A PROPOSAL TO ELECTRIFY A SECTION
OF THE
BOSTON AND MAINE RAILROAD
HAVERHILL DIVISION

by

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Signed
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<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgments</td>
<td>1</td>
</tr>
<tr>
<td>Object</td>
<td>2</td>
</tr>
<tr>
<td>Plan</td>
<td>2</td>
</tr>
<tr>
<td>General Discussion</td>
<td>3</td>
</tr>
<tr>
<td>Arguments for Electrification</td>
<td>4</td>
</tr>
<tr>
<td>Power Possibilities</td>
<td>6</td>
</tr>
<tr>
<td>Economies in Operation</td>
<td>6</td>
</tr>
<tr>
<td>Summation of Advantages</td>
<td>13</td>
</tr>
<tr>
<td>Advantages Derived by the Public</td>
<td>14</td>
</tr>
<tr>
<td>Classification of Systems</td>
<td>16</td>
</tr>
<tr>
<td>The Third Rail System</td>
<td>20</td>
</tr>
<tr>
<td>Return Circuit</td>
<td>22</td>
</tr>
<tr>
<td>Disadvantages of Third Rail System</td>
<td>23</td>
</tr>
<tr>
<td>System Selected</td>
<td>24</td>
</tr>
<tr>
<td>Multiple Unit Car Control</td>
<td>26</td>
</tr>
<tr>
<td>Rheostatic Control</td>
<td>27</td>
</tr>
<tr>
<td>Multiple Unit Control</td>
<td>31</td>
</tr>
<tr>
<td>Automatic Control</td>
<td>32</td>
</tr>
<tr>
<td>How Motor Control Operates</td>
<td>33</td>
</tr>
<tr>
<td>Details of Motor Controller</td>
<td>34</td>
</tr>
<tr>
<td>Contactors</td>
<td>35</td>
</tr>
<tr>
<td>Air Engine and Cam Shaft</td>
<td>35</td>
</tr>
<tr>
<td>Line Breaker</td>
<td>35</td>
</tr>
<tr>
<td>Reverser</td>
<td>36</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>-----------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Comparison of Electrified and Steam Systems</td>
<td>88</td>
</tr>
<tr>
<td>Power Calculation</td>
<td>89</td>
</tr>
<tr>
<td>Calculation of Resistances for Motor Control</td>
<td>91</td>
</tr>
<tr>
<td><strong>Car Equipment</strong></td>
<td></td>
</tr>
<tr>
<td>Motors</td>
<td>105</td>
</tr>
<tr>
<td>Efficiency Curves</td>
<td>107</td>
</tr>
<tr>
<td>Motor Ventilation</td>
<td>109</td>
</tr>
<tr>
<td>Auxiliaries</td>
<td>110</td>
</tr>
<tr>
<td>Electric Car Heaters</td>
<td>111</td>
</tr>
<tr>
<td>Car Lighting</td>
<td>112</td>
</tr>
<tr>
<td>Photos of Equipment</td>
<td>113</td>
</tr>
<tr>
<td><strong>Substations</strong></td>
<td></td>
</tr>
<tr>
<td>Supervisory Control</td>
<td>118</td>
</tr>
<tr>
<td>Rectifier and Feeder Connections</td>
<td>119</td>
</tr>
<tr>
<td>Manual Control</td>
<td>120</td>
</tr>
<tr>
<td>Rectifier Transformer Circuit</td>
<td>121</td>
</tr>
<tr>
<td>Method of Control</td>
<td>122</td>
</tr>
<tr>
<td>Direct Current Power</td>
<td>123</td>
</tr>
<tr>
<td>Rectifiers</td>
<td>124</td>
</tr>
<tr>
<td>Comparative Efficiencies</td>
<td>125</td>
</tr>
<tr>
<td>High Speed Circuit Breakers</td>
<td>127</td>
</tr>
<tr>
<td>Switching Equipment</td>
<td>128</td>
</tr>
<tr>
<td>Plan of Substation</td>
<td>130</td>
</tr>
<tr>
<td><strong>Power Supply</strong></td>
<td></td>
</tr>
<tr>
<td>Character of Load</td>
<td>132</td>
</tr>
</tbody>
</table>
Equipment
Voltage Regulation
   Signal System
Track Circuit
   Air Conditioning Equipment
Refrigerating Equipment
Photos of Equipment
A. C. Receptacle
Generating Unit
Power Supply
   Future Demand
Industrial Expansion
Economic Results Due to Electrification
OBJECT

The object of this thesis is to present a plan to relieve the traffic congestion and provide a better and more comfortable service for its patrons, and to increase the capacity, which had about reached its limits with steam operation.

PLAN

The plan as presented consists of the electrification of the main line from the North Station up to and including Haverhill of the Boston & Maine R. R. Electrification of the road between these two points will take care of the large commuting traffic traveling daily to and from Boston.

Although the line continues from Haverhill to Portland, the traffic between these two points is seasonable and is very light, consequently electrification beyond Haverhill will not be attempted. It would be uneconomical to do so, even in times of prosperity.

A detailed study has not been made, due to insufficient time, however a preliminary study of the various systems of operation has been made and of different types of equipment and the selections made have been done after careful study and are what we believe the best suited for the proposed electrification of this section of road.

To take care of the present and future increase in traffic. It would be uneconomical to increase the number of tracks, with the steadily increasing prices of land. An im-
provement must therefore be made in the motive power, and we believe electrification of this section is the only practical method of increasing the capacity of this line.

GENERAL DISCUSSION

A comparative study of the steam and electric operation reveals the following differences. First of all the steam locomotive is essentially a primary unit; that is, each locomotive is independent of all other units on the line. For this reason a general tie-up of the system may be less liable than when the entire system depends on one power house and one transmission line for its energy. This consideration, which is always advanced when a comparison of electric and steam traction is undertaken, holds only partially for the section under discussion. The reason is that on grades, where breakdowns are most liable to occur, the trains are run in rush hours about as closely as the automatic blocks will permit. If the engine on one train breaks down, therefore, not only does that train have to stop, but in a very short time, the following train is forced to stop and before long, traffic is seriously congested. The increased reliability of the electric operation over the steam locomotive, considered individually, would therefore tend to counterbalance the possibility of a complete tie-up.

The independence of the steam engine is detrimental in that there is no overload capacity available, while the power which electric operation may exert for a short time is
limited only by the mechanical rigidity of construction and the adhesion of the wheels.

The limiting factor in steam locomotion at present is the boiler. The output of the engine is determined by the ability of the boiler to give steam. At first sight there appears to be several methods of increasing the capacity of the boiler. First, one naturally thinks of enlarging its size; but a little study shows that the limits in width, height, and length of boilers and rigid wheel-base, have already been reached, so that this is out of the question. Hence we are led to believe that the ultimate capacity of the steam locomotive has about been reached.

Before speaking of the electric road a list of the disadvantages of the steam railroad will help the discussion.

(1) Slow service in that the acceleration and deceleration rates are low.

(2) Noisy, since the puff. Puff of the steam trains are very audible, especially at night.

(3) Very dirty. The coal dust flies all over both in the passenger cars, and on buildings near tracks.

(4) Conversion of fuel, since 25 percent of the coal ruined in the United States is used on Railroad, it is important to consider this feature.

Arguments for Electrification

(1) Availability for service

(2) Unrestricted power possibilities

(3) Economical operation
Records show that each road engine is available for service 25 to 35 percent of the time under normal and favorable conditions and that the full time of five men on an average is needed on each locomotive to make necessary repairs, keep it properly oiled and cleaned, and to give it periodical overhauling in the shops.

Such an engine in service will ordinarily handle about 35,000 tons trailing ten miles per annum and while doing so will deliver about 750,000 H.P. hour per annum at the draw bars. Reduced to a unit basis, the cost of steam locomotive repair and cleaning service, including material and labor is found to be 1.21 cents per H.P. hour, which is about ten times the cost of repairs and maintenance of the entire motive power equipment of an electric motor driven industrial plant, and 2.5 times that of an electric haulage system of equal capacity including repairs and maintenance of the distribution systems, transmission lines, and substations.

In contrast to the poor performance of the steam locomotive, operating records show that the electric locomotive will on the average spend two weeks each year in the repair shop for repairs and overhauling, also, since the electric motor has no power plant, no time is lost by requirement of making steam, cleaning fires, taking on coal and water, cleaning boilers and flues, and the necessity of daily hostler service. It is, therefore, available for service 90 to 95 percent of the time; a ratio of 3:1 as compared with the steam locomotive.
Power Possibilities

If a section of the road is operating near the limit of its capacity, it is evident that the provision for handling additional traffic may be made either by increasing the power of the locomotive, and, consequently, weight and speed of trains, or by laying additional tracks. Either of these methods involves a large expenditure.

Now, under electric train generation with the present scheme of multiple unit control, no such expenditure is necessary. Simply by the addition of more cars we can provide for all the traffic, since each car furnishes its own power.

Economies in Operation

Many improvements in design and operating conditions, such as compound engines, high superheaters, increased steam pressures, automatic stokers, traction boosters, fuel oil, etc., have been introduced by the railroads with the object of reducing the fuel consumption of locomotives. To some extent these have been successful, but to an electrical engineer familiar with methods of power house generation of current and with the savings promised by electrification, these savings appear hardly worthwhile. There are two important operating conditions which make it impossible for a steam locomotive of the present general type to have an efficient power plant, as measured by modern standards.
(1) Excepting one or two experimental equipments, all locomotive engines are built to run non-condensing. The energy thus thrown away in the exhaust steam which would be available to a condensing steam turbine is not less than 85 percent of the energy in the steam available to the locomotive engine above atmospheric pressure.

(2) The operating load factor is so low, and the standby losses are so great, that it is useless to even hope for moderate high efficiency.

The losses due to the first of the above conditions are inherent to non-condensing operation. In a main power house, such as used for electric train operation the exhaust steam could be utilized in low pressure turbines to generate further power.

As to the second condition, it can be said that the effect of poor load factor in reducing efficiency is more serious than is generally realized. Operating records show that the yearly load of a road engine is of the magnitude of about 5 percent. The operating load factor, or ratio, of actual load to rated load while in service and including idle time will average 15 to 20 percent. On this basis the consumption of a locomotive in actual service, allowing for standby and light load losses, will be increased by more than 45 percent. The above results obtain under constant load conditions.

As to standby losses, these on a suburban line, we are considering of importance.
In order to determine the saving in coal per 1000 trailing ton miles which may be effected by electrification, we may analyze some operating data applying to a section of a large and well managed trunk line railroad. The section is 300 miles long, single track, with ruling grade 1.00 percent and a short section of 10 miles, with a maximum grade of 2 percent.

Steam Service (Taken from G. E. Co. Records)

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ton miles -- locomotive only</td>
<td>262,000,000</td>
</tr>
<tr>
<td>Ton miles -- trailing load</td>
<td>2,102,000,000</td>
</tr>
<tr>
<td>Ton miles -- total</td>
<td>2,364,000,000</td>
</tr>
</tbody>
</table>

Coal consumed per 1000 trailing ton miles  lb. 129.6

Electric Service

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ton miles -- locomotive only</td>
<td>199,300,000</td>
</tr>
<tr>
<td>Ton miles -- trailing load</td>
<td>2,102,000,000</td>
</tr>
<tr>
<td>Ton miles -- total</td>
<td>2,301,300,000</td>
</tr>
</tbody>
</table>

Average watthours per ton mile at power house -- 26.15
K. W. per annum -- ----------------- 60,179,000.00
Lbs. of coal consumed per K.W.H. -- ------------- 1.92
Tons of coal consumed -- ----------------- 57,750.00
Coal consumed per 1000 trailing ton miles -- 55.00
Ratio of coal consumption, steam to electric -- 2.36

The above comparison does not include the less efficient train movements such as road and yard switching. The average coal consumption of steam locomotives over the whole country for all classes of service is more than three times the
amount required by an electric system capable of handling the same traffic.

There are many indirect reductions in operating costs which will follow the adoption of the electric system. These include such items as reduced maintenance of tracks and structures due to decreased axle weights, the use of shorter wheel bases, and improved riding qualities of the locomotives, savings in maintenance and cost of water supply, shop equipment, round houses and turntables, reduced operating costs due to reduction in company coal movements, and improved service to shippers due to increased speed and greater reliability in operation.

These savings all have monetary value, the magnitude of which may be determined in specific cases with a fair degree of accuracy. Nevertheless, we may neglect them entirely and still show that electrification will pay by density of traffic, by considering only the seven main operating items usually included in statements of operating costs. The following tabulated summary shows a comparison between steam and electric operation, as applying to two large railroad systems. The length of A is 330 miles long and 260 miles for Road B.

The costs are given in percentages, the basis being the total cost of the steam service.
<table>
<thead>
<tr>
<th>Item</th>
<th>Road A</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steam</td>
<td>Electric</td>
<td>Reduction</td>
</tr>
<tr>
<td>1. Fuel or power</td>
<td>33.80</td>
<td>27.50</td>
<td>6.30</td>
</tr>
<tr>
<td>2. Locomotive repairs</td>
<td>30.40</td>
<td>10.70</td>
<td>19.70</td>
</tr>
<tr>
<td>3. Lubricating supplies</td>
<td>2.35</td>
<td>1.41</td>
<td>0.94</td>
</tr>
<tr>
<td>4. Engine house supplies</td>
<td>4.62</td>
<td>0.77</td>
<td>3.85</td>
</tr>
<tr>
<td>5. Engine men</td>
<td>13.76</td>
<td>6.82</td>
<td>6.94</td>
</tr>
<tr>
<td>6. Train men</td>
<td>15.07</td>
<td>8.10</td>
<td>6.97</td>
</tr>
<tr>
<td>7. Maintenance trolley</td>
<td>------</td>
<td>4.32</td>
<td>-4.32</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>59.62</td>
<td>40.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Road B</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steam</td>
<td>Electric</td>
<td>Reduction</td>
</tr>
<tr>
<td>1. Fuel or power</td>
<td>38.34</td>
<td>32.70</td>
<td>5.64</td>
</tr>
<tr>
<td>2. Locomotive repairs</td>
<td>23.65</td>
<td>8.35</td>
<td>15.30</td>
</tr>
<tr>
<td>3. Lubricating supplies</td>
<td>2.39</td>
<td>1.44</td>
<td>0.95</td>
</tr>
<tr>
<td>4. Engine house supplies</td>
<td>9.00</td>
<td>2.50</td>
<td>6.50</td>
</tr>
<tr>
<td>5. Engine men</td>
<td>13.60</td>
<td>8.22</td>
<td>5.38</td>
</tr>
<tr>
<td>6. Train men</td>
<td>13.02</td>
<td>7.82</td>
<td>5.19</td>
</tr>
<tr>
<td>7. Maintenance trolley</td>
<td>------</td>
<td>2.39</td>
<td>-2.39</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>63.43</td>
<td>36.57</td>
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</tbody>
</table>

It can be seen that the net saving in operation is 40.38 percent for Road A and 36.57 percent for Road B. Expressed in terms of capital cost these savings are 16.3 percent and 17.1 percent of the net cost of the electrification, after deducting replacement value of the steam locomotives.
If allowance is made for normal increase in traffic over the amortization period, the capital cost of the electric equipment may be fully paid off in 5 to 7 years. The two cases may be considered fairly representing the economies to be expected from electrification of first class roads.

