variable; flange friction due to rocking and jarring of trucks and to wind, large and exceedingly irregular; and finally the work against gravity due to the irregularities and flexure of track, very variable and at times very large. The bearing and rolling resistance of wheels on the track, together constitute the principal component of train resistance at low speeds, and may be considered to remain fairly constant irrespective of the speed. The flange and gravity components evidently depend on the condition of the track and the swaying of the train, and therefore on the speed. Their value at very low speeds can be considered negligible but at moderate and high speeds, they are of more or less indeterminate importance.

The air resistance can be divided into head pressure, rear suction, and side eddy friction. The relative importance of these divisions is not definitely known, although the head pressure is conceded to be the most important of the three.

All investigators agree that although the air resistance is negligible at low speeds, it comprises the greater part of the total train resistance at the higher speeds.
METHODS OF DETERMINATION

The actual value of train resistance has usually been determined by one of two methods, viz.:—By the use of a dynamometer car which registers the drawbar pull, or, by investigation of speed time curves obtained while coasting. The first method was used in all early experiments and has also been used on most extensive investigations of the resistance of steam trains, such as those conducted by J.A.F. Aspinall on the Lancashire and Yorkshire Railway in 1899 and 1900, and by Prof. E.C. Schmidt on the Chicago branch of the Illinois Central in 1908 and 1909. The dynamometer is an instrument which records graphically the magnitude of the drawbar pull. A graphical record of the speed may also be obtained on the same chart by any one of a number of simple methods. At constant speed on a level track, the pull recorded by the dynamometer is the total force that must be exerted to overcome train resistance. From the value of the speed and drawbar pull as obtained from the corresponding points on the record, a curve showing the relation between train resistance and speed may be plotted directly.

The dynamometer car must of course be placed behind the locomotive, and consequently the value of train resistance obtained does not include the component of air resistance due to head pressure. This method is only applicable in cases where the power is concentrated at the head of the train. This fact
prohibits its use in connection with motor car trains.

As a modification of this method, the use of a long cable between the dynamometer car and the train has been suggested. The chief advantage of this method is that with the cable long enough, the pull recorded by the dynamometer includes the head pressure. In case the weight of the cable is such that the sag reach the ground, a light supporting truck can be used without introducing an appreciable error.

By the second method the train is brought up to speed and the power shut off. Frequent readings of speed and time are taken, and the speed-time curve plotted from the point where the power is shut off till the train comes to rest. The retardation is then determined from the curve at a number of different points. By the use of the formula:

\[ F = Ma \]

where \( F \) is the retarding force.

\( M \) " " mass of the train.

\( a \) " " retardation.

the total retarding force can be determined.

The speed-resistance curve may then be plotted from the determinations and corresponding speed readings. This method has not met with the approbation of a great many investigators. Their objections, however, seem vague and should not wholly condemn the method. J.E. Blood has made the statement that the results obtained by its use are not reliable owing to the fact that the forces acting while coasting are
not the same as while running with the power on.

Mr. S. T. Dodd has suggested a third method which has been used with a marked success in recent investigations, notably those carried on by the Electric Railway Test Commission. By this method Mr. Dodd determined the total motor input from the current and voltage readings. The output was then obtained from this data and the efficiency curves of the motor. This output was the power required to overcome train resistance.
A DESCRIPTION OF VARIOUS TESTS

A detailed study of a number of characteristic tests has been made with the idea of comparing the methods used and results obtained, and determining the class of service for which each is adapted. The tests referred to are the Berlin-Zossen tests carried on by the Studenten Gesellschaft from 1901 to 1903 on the Berlin-Zossen military railway; tests of the Electric Railway Test Commission on the Indiana Union Traction Company Lines in 1904 and '05; J. Lundie's test on the South Side Elevated Railway of Chicago in 1898 and '99; W. J. Davis Jr.'s tests on the Buffalo and Rockport Railway in 1900; and the conclusions of J. B. Blood.