Another advantage is the much increased acceleration rate that the electric motor has over the steam engine. Below are shown typical acceleration curves of both. From these curves it can be seen that an electric motor accelerates to maximum speed in about one-fifth of the time it takes a steam engine. The acceleration rate for the motor is about 5 times as great. The breaking characteristic of the electric motor is also faster than the steam engine rate. The maximum safe breaking rate for a steam engine is 2 miles per hour per second, while for an electric motor it is 2.5 miles per hour per second.

Now this shows how an electric train can easier make up time when running late since it starts and stops much quicker than a steam engine. This is a very important consideration especially in rush hours when traffic is heavy and every minute counts.
At the present time on the Haverhill line there is, as can be seen from the grade map, a maximum grade of .65. During rush hours under heavy load the steam engine which the Boston & Maine has in use slows down considerably in order to make the grade. Now with the electric motor power it can easily be made since each car can contribute its motor power and so get tremendous power, causing no great decrease in speed. Since each car of its own power can pull the maximum load over the grade, therefore we can put on as many cars as necessary to carry the traffic and still make the grade.

At present the Boston & Maine R. R. operates no trains on the Haverhill Line after 11:40 P.M. as seen on the train schedule. The reasons for this are many. First it costs too much to hold an engineer, a fireman, and two or three brakemen all night, especially since there are not many passengers. Second the standby losses are great. The time between trains on the average is about 1 hour, most of which is standby period. All this time steam must be kept up and coal is being burnt. Also the company has to pay the fireman on an average of at least one hour a day for starting up the fire and banking the fires at night.

Now, under electric operation what can be done? As already noted, there is no loss in standby. When the train is not moving, the motors take no current from the line. Again, no fireman is needed, eliminating quite a number of men's wages that have to be paid. Hence all that would have to be required
to run, say a two car train all night, would be two men instead of four, as is required now. This would enable the company to increase their night service, benefiting the commuters and themselves.

A Summation of the Advantages of Electrification
in General

(1) Higher schedule speed, enabling a larger mileage to be obtained from a given amount of rolling stock and a greater number of trains to be operated over a given length of track.

(2) Continuous and regular movements of trains and in consequence economical employment of train crews.

(3) Greater flexibility in making up trains to meet varied requirements of traffic both through the day and on special occasions.

(4) Ability to reverse trains at terminal rapidly with switching of engines reducing time wasted and track needed. This has already been discussed as being very essential especially at North Station.

(5) Elimination of inefficient water and coal handling, lighting, and heating equipment.

(6) Reduction in repairs and in increased lift of track due to weight of train, driving machinery being distributed over the entire train instead of being concentrated.

(7) Reduction of operating expenses per mile.
(8) Increased revenue due to increased traffic which would follow electrification.

The Advantages Derived by the Public

(1) Regular and more frequent service throughout the day.
(2) Greater punctuality due to ability to make up time.
(3) General improvement in smoothness and safety of working and less risk of accident due to automatic controlled starting and stopping devices.
(4) Prevention of fires on property adjacent to line arising from sparks from locomotives. There have been many huge fires started from the sparks thrown out by locomotives.
(5) Almost noiseless operation and elimination of dust and smoke.
(6) Satisfactory heating.

Now having seen the advantages of electrification, it must be noted what limitations must be set in order to fit the conditions on the Haverhill Line. In order to become familiar with the names of stations and towns which may be mentioned later in this discourse there is listed below the stations on the various lines with the distance of each from the starting place of each, namely North Station.
<table>
<thead>
<tr>
<th>Station</th>
<th>Distance (miles)</th>
<th>Station</th>
<th>Distance (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Station</td>
<td>0.0</td>
<td>Reading Heights</td>
<td>0.5</td>
</tr>
<tr>
<td>East Somerville</td>
<td>1.5</td>
<td>North Wilmington</td>
<td>3.8</td>
</tr>
<tr>
<td>Edgeworth</td>
<td>2.3</td>
<td>Wilmington Junction</td>
<td>1.6</td>
</tr>
<tr>
<td>Malden</td>
<td>0.9</td>
<td>Lowell Junction</td>
<td>1.7</td>
</tr>
<tr>
<td>Oak Grove</td>
<td>0.5</td>
<td>Ballardvale</td>
<td>0.9</td>
</tr>
<tr>
<td>Wyoming</td>
<td>1.0</td>
<td>Andover</td>
<td>2.2</td>
</tr>
<tr>
<td>Melrose</td>
<td>0.5</td>
<td>Shawsheen</td>
<td>1.2</td>
</tr>
<tr>
<td>Melrose Heights</td>
<td>0.8</td>
<td>Lawrence</td>
<td>2.1</td>
</tr>
<tr>
<td>Greenwood</td>
<td>1.0</td>
<td>North Andover</td>
<td>1.3</td>
</tr>
<tr>
<td>Wakefield Junction</td>
<td>0.9</td>
<td>Wood Hill</td>
<td>2.2</td>
</tr>
<tr>
<td>Wakefield</td>
<td>0.5</td>
<td>Bradford</td>
<td>2.0</td>
</tr>
<tr>
<td>Reading</td>
<td>2.1</td>
<td>Haverhill</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Classification of Systems

Having decided on the reasons for electrification, it leaves the problem as to what type of electric service will be most desirable. The problem of the Railway engineer is:

1. Determination of equipment to yield proposed service.
2. The characteristics of distribution systems.
3. The location and capacity of substation and substation equipment.
4. Capacity of main generating station.
5. Cost of system and probable operating expenses and approximate income on investment.

In order to investigate these problems the following classification of systems will be of value:

Classification of Traction Systems

1. Low Tension distribution
   A) A.C. Systems
   B) D.C. Systems
   C) Third rail systems
   D) Overhead contact systems

2. High Tension Distribution
   A) A.C. System
   B) D.C. System

These can best be classified by grouping into
1. Overhead Distribution
2. Third Rail Distribution
Overhead contact used for heavy traction is a development of the overhead trolley used by street railways. The use of high voltage has made necessary the design and construction of the overhead system which can be satisfactorily insulated and which can be placed in a position where accidental contact by persons is reduced to a minimum.

This is done by having the current transmitted over wires supported by structures designed for holding up the wires. These structures must be strong enough to withstand the pressure of the wind and wire tension which is quite considerable. They must also be fairly close together in order that the conductors do not sag too much. They are normally spaced at 300 feet apart. Special designs of conductors must be made for each of the classes. For single phase A.C. the overhead contact usually consists of supports of structural steel and catenary wire construction. Catenary construction involves the use of steel messenger cables freely suspended in spans with a convenient sag between supports located at fixed intervals. Some of the latest type of messenger cables consists of copper and bronze core. The messenger cables support the contact wires by means of vertical hangers of varying length. These hangers are spaced at intervals of from ten to fifteen feet and are adjusted to support the trolley wires at a uniform height above the track. The span of the catenary messengers vary from 150 feet to 300 feet on straight track, this distance being reduced on curves to provide for proper suspension of the contact wire. There are in general three types of catenary con-
struction, the single, the double, and the compound. The single catenary involves the use of single messenger cables attached to insulators on the supporting structures and of hangers dependent from the messenger cable, which supports the trolley wire in proper position above the track. The double catenary has two catenary messenger cables supporting the trolley wire, these messengers being supported a few feet apart at the same elevation. The trolley wire is suspended before the messenger cables. Compound catenary construction involves the use of two messenger wires, one being carried on the main supports without insulation, the other being supported by intermediate insulators dependent from the first messenger. The trolley wire is supported by hangers dependent from the second messenger, as in the case of the single catenary construction. The insulators for the single overhead contact which distinctly support the catenary construction are subjected to heavy mechanical and electrical strain. Porcelain is generally used for insulators when mechanical loads either in compression or tension are high. Impregnated wood is sometimes used in tension on installations where both steam and electric services are operated. As will be the case here, the insulators must be of particularly high electrical strength since the deposits from the locomotive gases tend materially to reduce the insulating capacity. In single or double catenary construction the messenger cables are usually supported by means of a suspension or pin type insulators attached to the overhead structures.
Suspension insulators are used with compound catenary construction, the messengers which directly support the contact wires being insulated from the primary supporting messenger at the points of suspension. The primary messenger cables are ordinarily attached directly to the supporting structures without insulation. Thus overhead system requires a system of supporting structures. There are usually anchor bridges which are located every two miles or less along the line. These are strong structures which sustain the vertical loads due to the weight of the messengers, hangers, and contact wires, and also resist when necessary the longitudinal load pressure. Intermediate supports are designed to sustain vertical loads due to the weight of the catenary system and also longitudinal stresses. These are placed between the anchor bridges at such intervals as may be necessary to provide the desired messenger span.
The Third Rail System

The contact conductor is the link in a traction system by means of which the power is delivered to the locomotives or motor cars. In all systems the contact consists of stationary conductors located along side or above the track to be served. The conductor must be insulated and protected to insure safety and continuity of operation. Also, it must be so located as to provide a minimum interference with existing structures or rolling equipment. The current is taken directly from the contact conductor or conductors by means of a rolling or sliding device attached to the locomotive or motor car. The contact equipment requires careful design and construction and constant attention in maintenance in order that it may satisfy the physical and traffic conditions incident to normal operation.

A third rail system consists of a conductor placed along side the track, supported a fixed distance above the gage line and above the level of the track rail. The location of the third rail is standardized by the American Railway Association. This location has been established to provide space for insulation to prevent interference with existing structures and rolling equipment and to permit of safe and satisfactory operation of locomotives or motor cars.

The third rail is supported by means of insulators constructed of such materials as are suitable for the voltage employed in the rail. The rail is usually provided with some form of guardrail or ring to serve as a protection against
accidental contact to employees or others. The conductor rail is generally of a composition having a lower electrical resistance than still ordinarily used in ordinary track rails. The standard lengths are 30 to 35 feet. The rails are joined by means of fish plates, and to insure electrical continuity are bonded with copper bonds.

In all third rail installations it is sought to provide continuous contact for the locomotives or motor cars by having the third rail along the track at all points. Gaps are necessary, however, at many points to accommodate various track conditions such as railroad crossings, crossovers, and slip switches and to allow for rail and street grade crossings. The motor cars are equipped with contact shoes at both ends and when gaps are short no other means are necessary to provide contact since the distance between the shoes is sufficient to span the gaps. Gaps of even greater length may often be crossed by allowing the train to coast over the distance where physical conditions make it necessary to provide long gaps in the third rail, other arrangements are provided to supply the contact.

The electrical continuity of the third rail circuit at gaps is maintained by installing copper jumpers under ground between the ends of the rails. These jumpers consist of insulated cables installed in conduits of iron pipe or other duct material. Electrical connection between the third rail and overhead contact rail is made by means of insulated copper cables.

The third rail conductor is sometimes reinforced electrically by a system of feeders direct from the substation.
Such feeders are employed when the conductivity of the maximum desirable size of the rail is not sufficient to maintain the minimum voltage required with economical substation spacing. The feeders and third rail conductors are arranged in circuits through the agency of switching stations located at intervals along the tracks. At these switching stations, circuit breakers, either automatic or manual are provided so that the tracks may be sectionalized in case of short circuit or other faults.

**Return Circuit**

By the return circuit is meant the method of returning the current from the motor power units to the station. In nearly all cases the track rail will be used for this purpose. In order to do this the rails must be bonded at joints and connected to substations.

There are three points to consider when designing a return circuit:

1. Track bonding or electrically connecting rail ends at joints.
2. Cross bonding or electrically connecting the rails of adjacent tracks.
3. Substation connections or electrically connecting the track rails to substation bus bar.

For all main line track, both rails will be bonded, while for yard tracks only one rail will be bonded. Two bonds per joint is used in all cases, as in single bonding, a break
or poor contact will not only increase the resistance of the return circuit, but may affect the signal circuit.

The location and frequency of cross bonds between main track is largely dependent upon the length of signal block where automatic signals are used. Therefore, the main tracks will be bonded about every mile and yard and industrial tracks about every 1,000 ft.

At each substation all tracks, the contact conductors of which are supplied from each substation, are connected electrically with the negative or grounded substation bus bar to supply a path for the return circuit. Those connections are to be made of bare copper cables of 2,000,000 circular mils laid underground with terminal connected to rail in some manner as are bond terminals.

**The Disadvantages of Third Rail System**

1. Limits the voltage to a low value, giving excessive line voltages.

2. Complexity of the yards and switching points makes use impractical.

3. Because of limiting low voltage, the extent of the electrification is limited and can only be extended at a great expense by installation of numerous substations.
System Selected

Multiple unit equipment was chosen for this electrification, because it would provide better acceleration, more uniform speeds throughout the suburban road. There will be more economical operation during off peak periods. The entire line would be more flexible, switching movements will be eliminated, turntables, and switching yard at Somerville will no longer be necessary.

\footnote{Comparison of plans on the Delaware Lackawanna Railroad for performing the needed service with equal reliability showed that 3000 volt direct current system to have an advantage over the alternating current in first cost for investment and in operating cost, as well as in operating characteristics for equal weight of motor equipment. The advent of 3000 volt mercury arc rectifiers of large capacity in individual units improved the substation status for direct current system in first cost and operating efficiency. When considering the adoption of rectifier substations the Electrification Committee and the consulting engineers had before them to guide their considerations a record of the steadily increasing use of rectifiers for 600 volt for street railway and rapid transit service in this country and abroad. The amount of such equipment had reached a very large total, and the reliability of performance had been proved excellent. Fifteen hundred volt rectifier equipment also is extensively used abroad with good performance and to a small extent in this country.}

1 General Electric Review Nov. 1931.
The mercury arc rectifier is not new, but its application on such a large scale, is a recent advent in electrification projects. Its characteristics are ideal for railroad work. Its high efficiency, especially at 3000 volts d-c., its small weight and floor space, capacity for overloads render it very attractive. Another important factor of this electrification, is that the power supply for operating the trains will be purchased from the New England Power Co. The company power lines run almost parallel to the road to be electrified, similar to that used on the Delaware and Lackawanna electrification, which has fully proven its anticipated results. An investigation and explanation of the proposed system will now be given.
Multiple Unit Car Control

The motor control equipment of an electric car or train serves to regulate the speed of the car and direction of rotation of the motors and to govern their action, during periods of acceleration. The most important function of a railway motor controller is to maintain a sufficiently uniform change of velocity during initial acceleration, due consideration being given to the comfort of the passengers. Hence the variations in starting current from the average values necessary to produce the required tractive effort for the specified rate of acceleration must be so restricted that the accompanying fluctuations in torque will not be injurious to the equipment or unpleasant to the comfort of the passengers, and the maximum current attained will not give rise to commutation difficulties.