The Berlin-Zossen test was one of the most complete and exhaustive of the above named. The tests on train resistance were only a part of a very complete study of the problems of electric train operation. The dynamometer method was used first. The operation was at low speeds to eliminate air resistance as much as possible. On account of the great weight of the motor car, which produced a decided variation of the drawbar pull at each revolution of the drivers of the locomotive, and was especially marked at low speeds, it was impossible to obtain a smooth curve of the drawbar pull by this method. For this reason the coasting method was adopted. It was found
necessary to make grade corrections at low speeds, but at high speeds the slight grade variations were found to be negligible. Curves between total train resistance and speed were plotted for speeds below twelve and one-half miles per hour and the separate curves plotted for speeds up to seventy five miles per hour. In the former, the effect of grades was considered, while in the latter the effect was not taken into account. Two cars were used in the tests, car "A" and car "S". Car "A" had been allowed to stand for more than a year. During this time the truck bearings and king bolt had not been cleaned. On the other hand car "S" was in good running condition. During the first tests the frictional resistance of car "A" was found to greatly exceed that of car "S". This furnishes reliable proof of the statement that at low speeds the train resistance is influenced by the condition of the bearings of the car. Separate curves representing the air resistance were also plotted. The results obtained on air resistance comprised the most valuable information afforded by the experiments.

Two important phases of the air resistance were taken up, viz; the magnitude of the head pressure in terms of the velocity of the car, and the nature of the eddy currents about a moving car. The former was measured by a special apparatus consisting of a small flat disk fastened to a ball bearing shaft and held in the direction of motion by a spiral spring. The air pressure against the disk compresses the spiral
spring and through lever arms operating over a scale on the inside of the car, the pressure was read directly. Normally the plane of the disk was perpendicular to the direction of motion. It was connected to the shaft, however, by means of a ball and socket joint, so that it could be turned in any direction. In this manner the head pressure could be taken from all angles. All the pressure readings were corrected for wind velocity, since it was required to determine the relation between pressure and velocity in still air. From the readings of speed and pressure the relation between the pressure on the effective car front of nine square meters and the speed of the car in still air was determined. By effective car front is meant the projected area on a plane perpendicular to the direction of motion. The formula

\[ P = 0.0052V^2 \quad \text{or} \quad P' = 0.00177V'^2 \]

was deduced from these results, where

- \( P \) is the pressure in pounds per square meter.
- \( V \) is the velocity in kilometers per hour.
- \( P' \) is the pressure in pounds per square foot.
- \( V' \) is the velocity in miles per hour.

The nature of the eddy currents was determined by means of manometer tubes projected from the car at several points. By this means a cone of compressed air of uniform pressure was found to exist up to 4.5 meters in front of the car, and to extend to the rounded corners of the car sides. In the rear a similar cone of undisturbed air was found.

The Electric Railway Test Commission was appointed at
the St. Louis Exposition in the fall of 1904 to carry on tests similar to the Berlin-Zossen tests. A special car designed primarily for separating the components of the total resistance was used. This car consisted of an interurban car body mounted on a steel flat car. The side sills were supported by specially chilled steel rollers running on steel rails on the floor of the flat car. The vestibule was independent of the body, but was carried by means of a link suspension. In order to guide it and to transmit the pressure to the weighing device, a steel trussed oak frame attached to the vestibule projected into the car and was guided on all sides by small bearings. The controller and trolley pole were mounted on stands resting on the floor of the flat car, and were not connected to the body of the car in any way. The vestibules, front and rear, and the sides were connected by means of lever arms to delicate scales by which the air resistance on the front, rear and sides was accurately measured. The method of mounting the trolley and controller eliminated the slight inaccuracy due to friction of the trolley wheel on the wire and stiffness of the controller cables.

Four types of vestibule were used; flat, standard, parabolic, and parabolic wedge. Very complete results were obtained, as shown in Fig. IIa and Fig. IIb, showing the relation between air resistance, speed and shape of car vestibules. The method used to determine the total resistance was that suggested by S.T. Dodd. The input to the motors was taken at regular intervals and also by means of a continuous graphical record. By using the efficiency curves of the motors the output was
determined and converted into pounds tractive effort. The frictional resistance was determined by subtracting the total air resistance, measured by means of the scales, from the total train resistance.