With D. C. motors there are two general methods of control in use:

1. Rheostatic control
2. Series parallel control

Rheostatic Control:

This method is used with one or more motors. Resistance is connected in series with the motors and varied to give varied voltages which are applied to the motors.
Successive portions of the resistance are shortcircuited by closing switches 1, 2, 3, and 4 in order named thus gradually increasing the voltages applied to the motor terminals. This method is seldom used because the loss in the regulating resistance does not allow economical operation.

Series Parallel Method:

This method is used extensively for equipments with two motors per car having any number of cars. The car is started from rest and accelerated by first placing the two motors per car in series with a resistance and then cutting out the resistance step by step until the motors are operating in series on full voltage. Then each motor is taking half the rated voltage. Since with all the resistance out there is no unnecessary $I^2R$ loss, this is called a running connection, and the controlling mechanism is said to be on a running point. To increase the speed further the motors are then placed in parallel with a resistance in series across the line and the resistance is then gradually cut out until the motors are running on full voltage across the line. This is also a running connection.

There are three different methods of accomplishing the transition from the series to the parallel position.
1. Shunting or shorting one of the motors.
2. Opening of the power supply circuit.
3. Maintaining full current through all the motors during the transition period.

On single car type equipments the first method is extensively used, the method being as follows: The starting resistance is gradually cut out until the motors operate, as before, on full line voltage in series across the line. Then a part of the resistance is reinserted in series with the motors, and then one of the motors is shortcircuited, thus connecting the other motor across the line at full voltage with a protective resistance in series with both motors. Then the shortcircuited motor is connected in parallel with the first; the resistance still in series. Finally the resistance is gradually cut down in successive steps until the motors operate in parallel at full line voltage.

The second method namely, opening the power circuit, is merely an extension of the first and is used only with motors of very large capacity. The method is hardly ever used since it is very much inferior to the next method which meets the same requirements much more effectively.

The third method is used with multiple unit control, and is used with large motors and high voltage. During transition full motor current is carried by means of a bridge.
The following operations take place:

Switches A and B are closed, thus placing both motors and all the resistances in series between the trolley or third rail and ground. This is slow speed that is suitable for switching in terminal yards and is passed over very quickly at the usual rate of acceleration. The first movement of the handle closes simultaneously switches 5, 6, and 7, cutting out resistance. Then switches 1, 2, 3, and 4 are closed consecutively, followed by the closing of switch C, and then subsequently switches 2 to 7 are opened, putting in the resistance then switch B is opened, placing the motors in series across the line then bridging through switch C. Then switches A and B are closed. This forces two currents to flow through C in opposite directions, one path through the rail to motors to ground, other through resistances to ground. Hence there is no current flowing through C and C is opened, placing the two motors in parallel with resistances in series with each. Then switches 2 and 5, 3 and 6, 4 and 7 are closed progressively, so as to cut out the same amount of resistance from each motor.
circuit, finally placing both motors across the line at full voltage. This method is very desirable since no motor is subjected to a sudden increase in voltage neither is the circuit opened at any time. The variations in torque are therefore steady, causing no discomfort to passengers. The whole scheme takes place during one movement of the controller handle and is very fast; the entire time being only a few seconds.

All types of control apparatus includes methods for reversing the direction of rotation. In series motors with no commutating poles the standard method is to reverse the armature current, while on commutating pole motors the field is usually reversed.

The manipulation of switches is accomplished directly by hand or the intervention of an auxiliary control. The motor-man moves a hand at the top of the control box which causes the rotation of a vertical cylinder, which has arcs of metal contacts on it, permitting contact with stationary fingers in desired sequence, which by means of suitable wiring connects the motors to the different switches and taps of the rheostats.

The direction of the motor rotation is changed by moving a reversing lever and thus actuate a smaller cylinder which is mounted beside the main cylinder of the controller and is provided with connections for making reversal. Interlocking devices are supplied so that the reversing switch cannot be moved unless the controlling handle is on the "off"
position, that is, contact with the overhead wire is broken. Cutoff switches are provided, so that a defective motor or group of motors may be disconnected without interfering with the operating of the remaining motors. Arcs that are liable to ensue upon breaking a circuit, are disrupted by an electromagnetic field which is set up by metal strips, which are inside of the insulating strips, between contacts and which connect to the cover which is connected to the line.

**Multiple Unit Control:**

The system of motor control in which the switches are operated electrically or pneumatically through the intervention of an auxiliary circuit is called multiple unit system, since it is designed to operate several motor cars coupled together in a train, all motors being simultaneously controlled from any master control on the train. The apparatus for each motor car consists of a motor controller and two master controllers. These will be described in detail later.

The General Electric Multiple Unit P. C. Control will be used on all cars. Hence we will discuss the P. C. type fully.

The General Electric Multiple unit control system is primarily designed to permit a train of motor cars when coupled in any combination to be operated as a single unit from either end of the train.

The motor controller comprises a set of apparatus which handles directly the current for the motors while the master controller merely governs the operation of the motor
controller, and, consequently does not handle the larger currents necessary in the motor circuit.

The latest type using the latest development of this system, namely the cam operated motor control is the P.C. 104 type. This type has the following improvements:

1. A definite sequence of contact or operation preventing the trouble sometimes encountered from improper functioning of independently operated contactors.

2. Interlocks on individual contactors eliminated.

3. Simplicity of electric control circuits.

4. The contactor arc shutes assembled in a single group that swings downward, exposing all contactor parts.

**Automatic Control:**

The cam operated contactors are provided with magnetic blowouts on each contactor which is capable of interrupting 3000 amp. at 3300 volts. These contactors with their definite sequence of opening and closing and elimination of electrical interlocks makes possible an easy automatic control. With automatic control, the master controller operates directly through the train wires, the motor reverser, line breaker, and the rotation of the cam shaft. This master controller with control equipment gives automatic or manual acceleration in either series or parallel combination of the motors.

Closing the contactors for the first step, the main line breaker is closed, and all the control resistance is in circuit. Automatic acceleration does not progress beyond this point as long as the master controller remains on this position.
The succeeding positions of the cam shaft and the closing of the contactors is controlled indirectly by the master controller through the accelerating relay and under its direct control.

The scheme of operation is that as each section of resistance is cut of the circuit and increased current passes through the motor and the series coil of the current limit relay. If this current is sufficient to open the relay contacts, the progression of this cam shaft is arrested until the current falls to a predetermined value and in this manner automatic current limiting is obtained.

At any time during the acceleration the master controller can be moved to the last, or full parallel position and the motor controller will progress under its direction of the accelerating relay to the full parallel position unless the engineer elects to use manual control.

If the master controller is left in the parallel position the progression of the motor controller to full parallel is completed after which the motor fields are shunted at the direction of the field-shunting relay. This field-shunting relay is adjusted for a predetermined value and will hold the motors in the full field connections until the current has dropped to the value for which this relay is set.

**How the Motor Controller Operates:**

The cam shaft is rotated by a rack and pinion, the rack being connected to the pistons of an air engine. Air is admitted to, or exhausted from, the air cylinder by means of
magnet valves controlled by the master controller. When de-
energized, the "off" magnet valve exhausts air from the other
cylinder. When the master controller handle is turned in
starting, the reverser is thrown, the line breaker is closed,
and both the "on" and "off" magnets are energized. This supplies
air to the "on" cylinder and allows air to escape from the
"off" cylinder. The rack moves forward, rotating the pinion
and cam shaft until the "off" magnet is de-energized. When
this occurs, air pressure is applied to the "off" cylinder,
equalizing the pressure on both pistons, causing the rack to
remain stationary on the first position. Subsequent positions
of the motor controller are obtained by alternately energizing
and de-energizing the "off" magnet valve as the current limit
relay drops out and picks up. When the master controller is
turned "off" both magnet valves are de-energized, and air is
thus exhausted from the "on" cylinder and pressure maintained
in the "off" cylinder. This causes the rack to move backwards,
rotating the pinion and cam shaft to the "off" position.

Details of the Motor Controller:

The controller contains the following elements:

1. Contactors, which make the electrical combinations
of the motors and regulates the starting resistance in
circuit with them.

2. Air engine and cam shaft for operating the contactors.

3. Line breaker.

4. Reverser.

5. Overload relay.

6. Accelerating relay.
Contactors:

Each contactor consists of a movable arm operated by the cam shaft, and a stationary contact with a magnetic blowout coil, both of which are mounted on an insulated base, the latter being supported by two bolts. It is provided with a powerful magnetic blowout, which is sufficiently strong to individually break excessive overload currents. The contactor and chutes are assembled in a single unit.

Air Engine and Cam Shaft:

The air engine consists of two-cylinder balanced-pressure engine, and air valves magnetically controlled. Teeth are cut in the rod connecting the piston heads, forming a rack which engages with a pinion mounted on the end of a cam shaft. The magnet valves are energized at proper intervals by completing the proper circuits through the master controller and accelerating relay. In this manner the rack and cam shaft are advanced or stopped at points, corresponding to the master controller drum. Since the cams are rigidly fastened to a hexagonal shaft, a definite sequence in timing of closing and opening the contactors is obtained.

Line Breaker:

The line breaker is closed independently against gravity and heavy springs by means of an air cylinder controlled by a magnet valve. The breaker is provided with an extra powerful blowout coil and extended arc chutes designed
to break any current met in railway service. The reason for making the line breaker operate separately from the cam operated contactors is to procure an additional link in the chain of protective features embodied in the control system. When the master controller is thrown to the off position, the motor current is broken by the line breaker before the cam shaft has barely started to turn off. It immediately opens the circuit in case the overload relay trips. By confining practically all the serious arcing to this line breaker, inspection and maintenance are reduced to a minimum.

Reverser:

The reverser compartment at one end of the motor controller contains an air operated reversing drum. The drum is thrown either to the forward or reverse position by energizing the correct magnetic valve through a train wire from the reverse drum of the master controller. These magnet valve circuits are electrically interlocked with the line breaker so that the drum cannot be thrown unless the line breaker is open, and the line breaker cannot be closed unless the drum is either in the forward or reverse position as indicated by the reverse handle.

Overload Relay:

The overload relay consists of principally a main circuit series coil with its tripping and interlocking mechanism, together with a shunt reset coil, all mounted on an insulated
base. The air gap can be accurately adjusted, so that the line breaker is immediately tripped in case the current exceeds a safe predetermined value.

**Accelerating Relay:**

The accelerating relay includes series and auxiliary shunt coils mounted on an insulated base. The series coil mechanism may be adjusted for a wide range, so that a setting can always be obtained, which will give a uniform increase in speed in passing from step to step.

**Master Controller:**

The master controller in general is similar to the standard type of controller, but, since the current to be handled is of small value, it is very much reduced in size and weight. The frame is weatherproof, with cover designed to facilitate ready inspection. The back is made of cast iron, so shaped as to give maximum rigidity and strength. The controller is provided with a dead man's handle release by means of which all power is cut off from the motors in the event of the handle being released, and makes an emergency air brake application. Due to the fact that the two motors operate permanently in series, each pair can be treated as one motor as far as the connections to the reverser are concerned. The fields of the two motors connected in series are handled as a unit and a two motor reverser is all that is necessary for the four motor equipment. This reverser is operated by air pressure and is
mounted behind the motor cut-out switches. The handle has a total of six positions: off, switching series, series bypass, parallel bypass, and parallel. The intermediate accelerating points of the motor controller may be maintained by the proper manipulation of the handle, but ordinarily, these points would be controlled by the accelerating relay.

**Main Switch:**

A combined main switch and fuse box is used for the proper disconnection and protection of the main and auxiliary circuits. It is of rugged construction and mounted on a slate base and installed in a sheet metal box lined with asbestos. The box is provided with a cover held closed by a mechanical spring clamp.

**Train Control Couplers:**

The mechanical design of the receptacles is such as to facilitate installation, inspection, and maintenance. Many advantages are incorporated in the design of these receptacles which make them extremely desirable and reliable.

**Train Line Jumpers:**

The jumper consists of two plugs connected by means of special jumper train cable made in accordance with standard railroad specifications. The individual conductor connections are made the same as those in the receptacles.
Auxiliary Contactors:

Two contactor boxes are used to control the auxiliary circuits on the motor trailer unit, one containing six contactors for the motor car and the other three contactors for the trailer car. Each of these contactors is capable of interrupting its 3000 volt auxiliary circuit. A contactor is provided for each of the following circuits, cab heaters, two car heater circuits, air conditioning, and compressor. The three contactors on the trailer car are for the heater circuits only.

The following Important Features are Embodied in this P.C. Control Equipment

(1) Automatic acceleration with resulting power saving, improved passenger comfort, and low maintenance.
(2) Elimination of complicated interlocking.
(3) Master control has a dead mans release.
(4) Line breaker and contactors have powerful blowout coils, insuring positive arc rupturing with low maintenance.
(5) The overload relay trips the line breaker before excessive current can harm the equipment.
(6) The reverser is interlocked with the line breaker so that the former cannot be thrown out unless the latter is open.
(7) Power cannot be applied to the motors unless the reverser is in the position indicated by the reverse handle at the master controller.
(8) Should the power fail, the motor controller returns automatically to the "off" position, the car starts automatically without jar when power is restored.

(9) In case the line breaker sticks, any one of the four series contactors can rupture at overload.

(10) All parts of the motor controller are particularly accessible for inspection and maintenance.
Selection of Motor Equipment

The use of a 3000 volt direct current system implies the use of a series motor, since the series motor is the only motor which has satisfactory generating characteristics for traction purposes. These are namely:

At low speeds it exerts a very high torque which is desirable, since at starting very large torques are needed to produce motion.

At high speeds it exerts very low torques and since torque varies as the square of the current, the current is low due to the above characteristics, the demand on the power house does not fluctuate violently since the power is equal to the product of the speed and current.

The size of motors to be installed on the cars must be such that they will perform the proposed service at a desired schedule speed. To do this, the motors must exert the necessary torque to overcome the train resistance in order to produce the desired rate of speed and acceleration and operate without heating. To determine the motor capacity for the proposed service a knowledge of the load under which the motor must operate is essential. The load is extremely variable, fluctuations between no load at stopping points and a maximum at start. The method of procedure is as follows.

Assume a trial equipment (which can be very accurately assumed by comparing with existing installations) and from the motor performance curves obtained from the manufacturer, plot
curves of speed of the car in traversing the entire roadway and of motor current. The first curve shows whether or not the prescribed schedule speed can be maintained, allowing a margin for making up delays, and the latter curves show whether or not the assumed motor equipment can endure the service without such extreme heating as to endanger the insulation.