In the fall of 1898 John Lundie carried on a number of extensive tests to determine the relation between train resistance and speed for passenger trains of all weights and running at all speeds. These tests were conducted while the trains were in actual service, on the South Side Elevated Railroad of Chicago. The coasting method of determining train resistance was used in these tests. Mr. Lundie assumed that if the retarding force consisted of friction alone, the speed-time curve for coasting would be a straight line. From the dip which occurred in the actual speed-time curves obtained, he concluded that the air resistance varied directly with the speed. He also found that the total train resistance varied with the weight of the train. His results as plotted give a series of straight line curves, through a common point on the axis of "Y". The ordinate of this point gave the first term of his formula:

$$ R = 4 + S(0.2 + \frac{14}{35 + T}) $$

where

- $R$ is the train resistance in pounds per ton.
- $S$ is the speed in miles per hour.
- $T$ is the weight of the train in short tons.
Fig III

Train Resistance - lb. per ton

Results of Lundie's Tests on Train Resistance

Speed - miles per hr.
The expression by which "S" is multiplied is proportional to the tangents of the angles made by the lines developed for different weights of trains, and is the characteristic of a rectangular hyperbola. The term 0.2 is an intercept on the axis of "y"; 14 is the constant product of "X" and "Y" with the intersection of the asymptotes as origin; and 35 is an intercept on the axis of "X". Mr. Lundie later modified this formula to the form

\[ R = 4 + S \left( 0.24 + \frac{4.8}{T} \right) \]

The actual curves from which the formula was derived are shown in Fig. III.

Mr. W. J. Davis Jr. conducted a number of tests for the General Electric Company in March 1900, on the Buffalo and Rockport Railway. In these tests a train of three non-vestibule passenger coaches and a baggage car was drawn by a 37 ton electric locomotive, geared to give a maximum speed of 55 miles per hour to 60 miles per hour at average line voltage. The coaches weighed on the average 26 tons each without load. Mr. Davis used the same method as Mr. Lundie to determine the train resistance, viz; the coasting method. Tests were first made with the entire train. The coaches were then removed one at a time and the tests repeated in each case until finally only the locomotive remained. The power losses due to friction in the gears and bearings of the locomotive, as determined in the factory were subtracted from the total resistance. During the greater part of the
test there was not enough wind to affect to any appreciable extent the running resistance of the train.

The constant for wind pressure was determined by a series of tests made after the regular run. A wooden wind shield was mounted on the front end of the locomotive, hinged at the lower end, and fitted with a system of levers and an adjustable spring balance in the cab to register the pressure. The equation deduced from these results was:

\[ P = 0.004 V^2 \]

where

- \( P \) is the pressure in pounds per square foot.
- \( V \) is the speed in miles per hour.

From the results of the tests on total train resistance the following general formula was deduced;

\[ f = b + cv + \frac{dAV}{T} (1 + m(n - 1)) \]

Where

- \( f \) is the train resistance in pounds per ton.
- \( v \) is the velocity in miles per hour.
- \( T \) is the weight of the train in short tons.
- \( b \) is the journal friction.
- \( c = 0.13 \) = coefficient of rail friction.
- \( d = 0.0035 \) = wind coefficient.
- \( A \) is the cross-sectional area of the car.
- \( n \) is the number of cars.
- \( m \) is the coefficient showing proportional section of trailing car considered as affecting total windage. It was found that the addition of one car increased the effective cross
section by approximately ten per cent. Therefore \( m = 0.1 \).

The value of "b" was found to vary with the weight of the train.

In 1899 Mr. J.B. Blood developed the first rational formula for train resistance. His data was taken from some tests carried on by himself, a few years previously, on the Metropolitan West Side Elevated of Chicago, and from tests carried on by other investigators along the same line. Mr. Blood considered that in order to obtain a formula applying to all conditions, each component should be considered separately. The complete formula would then consist of the following terms, as shown by previous experiments; one term representing the bearing friction; one the rolling friction on the track; and one the air resistance.

Mr. Blood agreed with other investigators that the first term does not vary with the speed and is thus constant. He concluded that the second term depends only on the first power of the speed. Since previous formulas have shown that the third term containing a factor of the first or second power of the speed does not give correct results for both low and high speeds, Mr. Blood has concluded that some intermediate value of the exponent should be used. Mr. Blood logically concluded that, in as much as the head and stern resistance, which comprises the greater part of the air resistance, does not depend on the weight of the train; in order to get the train resistance in pounds per ton, a weight factor should appear in the denominator of the last term of the equation. The equation which he considers to represent actual operating conditions follows:

\[
R = 4 + 0.15 M + \frac{0.3m^{1/3}}{T}.
\]
where

\[ R \] is the train resistance in pounds per ton.

\[ M \] is the speed of the train in miles per hour.

\[ T \] is the weight of the train in short tons.