Data necessary to determine the curves is:-

1. Schedule speed required.
2. Weight of car or train with load.
3. Number and distribution of stops.
4. Average length of stops.
5. Voltage.
6. Grade and curve conditions.
7. Performance curves at full line voltage, with a definite gear ratio.
8. Rates of acceleration and braking.

**Train Resistance**

The tractive effort, or force exerted at the rim of the car wheels, required to propel a car at a constant speed on a straight level track, is only necessary to overcome at that speed the resistance offered to rolling friction and flange friction on the truck and wind pressure (still air) called under the single term, train resistance. Hence on grades and curves the resistance increases.
There are many ways of finding the various resistances for each roadway, but empirical formulas have been formulated which give satisfactory results.

**Formulae**

Total train resistance = TR + CR + GR + AR

In this design the resistance has been divided into four parts.

1. Resistance on straight level track in still air.
2. Resistance on grades.
3. Resistance on curves.
4. Resistance for acceleration.

R or the train resistance, first part, as given above differs for various cars in the train. There is a definite speed resistance curve for the leading car, trailing motor car, and trailing non-motor car. These three curves are explained fully by the Davis speed resistance curves on the following pages.

The second part is the resistance due to the grades. The grade conditions are of particular consequence in suburban work where speeds are high and stops frequent. In city work grades are not as important since grade and train resistance form a relatively smaller proportion of the average total tractive effort. Over an ordinary rolling profile, with the terminal elevations not very different the equivalent grade to be allowed for in the typical run may be obtained by the following relations:
Equivalent grade = \( \frac{\text{sum of rises and falls in one direction}}{2 \times \text{round trip distance}} \)

A more conservative formula is given:

Equivalent grade = \( \frac{\text{sum of rises and falls in one direction}}{3/4 \times \text{round trip distance}} \)

From test it has been found that 20 lbs. per ton are required to hold a 1 ton mass on a 1 percent grade. Therefore we get for heat determination of grade resistance:

\[ R = (T) \frac{\text{sum of rises and falls in one direction}}{3/4 \times \text{round trip distance}} \]

Where \( T \) is in tons.

This is based on the assumption that one-half of the potential energy in a car by reason of its position on the top of the hill will be available as kinetic energy to assist it down hill, up the following rises, or on the level, and the other half is wasted on the brake shoes in coming to stops or slow downs.

The force necessary to accelerate a given body is proportional to the product of mass and the acceleration.

\[ F = \frac{W}{G} \times A = F \]

\[ F = \frac{W \times 5280}{32.2 \times 3600} \]

And for 1 ton acceleration at one mile per second per second.

\[ F = \frac{2000 \times (5280)(1)}{32.2 \times 3600} = 91.1 \text{ lbs. per ton.} \]
This is for translation only, a certain amount of additional force is necessary to bring the rotating masses (wheels, axles, gears, armatures) up to speed. The increase amounts to 5 to 15 percent roughly, depending on the particular equipment. It is very convenient to allow 8.9 percent for this rotational effect, making the figure 100 pounds tractive effort per ton for an acceleration of 1 mile per hour per second.

The average curve resistance is found from the following formulae.

\[
\text{Average degree of curvature per mile} = \frac{\text{Length of curve} \times \text{degree of curvature}}{\text{Length of track}}
\]

The Curve Resistance or CR = \(T(0.6)(\text{no. of degrees curvature})\)

The factor (0.6) was determined from test.

\(T\) is weight of train in tons.

The average length of run is obtained by dividing the total mileage by total number of equivalent stops. The term equivalent stops is used to cover "slow downs" in addition to the actual stops. It is apparent that if the brakes are applied to reduce the speed it will be necessary to bring the car back to speed again by the use of energy, even if it has not actually come to rest. It is necessary to allow for this extra energy and a convenient means of providing for it is to increase the number of stops. It is customary to count two "slow downs" equal to one stop.
In order to get the proper motor for the cars it is necessary to have a motor which can propel the car at schedule speed over the hardest route.
Profile and Alignment Chart
Calculation of Equivalent Grades

Equivalent grade = $\frac{\text{sum of rises and falls in one direction}}{3/4 \text{ round trip distance}}$

Equivalent grade for entire road

Rises and falls from Boston to Haverhill

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<th>Falls</th>
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<td>41.65</td>
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<tr>
<td>North Andover</td>
<td>9.7</td>
<td>12.80</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>36.7</td>
<td>30.6</td>
</tr>
<tr>
<td></td>
<td>9.9</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Sum of Rises = 275.36 ft.  Sum of Falls = 234.64 ft.

Total sum of rises and falls = 275.36 + 234.64 = 510.00 ft.
Round trip distance = 2(33) miles or 2(33)(5280) =
348,480 ft.

Equivalent grade = \frac{510.00}{348480(.75)} = .00195

Equivalent grade = .195 percent

This means that the equivalent rise per hundred feet of track is .195 feet.

This is a very small grade.

Since 20 lbs. are required to hold one ton on a 1 percent grade, (.195) times 20 lbs. are required to hold one ton on our equivalent grade.

Train grade resistance = (.195)(20)(W) \quad W \text{ in tons of}
= 3.9 W \text{ lbs. train}

A more accurate method for determining train grade resistance is to break the profile up into sections which are representative for the grade in that section and in the same way as above calculate the equivalent grade for that section and use this value for this section of the road when calculating the speed time curve.
This might be broken up as follows:

1. Boston to Greenwood which is constant up grade.
2. Greenwood to North Reading which is quite level.
3. North Reading to Post B-15 is a relative steep down grade for this road.
4. B-15 to B-19 just beyond Wilmington Jct. a gradual up grade.
5. B-19 to Andover, level track a slight dip and rise in the track, but acceleration and deceleration due to fall and rise will balance giving no effect on time schedule of through train.
6. Andover to B-29, a steady down grade.
7. B-29 to Haverhill a steady rise.

Calculation:

Grade 1.

Sum of rises and falls = 26.75 + 2.26 + 72.20 = 101.21 ft.
Round trip distance = 2(45000) = 90,000 ft.
Equivalent grade = \( \frac{101.21}{90000(.75)} \) = .0015 or .15 percent.

Grade 2.

Sum of rises and falls = 17.90 + 9.08 + 5.1 + 2.24 + 7.70 + .62 + 1.96 + 27.86 = 72.46 ft.
Round trip distance = 2(21,000) = 42,000 ft.
Equivalent grade = \( \frac{72.46}{42000(.75)} \) = .0023 or .23 percent.
Grade 3.

Sum of rises and falls = 35.20 ft.
Round trip distance = 2(13000) = 26,000 ft.
Equivalent grade = \(\frac{35.20}{26,000 \cdot .75}\) = .00182 or .182 percent

Grade 4.

Sum of rises and falls = 10.0 + 7.07 + 25.9 = 42.97 ft.
Round trip distance = 2(21,000) = 42,000 ft.
Equivalent grade = \(\frac{42.97}{42000 \cdot .75}\) = .00136 or .136 percent

Grade 5.

Sum of rises and falls = 29.3 + 2.2 + 11.7 + 23.5 = 66.7 ft.
Round trip distance = 2(20,000) = 40,000 ft.
Equivalent grade = \(\frac{66.7}{40,000 \cdot .75}\) = .00222 or .222 percent

Grade 6.

Sum of rises and falls = 25.56 + 2.56 + 5.00 + 13.65
41.65 + 9.7 + 12.80 + 2.5 + 1.70 = 115.12
Round trip distance = 2(35000) = 70,000
Equivalent grade = \(\frac{115.12}{70,000 \cdot .75}\) = .0022 or .22 percent

Grade 7.

Sum of rises and falls = 36.7 + 30.6 + 9.9 + 1.4 = 78.6 ft.
Round trip distance = 2(19000) = 38,000
Equivalent grade = \(\frac{78.6}{38,000 \cdot .75}\) = .00278 or .278 percent
For local trains however (that is trains that stop at every station the equivalent grade is necessary between stations. This may be determined by either of the two above methods depending on the ground conditions.
**Davis Table of Train Resistance**  
General Electric Company

**Multiple Unit Trains**

The car bodies are of slightly smaller cross section but of about the same length as main line passenger cars. The leading car of course takes the place of locomotive with respect to head air pressure. For convenience the suction effect on the rear car may be considered as part of the leading car resistance.

The formula for train resistance of leading car is:

\[
R = 1.3 + \frac{2.9}{w} + 0.045V + \frac{0.0024 AV^2}{wn}
\]

For cars equipped with 2 bogie trucks of 2 axels \( n=4 \)

**Leading car train resistance in lbs./ton**

<table>
<thead>
<tr>
<th>Speed m.p.h.</th>
<th>Average weight of car in tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>5.8  5.3  4.9  4.6  4.4  4.1</td>
</tr>
<tr>
<td>40</td>
<td>6.9  6.3  5.9  5.5  5.2  4.9</td>
</tr>
<tr>
<td>45</td>
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</tr>
<tr>
<td>50</td>
<td>10.2 9.3  8.7  8.0  7.7  7.2</td>
</tr>
<tr>
<td>55</td>
<td>12.5 11.2 10.5 9.7  9.3  8.7</td>
</tr>
<tr>
<td>60</td>
<td>15.0 13.5 12.7 11.6 11.1 10.4</td>
</tr>
<tr>
<td>65</td>
<td>17.9 16.1 15.1 13.9 13.3 12.4</td>
</tr>
<tr>
<td>70</td>
<td>21.2 19.0 17.8 16.3 15.6 14.6</td>
</tr>
<tr>
<td>75</td>
<td>24.9 22.2 20.8 19.1 18.3 17.0</td>
</tr>
<tr>
<td>80</td>
<td>28.9 25.7 24.2 22.1 21.1 19.6</td>
</tr>
<tr>
<td>85</td>
<td>33.2 29.6 27.8 25.3 24.2 22.4</td>
</tr>
</tbody>
</table>
Multiple Unit Trailing Motor Car

This is the same as above except that it is not a leading car and does not include back end pressure.

Formula for trailing motor car train resistance is:

\[ R = 1.3 + \frac{2.2}{w} + 0.045 V + \frac{0.0034 AV^2}{wn} \]

For cars equipped with 2 bogie trucks of 2 axels.

<table>
<thead>
<tr>
<th>Speed m.p.h.</th>
<th>Average weight of cars in tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>40 45 50 55 60</td>
</tr>
<tr>
<td>10</td>
<td>5.2 4.7 4.4 4.1 3.9 3.7</td>
</tr>
<tr>
<td>15</td>
<td>5.5 5.1 4.7 4.5 4.2 4.0</td>
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<tr>
<td>20</td>
<td>5.9 5.5 5.1 4.8 4.6 4.4</td>
</tr>
<tr>
<td>25</td>
<td>6.4 5.9 5.5 5.2 5.0 4.8</td>
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<tr>
<td>30</td>
<td>6.9 6.4 6.0 5.6 5.4 5.2</td>
</tr>
<tr>
<td>35</td>
<td>7.4 6.9 6.5 6.1 5.8 5.6</td>
</tr>
<tr>
<td>40</td>
<td>8.1 7.4 7.0 6.6 6.3 6.1</td>
</tr>
<tr>
<td>45</td>
<td>8.7 8.0 7.6 7.2 6.9 6.6</td>
</tr>
<tr>
<td>50</td>
<td>9.4 8.7 8.2 7.8 7.4 7.0</td>
</tr>
<tr>
<td>55</td>
<td>10.2 9.4 8.9 8.4 8.0 7.6</td>
</tr>
<tr>
<td>60</td>
<td>11.0 10.1 9.6 9.0 8.7 8.3</td>
</tr>
</tbody>
</table>
Trailing Car (no motor)

In this case .03 V is taken for flange resistance. The air resistance coefficient referred to the cross-sectional area of the car and based on an average car length of 67 ft. is found to be .00034.

The formula in this case is given as:

\[ R = 1.3 + \frac{2.9}{w} + .03 V + \frac{.00034 AV^2}{wn} \]

2 axels per truck, double truck carriages (n = 4)

Trailing car (no motors) resistance in lbs./ton

<table>
<thead>
<tr>
<th>Speed m.p.h.</th>
<th>Average weight of cars in tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5.0  4.5  4.3  4.0  3.8  3.6</td>
</tr>
<tr>
<td>15</td>
<td>5.3  4.9  4.5  4.3  4.0  3.8</td>
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<td>20</td>
<td>5.7  5.2  4.8  4.6  4.3  4.1</td>
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<td>25</td>
<td>6.1  5.6  5.2  4.9  5.0  4.4</td>
</tr>
<tr>
<td>30</td>
<td>6.6  6.0  5.6  5.3  5.4  4.7</td>
</tr>
<tr>
<td>35</td>
<td>7.2  6.5  6.0  4.7  5.8  5.1</td>
</tr>
<tr>
<td>40</td>
<td>7.7  7.0  6.5  6.2  6.3  5.5</td>
</tr>
<tr>
<td>45</td>
<td>8.3  7.6  7.1  6.7  6.8  6.0</td>
</tr>
<tr>
<td>50</td>
<td>9.0  8.3  7.6  7.2  7.9  6.5</td>
</tr>
<tr>
<td>55</td>
<td>9.8  9.0  8.3  7.8  8.5  7.0</td>
</tr>
<tr>
<td>60</td>
<td>10.5 9.7  9.0  8.4  9.1  7.5</td>
</tr>
</tbody>
</table>
Train Resistance Curves

The curves on the following pages are a result of the plotting of the various values given by the Davis Speed resistance curves.

Curves on sheet one are plotted just as given.

Curves DT1 is a plot of Train Resistance against speed of the leading motor car of a multiple unit train. The car as will be noticed gives a very rapid rise of train resistance with the increase of speed. This is due to the fact that the head end wind resistance and also the tail end suction are included in this train resistance. The tail end resistance or suction should by right be placed on the last car of the train but to make matters simpler it is placed on the first car since it is easier to consider this as a lump resistance instead of two separate items. The rapid rise of the curve is as said before due to air resistance. This value varies or increases as a power between 2 and 3.

Curve DT2 is the result of the resistance speed plot for a trailing motor car of the multiple unit train. The difference between curves DT2 and DT1 is due to head end and tail suction resistance of the train. Curve DT2 is quasi flat but rises slightly. It appears to be almost a straight line. This is due to the fact that the bearing resistance increases only slightly with the speed and then as a almost straight line function.

Curve DT3 is the plot of train resistance against speed of a non-motor trailer car. It also is a straight line
Train Resistance Curve
10 Car Multiple Unit Train
Street and Local Track
Still air Standard Journal

Pounds Tractive Effort

Miles Per Hour

0  20  30  40  50  60
function parallel to DT2 but of a slightly lower value. This is due to the fact that the car is slightly lighter than the motor car.

Sheet II is the total train resistance multiple unit trains on straight level ground in still air. The trains are made up of 24, 28, 30, and 32 cars each. Each train is made up of double units consisting of one motor car and one trailer car permanently connected together.

The curves on sheet II were obtained from sheet I in the following manner:

Wt. of motor car train and load is 80 tons
Wt. of trailer car train and load is 60 tons
For a two car train, train resistance = 80 times (train resistance for head end motor car) + 60 times (train resistance for trailer no motor car)

For a 10 car train, TR = 80times (train resistance of head end car) + 5 times 60 times (train resistance for no motor trailer car) + 4 times 80 times train resistance of following motor car.

By calculating and plotting from curve and sheet I we get curve for 10 car train on sheet II.

Train resistance curves for any no. of cars may be plotted in the same way.
Characteristic Curves of the OE-700
1500/3000 Volt

Speed

Torque (ft-lb)

Current in Amps

0  80  160  240  320 A
Speed Time Calculation from Boston to Willington

Train to be made up of 10 cars - 5 motor cars and 5 trailers
Each car to have 4 motors.
Length of run = 7930 ft.
Equivalent grade = .15 percent
Average curvature = 1 degree

Train resistance (TR) given by curve II
Train resistance due to curve = .6 lbs. per ton \( (CR) \)
Train resistance due to grade = \( 20(.15) = 3 \) lbs. per ton \( (GR) \)

Wt. of motor car = 148,200 lbs.
Wt. of trailer car = 110,000 lbs.
Wt. of load = 140(80)(10) = 112,000 lbs.
80 men per car - average wt. of man = 180 lbs.
Total wt. of train = 1,291,000 lbs.
Total wt. of train and passengers = 1,403,000 lbs. = 701.5 tons

First part of speed time curve has constant acceleration until speed is reached which corresponds to the hourly current rating of 1 motor.

Acceleration desired = 1.5 miles per hour per sec.

\[ \text{TE for acceleration} = 1.5(701.5)(100) = 105,000 \text{ lbs.} \]

Total tractive effort = 105,300 + 3,300 = 108,300
Tractive effort per motor = 5415

Corresponding current for full field current = 229 amps

This is the hourly rating.

In this case hourly rating for one motor is 229 amps.

Corresponding speed is 32.8 miles per hour.
\[
\begin{align*}
TR & = 3250 = 3250 \\
GR & = 701.5(.6) = 421 \\
GR & = 701.5(3) = 2100 \\
\text{Total train resistance} & = 5771 \\
\text{Total tractive effort at } 32.8 \text{ m.p.h. for 20 motors} & = 20(5415) = 108,300 \text{ lbs.} \\
\text{Tractive effort for acceleration} & = 108,300 - 5,771 = 101,529 \\
\text{Acceleration} & = \frac{101,529}{701.5(100)} = 1.45 \text{ miles per hour per sec.} \\
\text{Time} & = \frac{32.8}{1.45} = 22.6 \text{ seconds} \\
\text{Distance} & = \frac{(22.6)(32.8)(5280)}{(2)(60)(60)} = 544 \text{ ft.} \\
\text{This gives the first point on the speed time curve.} \\
\text{Taking two mile increments.} \\
\text{New speed} & = 34.8 \text{ m.p.h.} \\
\text{New TTR} & = 421 + 2100 + 4700 = 7,221 \text{ lbs.} \\
\text{All resistances remain the same except TR which increases with the speed.} \\
\text{Corresponding TE} & = (4080)(20) = 81,600 \text{ lbs.} \\
\text{Tractive effort left for acceleration} & = 74,380 \text{ lbs.} \\
\text{Acceleration} & = \frac{74,380}{701.5(100)} = 1.06 \\
\text{Time} & = \frac{2}{1.06} = 1.89 \text{ seconds} \\
\text{Distance} & = (1.89)(34.8)(1.465) = 96.5 \text{ ft.}
\end{align*}
\]
Calculation is continued in this fashion until in this coasting, breaking, or free running is reached. Free running will not be reached on such short runs.

Free running is reached when TTR = TE and we get no acceleration.

Coasting:

A coasting period as the name implies is a period when the motors are shut off and the train is allowed to coast. Coasting cuts down the average speed but causes or results in a saving in electrical energy. It all depends on whether speed or electrical energy is more important, whether or not coasting will be used. Of course if speed of train exceeds 70 m.p.h. because of down grade or for some other reason the power will be shut off and the train will be allowed to coast.

Breaking:

Breaking in order to keep a high average speed will take place as fast as possible. This does not mean, however, that the train should decelerate with a deceleration as to cause discomfort or injury to the passengers. It is understood that for ordinary breaking, deceleration should not exceed 3 miles per hour per sec. A better value, however, and that used in this work is 1.7 miles per hour per sec.

Calculation of Breaking period: Breaking to take place at a deceleration of 1.75 miles per hour per sec.

\[
\text{Time for deceleration} = T = \frac{\text{Change in speed}}{1.75}
\]

Distance traveled = \( T(1.465) \text{(mean speed)} \)
The area under the speed time curve represents the distance covered. Of course this area does not always equal the distance between stations so some adjustments must be made to make them so. This may be done either by causing cut off to come earlier or change the rate deceleration. The area under the curve must equal the distance between stations within two hundred feet on a one mile run.
Sample Calculations of Speed Time Curves

Boston to East Somerville 1.5 miles

<table>
<thead>
<tr>
<th>Tractive effort</th>
<th>Train resistance</th>
<th>Grade + Curve Res.</th>
<th>TE</th>
<th>accel.</th>
<th>TE_{ac.}</th>
<th>accel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>108,300</td>
<td>3250</td>
<td>2520</td>
<td>102,529</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>81,600</td>
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<td>2520</td>
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<tr>
<td>60,000</td>
<td>4850</td>
<td>2520</td>
<td>52,629</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>5250</td>
<td>2520</td>
<td>32,290</td>
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<tr>
<td>29,000</td>
<td>5770</td>
<td>2520</td>
<td>20,710</td>
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</tr>
<tr>
<td>23,000</td>
<td>6200</td>
<td>2520</td>
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<tr>
<td>20,000</td>
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Breaking: -1.75

<table>
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<th>Mean Speed</th>
<th>Δ Time</th>
<th>Time</th>
<th>Δ Dist.</th>
<th>Dist.</th>
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<tbody>
<tr>
<td>ΔS</td>
<td>S</td>
<td>ΔT</td>
<td>T</td>
<td>ΔD</td>
<td>D</td>
</tr>
<tr>
<td>0 - 32.8</td>
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<td>22.6</td>
<td>544</td>
<td>540</td>
</tr>
<tr>
<td>32.8 - 34.8</td>
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<td>1.9</td>
<td>24.5</td>
<td>96.5</td>
<td>640.5</td>
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<td>34.8 - 38.8</td>
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<td>29.8</td>
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<td>909.5</td>
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<td>32.0</td>
<td>142.0</td>
<td>1310</td>
<td>7990</td>
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East Somerville to Edgeworth 2.3 miles

<table>
<thead>
<tr>
<th>Tractive effort</th>
<th>Train resistance</th>
<th>Grade + Curve Res.</th>
<th>TE</th>
<th>accel.</th>
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<tbody>
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<td>TE</td>
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<td>accel.</td>
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<th>Mean Speed</th>
<th>Δ Time</th>
<th>Time</th>
<th>Δ Dist.</th>
<th>Dist.</th>
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Speed Time Curve for 10 Car
Multiple Unit Train

Boston to East Somerville
Malden to Weyoming
15 Miles
Grade 2.15%
Curve 1°

Current Time Curve
Area = 6.01 Square Inches

\[ \frac{1 \text{ Square Inch}}{100} \times 3000 \times 5 = 1665 \text{ Kwh} \times k \]

\[ \text{Power Consumed} = k(6.01) \]
\[ = 16.55(6.01) \times 100 \text{ Kwh} \]
Greenwood to Wakefield

Mile = 1.4

l) reo = 6.05
KWH = 102.0
Speed Time Curve of Express Train
**Calculation of Express Run**

Boston to Andover 120,000 ft.

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*Braking*  

-1.75
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Speed Time Curve

Multiple Unit 10 Car Train

Average Station Stop = 20 sec.
Comparison of Electrified and Steam Systems

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Power Calculation of a 10 Car Train

The straight portion (beginning) of the speed time curve represents the control period. During the first half of this period the four motors on a car are in series and during the second half we have two sets of two motors in series, in parallel. Since, during this period each motor is carrying 228 amps it follows that during the first half of control each car is using 228 amps, while in the second period each car is using 456 amps. After free running is reached the current used per motor depends upon the speed. The current per car is obtained by multiplying current values, obtained from speed current curve, by two. It is convenient to plot a current time curve for each or one of the motor cars, on the same sheet as the speed time curve. These curves are shown in red one for each corresponding speed time curve. These curves not only show what current is being used at each instant but also give the energy consumed since the area under the current curve represents power when the voltage is constant.

\[
\text{Power} = \text{Area} \times 3000 \times K \text{ in kilowatt hours.}
\]

\[
\text{Area} = \text{area under the current curve in sq. inches measured with perlimeter.}
\]

\[
3000 = \text{Voltage of the system.}
\]

\[
K \text{ is a constant which is dependant on scale and units used.}
\]

In our case one sq. inch represented or 4000 amp seconds. Multiply this by 5 for a ten car train and we get our value of K used in formula.
The tabulated results on the previous page show as comparison in time and average speed of the steam and electric service. The superiority of the latter is at once obvious because of the high average speed. The values for the electric service were calculated from the speed time curve while the values for the steam service were calculated from the time tables.

The values for the local train were calculated from an average steam train. The values for the express run, however, were calculated from the fastest train over that section (steam).
Calculation of Resistances for Motor Control

In starting a D.C. motor such as used on the proposed electrification it is desirable to impress a low voltage across the terminals of the motor and increase it gradually with the speed until full voltage is supplied to the machines. The low starting voltage can be obtained best, by placing resistance in series with the line voltage. Then by cutting out a very little resistance at a time we get the desired gradual increase of voltage and thus have very smooth acceleration. However, there are two reasons why we cannot use this seemingly ideal system. First, the I^2R losses in the resistors are great and second, the great weight involved, if many contactors for small changes of resistance are used, is prohibitive.

A better method and, that used does away with the great contactor weight and heating loss. At low speeds, four motors are placed in series with a desired amount of resistance. The resistance need not be very high because the back e.m.f. of the four motors will tend to cut down the voltage across each motor. Resistance is then cut out in rather large steps until it is all removed (about 6 steps). The motors are then placed in two sets in parallel. One set having two motors in series. In series with the parallel arrangement is placed all the resistance as before. This resistance is cut out in steps as before. When all the resistance
is cut out the car is running free on the line, with two sets of motors in parallel. Of course it would be best to use two sets of resistances for series and parallel portions of control but again weight prohibits it. Instead by using convenient values of resistances and special switching arrangements very smooth acceleration can be obtained. The switching circuits are shown on page ... The general method of finding these values of resistance is as follows. First draw up a trial control diagram. Then from the voltage drops between steps and corresponding values of motor current we can calculate the changes in resistance. Then from the diagram of connections we calculate the resistance units on the car. Using these values of resistance a new or secondary control diagram is plotted. Readjustments are then made in the resistance values until the best or desired control diagram is obtained. Current values should not get too high.
Following example is calculation of resistances by this method:

2 Speed Control

1) All motors in series

2) Two motors in series

Total 4 motors 3000v.

2 in series permanently

Accelerating current = 185 amps

Internal resistance = .2236 ohms

Main field Resis. = .2518 ohms

Com. field Resis. = .0836 ohms

Total = .5560 ohms

IR drop in series control = (.556)(185) = 102.8 v.

Limits of series control current are 161 - 207 amps

\[
\frac{TE_a}{I_a} \frac{I_1}{EMF_1} = EMF_a
\]

\[
\frac{TE_a}{I_a} \frac{I_1}{TE_1} = \frac{4750}{3550} \times \frac{161}{207} = 1.05
\]

\[
V_a = (1.05)168 = 176.5
\]

\[
V_a = (1.05)300 = 315
\]

\[
V_a = (1.05)405 = 426
\]

\[
V_a = (1.05)490 = 515
\]

\[
V_a = (1.05)555 = 585
\]

\[
V_a = (1.05)615 = 646
\]
Voltage Drop between Steps for Series Control

\[ V_{18} = 176.5 \]
\[ V_{83} = 138.5 \]
\[ V_{34} = 111 \]
\[ V_{45} = 89 \]
\[ V_{56} = 70 \]
\[ V_{67} = 61 \]

<table>
<thead>
<tr>
<th>Resistance between steps</th>
<th>Total R per motor</th>
<th>Total R 4 motors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{18} = \frac{176.5}{207} ) = .852</td>
<td>3.149</td>
<td>12.60</td>
</tr>
<tr>
<td>( R_{83} = \frac{138.5}{207} ) = .669</td>
<td>2.291</td>
<td>9.6</td>
</tr>
<tr>
<td>( R_{34} = \frac{111}{207} ) = .536</td>
<td>1.628</td>
<td>6.52</td>
</tr>
<tr>
<td>( R_{45} = \frac{89}{207} ) = .43</td>
<td>1.092</td>
<td>4.36</td>
</tr>
<tr>
<td>( R_{56} = \frac{70}{207} ) = .338</td>
<td>.632</td>
<td>2.52</td>
</tr>
<tr>
<td>( R_{67} = \frac{61}{207} ) = .294</td>
<td>.294</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Parallel Control

IR drop in parallel control = 185(.556) = 102.8

Limits of parallel control = 161 - 212

\[ \frac{TE_2}{I_1} \frac{I_1}{TE_1} EMF_1 = EMF_2 \]

\[ \frac{TE_2}{I_1} \frac{I_1}{TE_1} = \frac{4890 \times 161}{3550 \times 212} = 1.05 \]
\[ V_2 = (1.05)660 = 695 \]
\[ V_3 = (1.05)870 = 915 \]
\[ V_4 = (1.05)1060 = 1115 \]
\[ V_5 = (1.05)1200 = 1260 \]
\[ V_6 = (1.05)1310 = 1380 \]

**Voltage Drop between Steps for Parallel Control**

\[ V_{18} = 695 - 646 = 49 \]
\[ V_{33} = 915 - 695 = 220 \]
\[ V_{44} = 1115 - 915 = 200 \]
\[ V_{45} = 1260 - 1115 = 145 \]
\[ V_{56} = 1380 - 1260 = 120 \]

<table>
<thead>
<tr>
<th>Resistance between Steps</th>
<th>Total R per mot.</th>
<th>Total R four mot.</th>
<th>Cal. R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ R_{18} = \frac{49}{212} = .231 ]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>[ R_{33} = \frac{220}{212} = 1.04 ]</td>
<td>3.235</td>
<td>6.46</td>
<td>6.52</td>
</tr>
<tr>
<td>[ R_{44} = \frac{200}{212} = .945 ]</td>
<td>2.195</td>
<td>2.195</td>
<td>2.09</td>
</tr>
<tr>
<td>[ R_{45} = \frac{145}{212} = .685 ]</td>
<td>1.250</td>
<td>1.25</td>
<td>1.51</td>
</tr>
<tr>
<td>[ R_{56} = \frac{120}{212} = .565 ]</td>
<td>.565</td>
<td>.56</td>
<td>.577</td>
</tr>
</tbody>
</table>
From Diagram of Connections