This formula seems to give fairly accurate results over a wider range of conditions than any other so far published.
Variation of Head Pressure

With Speed and Shape of Front

Determined

By Railway Test Commission
Rear end suction - 1b per 54 ft of projected area

Variation of Rear Suction

With Speed and Shape of Rear

Determined

By Railway Test Commission

Speed - miles per hr.
COMPARISON OF TESTS AND RESULTS

The results obtained by the Berlin-Zossen tests and the investigations of the Electric Railway Test Commission can be compared with difficulty since emphasis was placed on different phases of air resistance in each. The former consisted principally of a study of the condition of the air about the car relative to the direction of air currents, only slight attention being paid to the magnitude of the pressures. The latter consisted of a study of the actual values of the pressures about the car, and their relative importance in resisting the forward motion of the car.

The results obtained for head pressure in the Berlin-Zossen tests do not represent actual conditions. The head pressure in these tests was taken as the total pressure on a flat surface equal to the cars sectional area. From this it would seem that the head pressure depends entirely on the cross sectional area of the car and not on the shape of the head. The exhaustive tests of the Electric Railway Test Commission proved conclusively, however, that the shape of the car front had a decided influence on the value of head pressure. The results of the investigators are shown graphically in Fig. IIa, and can be considered accurate, due to the extreme delicacy of the instruments used and the care with which the measurements were taken.
The Berlin-Zossen investigators decided that if a rear suction existed at all, it was so small as to be negligible, while the Railway Test Commission found it to be of considerable importance at high speeds. This is shown in Fig. IIb, and is substantiated by the experiments of Dean W. F. M. Goss, who found that the head pressure was approximately 6.2 times the tail resistance.

The formula given by Davis gives results which are undeniably high for high speeds, although at low speeds it seems to be fairly accurate. The fault seems to lie in the third term, which deals with air resistance. The method of determining the coefficient of air resistance, explained above, is very unreliable. A great many determinations have been made, in a similar way, by other investigators, and in each case the results obtained are different. Siemens and Halske obtained a coefficient thirty per cent greater than Davis, although the same method was used by each. The same discrepancy can be seen in nearly all the coefficients obtained in this manner.

Aside from the fundamental inaccuracies of the method, another was introduced in Davis' coefficient by the apparatus used. The wind shield was hinged at the bottom and could swing back when the locomotive was running. This would add an additional factor in the results due to the component of the weight of the shield recorded on the weighing apparatus. Furthermore there is no allowance made for a variation in the shape of the vestibule. As was shown in Figures IIa and
IIb, this has a decided influence on the train resistance.

The same criticism on the lack of flexibility can be offered for the formulae of Lundie and Blood. Lundie's formula, although it may apply to the class of service in which the tests were made, will not necessarily apply to any other, since it is an empirical formula taken from the curves obtained. Since it has been proved conclusively that the variation of air resistance can only be represented by a straight line, it would seem that Lundie's graphical results, from which he derived his formula, are in error, since they were straight lines.

Aside from the point given above, Blood's formula seems to cover the greatest number of conditions of any. The conclusions, from which his formula was drawn, seems to be perfectly logical and have been worked out from all standpoints.
CONCLUSIONS

From the data at hand and a study of the above experiments it seems impossible to obtain any one formula which will apply to all conditions, and all classes of service with equal accuracy. This seems reasonable from the fact that there are so many widely varying factors which have an important bearing on the value of train resistance. Any formula which will take all of the factors into account will be so cumbersome that it will be of little practical use. The experiments that have been performed, however, are of great value, in spite of the fact that they can not be used for the determination of train resistance, in all cases. They show definitely and conclusively the importance of the many minor details of the train resistance problem, and furnish a foundation upon which future experiments of a more definite and practical nature may be based.

Judging from the difficulties that have been encountered in obtaining a universal formula, it seems that the problem might be more easily solved by the use of a separate set of curves for each condition. This method will eliminate the use of a formula and will be much more accurate. The field open to experimental work along this line is a very broad one. A practical and definite solution of the problem will be of immeasurable value to the entire railway world.
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