(2) \( R_6 = 1260 - 9.6 = 3 \) ohms

(3) \( R_1 = 9.6 - 6.52 = 3.08 \) ohms

(4) \( R_3 = 6.52 - 4.36 = 2.16 \) ohms

(5) \( R_4 = 4.36 - 2.52 = 1.84 \) ohms

(6) \( R_5 = 2.52 \) ohms

\[
\frac{1}{R_6} = \frac{1}{R_1 + R_2} + \frac{1}{R_3} + \frac{1}{R_4}
\]

\[
= \frac{1}{6.08} + \frac{1}{2.52} + \frac{1}{1.84} = \frac{4.56 + 11.19 + 1.53}{28.2}
\]

\( R_6 = \frac{28.2}{17.28} = 1.63 \)

\( R_7 = 0 \)

\( R_8 = 2.16 + 1.84 + 2.52 = 6.52 \) In one set of motors

\( = R_1 + R_5 = 3 + 3.08 = 6.08 \) ohms

\[
\frac{1}{R_9} = \frac{1}{R_1} + \frac{1}{R_3 + R_4 + R_6}
\]

\[
= \frac{1}{3.08} + \frac{1}{6.52} = \frac{6.5 + 3.08}{20.1} = \frac{9.58}{20.1}
\]

\( R_9 = \frac{20.1}{9.58} = 2.09 \)

\[
\frac{1}{R_{10}} = \frac{1}{R_1} + \frac{1}{R_6}
\]

\[
= \frac{1}{3.08} + \frac{1}{2.52} = \frac{2.5 + 3.08}{7.75} = \frac{5.13}{7.75}
\]

\( R_{10} = \frac{7.75}{5.13} = 1.51 \)
\[
\frac{1}{R_{11}} = \frac{1}{R_1} + \frac{1}{R_3} + \frac{1}{R_5} + \frac{1}{R_4}
\]
\[
= \frac{1}{3.08} + \frac{1}{2.16} + \frac{1}{2.52} + \frac{1}{1.84}
\]
\[
= \frac{10 + 14.3 + 12.5 + 16.8}{30.9} = \frac{53.6}{30.9}
\]
\[
R_{11} = \frac{30.9}{53.6} = .577
\]

Changing to new current limits

Changing \(R_{10}\)

\[
151 + 125 = 276
\]
\[
\frac{276}{2} = 1.38 \text{ Average } R
\]

\[
\frac{1}{R_{10}} = \frac{1}{R_1} + \frac{1}{R_5}
\]
\[
\frac{1}{R_{10}} = \frac{1}{1.38} + \frac{1}{2.52} = \frac{2.52 - 1.38}{3.48}
\]
\[
R_{10} = \frac{3.48}{1.14} = 3.05
\]
\[
R_1 = 3.05
\]
\[
R_1 = 3.05 + 3 + 2.16 + 1.84 + 2.52 = 12.57
\]
\[
R_2 = 3.05 + 2.16 + 1.84 + 2.52 = 9.57
\]
\[
R_3 = 6.52 \text{ (Same as before)}
\]
\[
R_4 = 4.36 \text{ (Same as before)}
\]
\[
R_5 = 2.52 \text{ (Same as before)}
\]
\[
\frac{1}{R_0} = \frac{1}{R_1 + R_2} + \frac{1}{R_3} + \frac{1}{R_4}
\]
\[
= \frac{1}{6.05} + \frac{1}{2.52} + \frac{1}{1.84} = \frac{4.62 + 11.1 + 1.52}{28}
\]
\[
R_0 = \frac{28}{17.24} = -1.62
\]

\[R_7 = 0\]

\[R_9 = 2.16 + 1.84 + 2.52 = 6.52\]

\[= R_1 + R_2 = 3.05 + 3 = 6.05\]

\[
\frac{1}{R_9} = \frac{1}{3.05} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_6}
\]
\[
= \frac{1}{3.05} + \frac{1}{6.52} = \frac{9.57}{19.9}
\]
\[
R_9 = \frac{19.9}{9.57} = 2.08
\]

\[
\frac{1}{R_{10}} = \frac{1}{3.05} + \frac{1}{2.52} = \frac{5.57}{7.7}
\]
\[
R_{10} = \frac{7.7}{5.57} = 1.38 \text{ ohms}
\]

\[
\frac{1}{R_{11}} = \frac{1}{3.05} + \frac{1}{2.16} = \frac{3.05 + 2.16}{6.6} = \frac{5.21}{6.6}
\]
\[
R_{11} = \frac{6.6}{5.21} = 1.26
\]

**Corrected Values**

\[R_1 = 12.57\]
\[R_7 = 0\]
\[R_9 = 9.57\]
\[R_6 = 6.05\]
\[R_9 = 6.52\]
\[R_6 = 2.08\]
\[R_4 = 4.36\]
\[R_{10} = 1.38\]
\[R_6 = 2.52\]
\[R_{11} = 1.26\]
\[R_6 = 1.52\]
\[R_{12} = 0\]
Car Equipment

In selecting car equipment there are many things which must be considered. First probably is the size of the car. This is determined by the traffic requirements and the weight of car that the rails can support.

In considering the size of car on the Boston and Maine, a number of things enter which are slightly different from those of any other service. The main traffic is of commuters travelling back and forth from various points between Boston and Haverhill. This means that the cars will hardly ever have a chance to refill. Also, most of the traffic occurs in the morning from 6 to 10 and in the evening from 5 to 9. During the remaining hours traffic is slow and almost any size car would do.

In arranging seats, it is necessary to study the type of service. Longitudinal seats certainly make entrance and exit much easier and also provide more room and greater comfort for those standing. In traffic this is of very great importance as it cuts down the time of stops and so aids in maintaining as high a schedule speed as possible. However, for long rides the horizontal seats are much more comfortable and provide more room for seats. Since the service in question is quite heavily populated, during rush hours, and the ride is quite a long one, a combination of the two seating plans should be used. Near the doors the seats would be arranged longitudinally to facilitate ingress and egress of
passengers. Then in the space between doors, horizontal seats would be used, so that the passengers riding the full length would ride in comfort.

The motor equipment has already been determined as consisting of four 235 H.P. motors.

(Truck, driving wheels, trailer wheels, truck bolster at no load the motors are capable of driving the cars at a maximum speed of 70 m.p.h. Motor and trailer car semi-permanently coupled together.)

The cars are all to be multiple unit all steel construction. This means that a train of cars can all be controlled from a single controller in any of the cars, usually from the front of the train. Therefore each car with its trailer can operate singly or in groups of as many cars as desired. Cut out switches will be installed in each car controller so that in the case of a breakdown in any motor, that motor may be cut out of the line and operation continue, using the other motors. The reversing of the train can be done by the motorman simply by throwing the reversing handle provided the controller is in the proper position.

The multiple unit operation has many advantages among which are the following:

1. Each car and its trailer makes a complete unit; trains may be made up of any number of units and be operated as one unit from the driving cab of one of the units.

2. The adjustment of train capacity throughout the day to suit the requirements of traffic is made by adding or
subtracting cars.

3. No switching at the terminals is necessary, it being only necessary for the motorman to walk from one end of the train to the other to reverse the direction of travel. This increases the station capacity and reduces train and signal movements.

4. Uniform schedule speed can be obtained regardless of size of train since each car can pull its own load and close headway is made practical.

5. Cost of motive power is made proportional to the paying load by adapting the capacity of the train to the traffic demands.

6. The weight is evenly distributed over the entire train instead of having a concentrated load at the locomotive.

Motors

Owing to the fact that so successful and gratifying were the results of the motors used on the Lackawanna electrification, that we have decided to use the same type on the proposed electrification. Special endurance tests were made by the Lackawanna engineers to determine whether the equipment would stand up under continuous severe service conditions and was carried on day and night, with time off only for the train crews to eat their meals. The entire 10,600 were completed in one calendar month. The test was made on a three-mile-track with an engineer on each end of the unit so that no time was lost in reversing the train. The average speed obtained under these conditions over the test track used was 30.7 miles per
hour. The unit often made as high as 600 miles per day. As a result of these tests it was found that the most economical acceleration rate from the standpoint of energy consumption and motor heating was approximately 1.5 m.p.h.p.sec. The average breaking rate adopted was 1.75 m.p.h.p.sec.

The motor to be used has many advantages over the regular series type used for traction purposes. It is much lighter in weight and smaller in size for its rated output, taking into consideration that it is a 1500 volt machine designed to operate two in series on 3000 volt direct current. It is a self ventilated motor with good stability and commutating characteristics.

The motor is made by the General Electric Co. and is known as the G.E. 700 - 1500/3000 volt. It has a continuous rating of 91 amps at 1500 volt with fields shunted 50 percent with a temperature rise not exceeding 105 deg. Cent. It has a one hour rating of 130 amps at 1500 volts with fields shunted 50 percent without exceeding a temperature rise of 120 deg. Cent. About 200 cu. ft. of air per minute is drawn through the motors at the continuous rating.

The following data apply to these motors (G.E. Review)

Gear ratio - 59:22 = 2.68

Maximum permissible accelerating current, full field 450 amps.

Acceleration rate - 1.5 m.p.h. per sec.

Maximum permissible armature speed - 1800 r.p.m.

(Corresponding car speed with 35 in. dia. wheels

70 m.p.h.)
Gear: 89 Teeth
Reduction: 2.681
Wheel Diam.: 38"
Resistance of complete motor (full field) 75 deg. C. - 0.544 ohms.

Weight of motor alone - 6000 lb.

Weight of motor with gear and pinion and gear case - 6600 lb.

Number of brush holder studs - 4

Number of brushes per stud - 1 (23/4 in. by 5/8 in.) or 2 (1 3/8 in. by 5/8 in.).

**Motor Ventilation**

The use of these high tension traction motors made the air supply for cooling these motors an important consideration.

From available test data it was found that practically all of the dirt, dust and snow caused by the movement of the car was below the window sills. It was therefore decided by the Lackawanna engineers that the air taken above this point would be practically clean. Air ducts were installed, with buffers and louvers in a compartment above the vestibule. A flexible air duct connects the car duct to the inlet of the motor. The motor is self ventilated, a fan on the armature draws the air through the duct system and inlet of the motor, which is on the commutator end of the motor. Air is drawn in through the armature inside of the commutator and forced over the field coils and armature to an outlet at the commutator end.
Auxiliaries

One of the most important features of railroad work of all kinds is an efficient braking scheme especially where trains cross public streets, does braking become of paramount importance.

In almost all electric traction air braking has been adopted as a standard because of its high and speedy braking power.

To bring a train to a stop some retarding force must be exerted on the wheels and also some body must be provided to carry away the heat generated when the retarding force acts on the wheels. This is most commonly done by having brake shoes which are of the form of an arc of a circle, putting the circumference of the wheel, pressed tightly against the wheel and retarding it.

Since the control equipment has already used compressed air in its operation, it is only proper that air be used for braking on our system.

On present day systems the automatic air brake system consists essentially of a source of compressed air, in this case a compressor; a reservoir which receives the air is maintained at constant pressure by means of a governor which automatically controls the operation of the compressor; a brake cylinder, the piston of which is connected to a system of brake levers in such a way that when the piston is forced outward by air pressure the brakes are applied. An operating valve in each car which controls the admission and release of
air pressure to the brake cylinder. In order to prevent excessive pressure accumulating, a safety valve is usually installed which operates at about 100 lbs. An emergency valve is always furnished which insures the quickest possible action in case of an emergency. This valve lets all the air in the cylinder escape in all the cars, braking being very quick and sharp.

The air brakes are interlocked with the master controller. In case the engineer removes his hand from the controller handle, the power will be shut off and an emergency application of the train brakes becomes effective. If at any time the electric power connection between cars is broken, the brakes will function purely pneumatically in this case of emergency. In conjunction with the air brakes, the doors will also be electro-pneumatically operated, controlled by the conductors button. A good scheme in connection with the doors is an interlocking system so arranged that when the doors are open in any of the cars the motors cannot operate and set the train in motion. The control of the doors is arranged that the doors of two cars can be controlled from one.

All the large apparatus which is required for control will be located under the car, as the air compressor, tanks, rheostats, etc.

**Electric Car Heaters**

Individual electric heaters under each seat shall be installed in preference to one large unit and blower under
each. It has been found that such individual units are more efficient, and more economical to install.

The heating units consist of two "U" type General Electric heater elements, and assembled by the Consolidated Car Heating Company, each element connected to a separate circuit. The heating element is wound with nichrome resistance wire placed in an iron tube and insulated from it with magnesium oxide. Fins are welded onto this tube to radiate the heat. Each heater circuit of 700 watts is controlled by a small contactor and thermostat.

The heating elements are placed directly underneath each seat and protected by a metal covering so that it is practically impossible for anyone to insert anything and come in contact with the element.

**Car Lighting**

A 300 ampere hour capacity 16 cell, 32 volt storage battery will be used for car lighting, headlights and control. This battery is charged by the generator forming part of the humidifying system. A push-button compartment control switch is provided and mounted in the cab, for the control of the car lighting circuits, dim and bright headlights, and vestibule lights.
Motor Controller Showing Motor
Cutout Switches, Air Engine, Cam Shaft

Main Line Breaker Showing Main Contacts Blowout Coils

Auxiliary Contactor Box
Substations

A substation is a station which contains devices which serve to alter the voltage or character of the current received from the transmission system and then deliver it through feeders the desired power to the distribution system. Substations, depending on the method used to operate them, may be divided into three classes: manual, semi-automatic, and automatic.

Regardless of its type, a substation must be a reliable source of power supply. It is considered reliable if it permits the maintenance of satisfactory train schedule. If the manually operated substation is taken as a measure of reliability, then additional expense of automatic substations must be justified by economy. In a system of manually operated substations attendants, of course, are necessary.

Unattended substations may be classified as either semi-automatic or automatic. The semi-automatic is one which is started manually and runs until shut down, according to some schedule, by one of a number of different methods. These methods may be a time switch, momentary interruption of an A.C. supply or by an attendant who enters the substation for that purpose. Since the semi-automatic is only attended during starting and possibly the shutting down period, it must be equipped with all of the protective devices such as are included in full automatic substation equipment.
General D.C. System Diagram

Showing Position of Rectifier Substation

Horizontal Scale
1" = 4 miles
Since the station runs continuously during its schedule period of operation, there will be no saving in light load losses such as would be affected by full automatic equipment. Load requirements may be such as to make this item negligible. The item of attendance is not entirely eliminated, and comparison shows that the additional equipment required for full automatic control is such that the attendance item will quite probably exceed the fixed charge on the additional investment.

The automatic substation eliminates the item of attendance and, therefore, makes possible to operate a number of stations with but little thought of that item. By dividing the system into small blocks, each to be supplied from a substation located at the load center of the block, we do away with the necessity of the great amount of feeder copper which is now required.

**General Description**

The automatic substation consists of an assemblage of contactors, relays, and other devices, especially adapted to automatic control features. This equipment with the master controller performs the usual function of starting, shutting down and fully protecting the substation, entirely independent of manual operation.

The automatic substation is usually started by a load demand on that part of the system within its particular district. This is accomplished by a voltage relay. The stopping indication is given by the operation of an underload
Simplified Wiring Diagram of Typical Substation.
relay when the load diminishes to an uneconomical point. Starting and stopping of the stations may also be accomplished by means of several remote control systems.

The station is amply protected by devices which perform the following functions:

(1) Start the rectifier when demand exists, or by supervisory control.
(2) Protect apparatus against injury during starting.
(3) Connect rectifier to substation bus.
(4) Protect rectifier against injury due to any cause while running.
(5) Shut down when demand ceases or when supervisory control indicates.

Automatic control also includes control of feeders, breaking contacts at overload and restoring when condition has been remedied. Also, all protective devices are automatically controlled.

**Supervisory Control**

Experience in the operation of automatic substations, particularly in metropolitan service has shown the necessity of some form of supervisory control. One system now in operation provides the facilities at a central substation for the supervisory control of all rectifiers and both A.C. and D.C. feeders at each substation. This control is superimposed over full automatic equipment so that independent of supervisory control, all functions are automatic.
RECTIFIER and FEEDER CONNECTIONS
By means of this system any rectifier may be started or stopped and any high tension circuit breaker may be opened or closed.

Inspection of the indicating panel in the load dispatcher's office gives a visible indication of the operating status of all rectifier and feeder circuits. In addition to these indications the load dispatcher has before him a continuous indicating and graphic record of the total load at each station. This is done by a system of remote meter indication.

The visual supervisory control is an all relay system, embodying the principle of step by step synchronous selection. The control keys and signalling lamps are located in the dispatcher's office. At the substation there are a number of interposing relays which serve to relay the signals from the relays to the power equipment.

**Manual Rectifier Control**

To start the rectifier the operator closes a switch and starts the ignition circuit. An arc is struck by the anode which is plunged into the cathode pool of mercury and is then withdrawn. This arc is transferred to the operating anodes and is maintained while the rectifier is in operation. When the arc is once established the rectifier oil circuit breaker is closed, and in turn automatically closes the negative circuit breaker. The positive breaker is then closed by hand connecting the rectifier to the bus.
Main Transformer 3φ Primary

Main Transformer 3φ Secondary

Interphase Transformer
Third Harmonic
Sixth Harmonic
Balancing Reactor
D.C. Smoothing Reactor
Negative Breaker and Resistance
Compounding Equipment
Capacitors Reactors
Negative Bus

Rectifier Transformer Circuit
A constant check of the equipment is maintained by means of protective relays. If the rectifier gets too hot or too cold, if the cooling water stops, or the vacuum is not sufficient, an alarm is given by indicating lights and bell, very similar to automatic control.

Method of Control

In case a dispatcher desires a central unit, he operates a key associated with the apparatus unit desired and operates a start key. The selector relays pull up in regular sequence with both equipments in exact synchronism, until the operated key is reached. The two signalling wires are thus connected to the key of the dispatcher's office and to the desired apparatus unit at the distant station. Operating current passes from the key through its associated selector relay to the signalling circuit. At the substation this current flows from the signalling circuit to the desired apparatus unit through its associated selector and interposing relays. The desired operation having been accomplished, the auxiliary contact on the apparatus units transmit a signal through the same selector relays and the signalling circuit to operate the lamps on the dispatcher's desk. The receipt of the correct answer releases the selector relays which continue to operate in synchronism until all have been pulled up and released. The equipment then comes to rest and remains at rest until needed to operate again.
A trunk line of four wires is used between the dispatcher's office and the distant station. By means of two of these wires and a synchronous circuit, selecting relays are kept in step and moved from point to point in definite sequence: that is, corresponding relays are operated simultaneously at the dispatcher's office and substation. The remaining two wires of the trunk line are switched, by the operation of these relays, from one apparatus control to another. The apparatus units at the substation are connected to a set of selecting relays and the dispatcher's control keys and supervisory signalling lamps are connected to a similar set.

There is no counting of impulses, no checking back of circuits, and no totalizing of impulse necessary. The selecting relays must operate in absolute synchronism at every step or not at all. In the latter case proper alarm signals notify the dispatchers should the system cease to function.

Direct Current Power

Power supply for the proposed electrification, is to be supplied from two substations, located at Greenwood and Shawsheen. Mercury arc rectifiers will be used exclusively for the conversion of A.C. power to 3000 volts D.C. for traction purposes.

Since the line is 33 miles long, two substations, one about 8.2 miles from Boston and the other 8.5 miles from Haverhill, will give suitable distribution of load.
In the system designed to distribute this power to the electrically operated trains, economy of first cost and operating maintenance, as well as reliability of operation and simplicity of detail, were the leading points receiving consideration.

At each substation of the railroad company 60 cycles, 3 phase, 66 kv. power is delivered through suitable circuit breakers and the secondary winding of the transformer. In laying out the substations for this electrification system, provision is to be made, both in size of the building and the arrangement of the immediate equipment, for the future units which can be installed when the load becomes excessive on the present equipment.

The substations themselves are to be large and roomy. They are to be constructed of red birch. Each substation has one large ventilator on the roof.

Rectifiers

Mercury arc rectifiers were selected because of their higher efficiency as compared with motor-generator sets, particularly at light loads, and their high overload capacity under unusual condition. Because of their small size and low weight, there was a considerable saving in substation construction, which was another contributing factor in their selection. A typical layout of the apparatus is shown in the following figure and is identical with the standardized layout used on the Delaware and Lackawanna Railroad. The use
Comparative Efficiencies, 3000 kw Mercury Arc Rectifiers and Motor Generator Sets (both including transformers)
of 12-phase connections provides a very smooth D.C. output, thus minimizing the amount of smoothing and filtering equipment to remove undesirable harmonics from the D.C. output.

Tests made with these rectifiers showed satisfactory performance under all conditions. Overloads of 50 percent for two hours, 200 percent for five minutes and 500 percent for fifteen seconds were carried. By a corresponding scheme practically flat voltage characteristics are obtained up to 150 percent load. Smoothing reactors are used to smooth out the voltage and current curves. Resonant shunts are also provided to eliminate harmonics which would cause disturbance on telephone and other communication circuits. The power factor is practically unity at full load and overloads. Water cooling with forced circulation and subsequent fan cooled radiator is new and novel in rectifier design. The positive bus of the rectifier is connected to the overload system. The tank and some of its auxiliary equipment is therefore at a potential of 3000 volts to ground. For safety purposes the rectifiers and auxiliary equipment are surrounded by a wire fence as shown in the enclosed figure.

If for any reason the arc blows out, surge eliminators are installed to take care of any high voltages induced in the transformer winding, and are connected across each leg of the main power transformer.
There are four resonant shunts tuned to frequencies of 360, 720, 1080, and 1440 respectively. These shunts are placed across 3000 volt positive and negative busses through a single pole double throw switch. The switch is in one position to energize the resonant shunt and to discharge it through the negative bus in the other position. There is also provided a 3000 ohm resistance connected across the resonant shunt group series to drain off the condenser charge.

Individual cooling equipment is installed close by each rectifier, consisting of a water storage tank and fan cooled radiator and are mounted on insulators. A short length of hose is used connecting the cooling equipment to the rectifier, to facilitate removal of tank, and ease of installation.

A water circulating pump is associated with each cooling equipment and operates continuously to supply water to the rectifier. The circulation of water is controlled by a thermostatic valve which controls the temperature within desired limits. The operation of the fan is automatic and is operated intermittently as required.

**High-Speed Circuit Breakers**

High speed circuit breakers are used for feeds to the catenaries. These are of air break, arc chute, magnetic blow-out type which close against a spring under solenoid control and with an opposing winding for accelerated opening under overload. The breakers are designed to open under short circuits before heavy short circuit currents can build up.
Each unit has also a high speed circuit breaker inserted in the negative bus adjusted to open on heavy short circuits. A resistor is placed across the breaker, so as to limit the current to about full load when a short circuit occurs.

These circuit breakers are adjusted to open automatically at a current lower than the negative circuit breaker, and also upon the rate at which the current is increasing. The circuit breaker can therefore be opened by the rate of rise as well as the magnitude of the current. They are designed to operate with a maximum rate of rise of three millions amperes per second, with an open circuit voltage of 3000 volts D.C. and a steady state current of 60,000 amps.

In case of arc back, the positive breakers, open very quickly when the current is reversed, to prevent power being fed into the rectifier which is arcing back from the catenary system. At the same time this arc back causes a short circuit on the power transformer. The oil circuit breaker supplying the transformer is made to open by the operation of the overload relays.

Suitable protection from mechanical injury and dust is provided by enclosing the breaker by transite board. A slit is provided where a handle can be inserted to operate the breaker.

**Switching Equipment**

All disconnecting switches are mounted in a cell
structure, and so constructed to close all openings and housing all the buses. The arrangement of these compartments is designed to eliminate all exposed grounded metal. A main and auxiliary bus is provided. The auxiliary bus can take the place of the main bus, by transferring the current through a transfer circuit breaker, for the purpose of maintenance of the main bus and of the feeder circuit breaker.

In addition to the indicating lamps in the dispatcher's office, there is on each circuit breaker a red and green indicating lamp. These are provided as a means of checking the position of the circuit breaker, before operating the disconnecting switches. The disconnecting switches are operated manually, while the circuit breakers can be operated manually, or from the dispatcher's office.

Outgoing circuits are carried in conduit and provided with line disconnecting switches, which may be used to clear the cell structure of all line parts, for maintenance purpose.
Plan of Typical Substation
Power Supply

With the electrification of the railway will follow the necessity of obtaining power to run the motors. Two methods are found available to obtain the necessary power.

(1) Construct and operate a new power house.
(2) Purchase power from a public utility company.

If a power house were to be constructed it would involve the purchase of property on which to erect such a plant. This in itself is quite an expense. Further than that, the construction of the building and the equipping of it would necessitate a large expenditure. Then there would also be a question if the railway could generate power at such a cost as to make the station pay for itself.

On the other hand, if power is bought from a public utility company no further construction is necessary on the part of the railway. It then pays only for the power it uses. The power company assumes all the responsibility of continuity of service and for the upkeep and repair of machinery, etc.

The progress of power generation (as will be shown later) is certainly in the direction of large centralized power plants. This is in line with the conservation of our natural resources, and a plan to link these large plants through a transcontinental transmission system. Such development naturally means greater efficiency of power generation and distribution with natural results of cheaper power.

Why then should the railroad company be bothered
with the operation of relatively small and inefficient power plants when their real business and only source of income is transportation? Would it not be better and perhaps cheaper to buy power from the central station and supply power to the cars from substations so located over the system as to give the best operating conditions?

It is our opinion that power should be bought, and not generated by the railroad company, since the section to be electrified is in a territory well supplied with existing generating and transmission facilities. This would be best for the railroad company as it relieves them of power production and transmission on a large scale.

After a thorough investigation of this matter we have decided to purchase power from the New England Power Company, whose lines run almost parallel to the road.

The system chosen will include two substations conviently located as shown in the following diagram. Each substation will be supplied by a separate 60 cycle, 6600 volt, three phase power. This method of power supply is a distinct advantage in reducing the likelihood failure at both substations. This is particularly important, since a failure of both stations would cripple the entire signal system, and thereby interrupt not only the electrified track but the through steam traffic as well.

**Character of Load**

The electrification of this road is primarily for
passenger service. The commuting service shows that the power requirements occur in two peaks 7:00 to 9:00 A.M. and 4:30 to 7:30 P.M. The bulk of the traffic on the Boston and Maine moves in one direction, southward in the morning and northward in the evening. This will place a high short time demand on the substation, but they are equipped with high overload capacity, the load curves of the substations will be very irregular.

The direct current system and rectifiers for the conversion of power for traction purposes were adopted because of the flexibility in use with different power supplies. There is no phase relation between substations so that there will be no necessity for high tension alternating current lines connecting them. Each substation will take balanced three phase power at practically unity power factor. The use of rectifiers prevents the supply of short circuit current from the traction system into the alternating current power system.

With the completion of The Fifteen Mile Falls power development, there will be more than ample power supply for the proposed electrification, and has the following electrical equipment:

Generators and Exciters by Westinghouse Electric & Manufacturing Company

4 -- 39,000 kv-a., 138.5 5.p.m., 13,800 v., 3 phase, 60 cycle, vertical generators.
4 -- 210 kw., 138.5 r.p.m., 250v., direct connected exciters.

4 -- 25 kw., 138.5 r.p.m., 250 v., direct connected pilot exciters.

Main Power Transformers by General Electric Co.

14 -- 13,000 kv-amp., 13,400-230,000 v., single phase, outdoor, water cooled transformers.

Oil Circuit Breakers by General Electric Co.

7 -- 230,000 v., 3 pole, single throw, electrically operated, oil circuit breakers.

Disconnecting Switches by Electric Power Equipment Company

22 -- 230,000 v., 3 pole, single throw, motor operated, disconnecting switches.

Voltage Regulation

The requirements for good voltage regulation are more severe than is frequently the case in a railroad electrification utilizing D.C. traction power because of the use of mercury arc rectifiers.

The generated voltage is to be kept constant by means of a rheostatic face plate control. It regulates the generator voltage by changing the resistance in the generator field circuit (the exciter voltage remaining constant). This type differs fundamentally from the vibrating type of regulator in that the vibrator type regulates the exciter voltage.
The rheostatic type has a motor operated face plate rheostat. This makes possible a high speed operation of the rheostat. The motor of this rheostat is controlled by two reversing contactor switches. These contactor switches are in turn controlled by the main contacts of the control element of the regulator. The main contacts are primarily controlled by the A.C. coil of the control element.

When the regulator resistance is set for a definite A.C. voltage the regulator remains in equilibrium as long as the voltage does not vary. As soon as the voltage varies the excitation of an A.C. coil in the output side of the generator varies accordingly. This A.C. coil controls an electromagnet which connects the two reversing contactor switches. If the voltage falls, the excitation decreases, causing the coil to cause the electromagnet core to drop. This energizes the reversing contactor switch which controls the motor, causing it to cut out resistance which increases the field, and hence raises the voltage again. Thus the voltage sent out over the transmission line is fairly constant.
Signal System

Railway signaling may be said to be the art of regulating train movements by means of indications by visual signals of fixed locations placed along the roadway. Its function is to prevent loss of life or property from collision or derailment and to save time and money by minimizing congestion and assuring the usage of track to its maximum capacity.

In practice, semaphores of various forms are generally used in connection with various colored lamps. In this type an arm, having round glasses is pivoted about a horizontal axis so that it may be moved either manually or by power, from a horizontal position to an inclined or vertical position in order to indicate the various conditions, affecting the movement of trains. All the signals are provided with lamps for use at night. With semaphore signals a lamp is provided for each arm and is so placed that as the arm moves to its various positions, the different colored glasses will move in front of the light, displaying the various colors.

The American Electric Railway Association's Committee on block signals has recommended as the preferred type of signals for electric roads, a semaphore having in the upper lefthand quadrant as viewed from an approaching train; the arm in horizontal position indicating "stop" in the inclined position (45° upward) indicating "caution" and the arm in vertical position indicating "proceed".
The usual type of automatic signal is the electric motor semaphore. The blade is pivoted near the top of a post along the road or attached to the catenary structures, the shaft to which it is connected carrying a crank connected to the "up" and "down" rod which is tubular. The lower part of this rod is connected to the mechanism proper, consisting of an electric motor and gearing by means of which the motor transmits motion to the "up" and "down" rod. A mechanism called a "slot" consisting of a magnet and latch is so arranged that if the magnet is energized to the motion of the motor is transmitted to the rod, raising the signal to clear position. By slightly decreasing the energy the rod is lowered to the "caution" position and totally de-energizing the magnet causes the rod to fall through force of gravity to the horizontal position indicating "stop".

The magnet is energized by means of the track circuit. The track circuit is defined as a path for an electric current formed by both rails of a known length, the ends of the rails are electrically separated from adjacent rails, a source of potential between the rails and one or more relays so arranged in the circuit so as to respond to variations in the potential difference between the rails produced by the train action on them. Thus when a train enters a block it energizes a relay which energizes the motor that controls the semaphore arm.

Under steam operation, the D.C. system of automatic block signalling is being used on the Haverhill line. Besides this, however, there has been signal control towers at North
AIR CONDITIONING EQUIPMENT

There are many divergent ideas of just what is meant by the term air conditioning. In general, it may be said that air conditioning embraces the artificial regulation of the atmosphere of an enclosed space involving control of temperature, humidity, volume of circulated air, movement and purity.

Experience and extensive tests have proved conclusively that comfort can be vastly improved in the summer time by lowering both the temperature and the humidity of the atmosphere, and that coupled with this reduction, there should be movement of air. Conversely, during the winter months the temperature and humidity usually should be increased.

The essential apparatus for the practical air conditioning of a passenger car comprises the following:

1. The air circulating system consisting of make-up air inlets, circulating air inlets, ducts, outlets, regulating equipment and motor-driven ventilating fans.

2. Air cleaning equipment usually consisting of some form of dry filter.

3. Cooling coils used for reducing the temperature of the circulating air, and at the same time condensing a portion of the moisture from this circulated air to accomplish dehumidification.
4. Refrigerating unit consisting primarily of a motor-driven compressor and a condensing radiator. The primary purpose of this unit is to pump heat out of the interior of the car and deliver it to the outside atmosphere. In other words, this unit is the heart of the system, as will be explained later.

5. Steam heating coils for increasing the air temperature in the winter.

6. Humidifying arrangement for increasing the moisture content of the air in winter.

7. A power supply for each individual car of the train.

At first glance the above items present quite a formidable array of equipment. Suffice to say, however, that all of this equipment can be readily combined into three compact factory-assembled units consisting of:

1. The air conditioning unit.
2. The refrigerating unit.
3. The axle generator unit.

These, together with the necessary control apparatus arranged for mounting in standard railway control cabinets constitute all that is required.

In the air conditioning unit are assembled apparatus necessary to cool, dehumidify, heat, humidify, and circulate the air in the car. Air filters for cleaning of the air are
usually supplied by the railroad. This unit is normally mounted under the roof of the car, and is arranged to circulate the air in the car through the medium of ducts, or by direct circulation as the railroad may elect.

In the refrigerating unit is combined the apparatus necessary for compressing the refrigerant, removing the absorbed heat energy from the system, and storing the surplus supply of refrigerant. This unit is suspended from the underside of the car floor with its front side practically flush with the car side-sheets. Its dimensions are such that it comes within the clearance diagram of any Class I railroad in the United States. The construction conforms to the most modern accepted railroad practice from the standpoint of light weight commensurate with adequate ruggedness, compactness, and ready accessibility for inspection and repair.

The axle generator is of 15 kw. capacity, which is sufficient to supply power for the air conditioning equipment, the lighting system and the car batteries. It is supplied complete with gear drive, and its dimensions are such that it is readily applicable to any standard two-axle or three-axle railway truck, and can easily clear any car center sill.

Construction

Air conditioning unit is completely assembled at the factory ready for application to the car. Each unit consists of the following component parts:
1 - Set of direct expansion cooling coils.
1 - Set of steam heating coils.
1 - Humidification equipment.
1 - Set of capillary tubes (for refrigerant expansion)
1 - Refrigerant strainer.
1 - Drain pan.

This assembly of equipment is so arranged that both the make-up air and the re-circulated air enters the unit at the rear and is passed over the cooling coils, heating coils and humidification equipment. It is then delivered by the blowers to the ducts or outlet grills as desired. An addition of approximately 25 percent make-up air is recommended as conforming to best modern practice and the design of the units is based on taking care of this condition.

For summer operation the air passing through the unit is not only cooled, but is also partially dehumidified. The cooling coils are so proportioned that their temperature is held slightly above the frost point. The result is that as the warm air comes in contact with the cold tube surfaces it is chilled below its dew point and gives up a portion of its water.

In the winter time the steam heating coils and humidifying equipment are brought into action and the air instead of being cooled and dehumidified is warmed and has moisture added to it. The temperature of the air being warmed by the steam coils is under the control of a thermostat. As the air passes through the unit, water is added to the air in sufficient amount to increase the moisture content and the air is then
distributed to the car in the same manner as for summer operation. As under summer operation, 25 percent make-up air is added and it is considered that this factor is most important in maintaining a "fresh" atmosphere.

Refrigerating Unit.

This unit is completely assembled at the factory ready for underfloor mounting on the passenger car. The following equipment is contained in the box structure:

1 - Two cylinder, vertical, single-acting compressor.
1 - Oil separator.
1 - Liquid receiver.
1 - Air cooled condenser.
1 - Enclosed 1000 r.p.m. nominal 32-volt shunt wound d-c. motor combined with one 1150 r.p.m. 220/440-volt, three phase, 60 cycle, squirrel cage induction motor. The motors are direct-connected through a flexible coupling to the compressor and have ample capacity for its operation.

1 - Propeller type fan
1 - Enclosed a-c. motor line starter of the "De-ion" type.

The assembly of the equipment in the unit is such that all the component parts are suspended from a rigid bedplate forming the top of the box. The front and bottom of the box consists of hinged and readily removable covers so that for inspection purposes these can be removed exposing all apparatus for convenient accessibility and maintenance. The general arrangement is such that any piece of apparatus can be removed and replaced without disturbing any other piece of apparatus.
Refrigerating Unit Covers Removed

15 k.w. Axle Generator and Gear Drive

Cooling Unit
The direct current compressor driving motor has been especially designed for this application in line with conventional railway experience and practice. The armature is carried on grease-lubricated anti-friction bearings, the frame is of rolled steel and the end housings are cast. Class B insulation is employed throughout.

Mounted on the same shaft and on the frame of the d-c. driving unit is the squirrel cage a-c. motor. This arrangement forms a very compact construction and eliminates the use of extra bearings for the a-c. unit. The rotor is of cast construction and the entire motor is left open to afford it maximum ventilation from the air passing through the box.

Mounted on the side of the d-c. stator is an ebony asbestos panel board to which all a-c. leads are brought out equipped with copper strap jumpers to enable the motor connections to be readily changed for either 220 or 440-volt operation.

Bolted to the flange of the a-c. motor spider is the propeller type fan. This fan is of cast aluminum alloy construction and can readily be removed for inspection and repair.

A-C. Receptacle. -- Mounted to the car underframe adjacent to the box is a three-phase a-c. receptacle. This is provided for the purpose of connecting the a-c. compressor motor to a commercial power supply at yards and terminals for the purpose of precooling the cars before departure. This receptacle is so arranged that when the plug is inserted the main contacts are definitely closed before control interlocks are energized for
closing the a-c. starting switch. Conversely, as the plug is removed the interlocks function to open the a-c. starter thereby eliminating all arcing from the contacts of the plug or the receptacle. Removal of the a-c. plug will further cause the a-c. motor to be automatically disconnected from the system and will cause the d-c. motor to assume its function of driving the compressor under power from the storage battery.

Generating Unit.

The large capacity generator has been built to fit the space available on standard trucks by an unusual compactness of design and a new type of armature coil which permits an armature core length about 15 percent shorter than that required with the usual type. A totally enclosed design is used for complete protection of the working parts through the widely varying and adverse conditions under which these generators must operate. Ventilating fins distributed over the exterior of the generator dissipate the heat very effectively to the air circulating around it when the car is in motion. The large size inherent with totally enclosed machines is thereby avoided. These factors together with other design experience has resulted in a generator of three times the former capacity with very little increase in overall size.

The mechanical construction throughout is in accordance with established standards for electric railway axle mounted motors. The generator has a rugged spline fit where it is bolted to the gear case, through which the torque is transmitted. The nose of the generator is carried on a
flexible spring mounting to minimize the vibration transmitted from the rails and allow ample lateral motion of the axle. A grease-lubricated ball bearing carries the armature at the commutator end while a cylindrical roller bearing takes the load at the pinion end. This bearing is lubricated by a splash feed of oil from the gear case.

**Power Supply.**

The power necessary to operate the air conditioning equipment is derived from three separate sources, depending upon the circumstances of the power demand as follows:

1. Commercial 60-cycle power applied through the medium of the a-c. plug for pre-cooling prior to leaving a terminal.

2. Storage battery while the car is operating at slow speeds or at wayside or other station stops where commercial 60-cycle power is not available.

3. From the axle generator while the car is traveling at any speed above 23 m.p.h.

When operating from a commercial 60-cycle power supply by means of the a-c. plug the refrigerant compressor is driven from the three-phase squirrel cage induction motor in the refrigerating unit. Control connections are such that should it be desired for any reason to charge the storage battery during this pre-cooling period it only becomes necessary to close a push button switch in the car panel box thereby changing the d-c. driving motor into a d-c. generator to act as a battery charging unit. This push button is the
same as that used for the manual starting or shutting down of the refrigerating unit when operating from normal d-c. power supply.

As soon as the a-c. plug is removed from its receptacle on the side of the car (provided the d-c. push button just referred to is closed) the refrigerating unit continues to operate receiving its power from the storage battery. The battery continues to furnish the power until the car has attained a speed of 23 m.p.h. and the axle generator picks up the load. Similarly when approaching a station and the speed drops below 23 m.p.h. the battery takes up its power supplying function and carries on during the station stop until speed is again resumed.

The axle generator supplies power to the air conditioning unit through the medium of the d-c. driving motor in the refrigerating box for all normal operating speeds. It also has ample capacity and proper voltage characteristics for charging the storage battery and supplying power for the lights.

This generator has the inherent characteristic of building up with fixed polarity direction regardless of the direction of motion of the car. This is accomplished without the use of brush shifting mechanisms. This inherent characteristic is attained by a small auxiliary generator mounted on the extension of the main generator shaft and frame. This auxiliary generator is used for exciting the main generator field. Its field is built of iron having high retentivity and the entire
auxiliary generator frame is magnetically insulated from the main generator frame by a non-magnetic material. The field of the auxiliary generator is excited by the main generator armature, its high retentivity acting to build up the flux in the same direction at all times. This reverses the direction of polarity of the auxiliary generator armature voltage corresponding to changes in direction of car motion. This reversal of polarity of the auxiliary generator armature voltage imposes a corresponding change in direction of polarity of the field excitation of the main generator. With each change in the direction of car motion there is a corresponding change in the direction of rotation of the main generator armature, but coupled with this is a corresponding reversal of the main generator field with the net result that the main generator armature voltage polarity remains constant.

The auxiliary generator serves an additional function in that it is possible by its use to regulate the field strength of the main generator by varying the strength of the auxiliary generator field. This makes it possible to have the voltage regulator function on comparatively very small values of field current as compared to field current values if voltage control was maintained by regulating the field strength of the main generator.

A regulator, similar to hundreds having many years of reliable service on railway motive equipment, regulates the auxiliary generator field strength. The essential parts of the relay are a moving coil, stationary coil and vibrating
contact. The moving element carries the coil in series with
the stationary coil. Both of these are connected across the
generator terminals and operate against spring tension. This
tension is adjustable by means of a thumb nut enabling calibra-
tion of the regulator for voltages between 32 and 45 volts.
Incorporated into this regulator is a series coil which auto-
matically produces a rapidly drooping characteristic of the
generator in the event that the latter tends to become over-
loaded. This protective is most important particularly where
attempts are made to charge a completely discharged battery.

This combination has the very marked advantage of
eliminating the necessity of the use of any carbon pile
regulating device for generator voltage control. The sensitivity
of the regulator functioning in this manner is such that any
suddenly applied normal loads such as the starting of the air
conditioning compressor unit results in only approximately a
one-volt drop in generator terminal voltage. This drop is
corrected in a period not to exceed two or three seconds. Con-
versely, a suddenly relieved load is similarly corrected.

A sensitive reverse-current switch is also provided
for preventing the discharge of the battery through the genera-
tor. Its function is such that when the generator voltage
exceeds the battery voltage by approximately 1/2 volt the reverse
current switch closes. If the generator voltage is less than
the battery voltage by approximately 1/2 volt the reverse
flow of current through the mechanism causes the switch to
open.
A modified constant potential system of battery charging is used. A series resistor is placed in the battery circuit which gives the necessary reduced battery voltage under discharge battery conditions and the battery reaches its fully charged state under a properly tapered charge. This method of battery charging is recommended by battery manufacturers to assure long battery life.
FUTURE DEMAND

The soundness of engineering projects depends upon their capacity to fulfil a real demand. In planning for this electrification the future demand was based upon the number of people to be served at some future date and their economic and social characteristics. In planning for the future the central aim of the Railroad Company is to supply the right amount of facilities in the right place. Of course this cannot be done except when based upon dependable forecasts of population and its distribution.

Several mathematical formulas have been devised on the assumption that future population can be determined from past trends by the mere application of figures in the formula. It is believed, however, that such formulas place too much emphasis upon the past trends, ignoring the fact that new influences are always appearing and the old influences are frequently ceasing to be of importance.

By the nature of things, no two cities present situations precisely alike; indeed, one of the most striking facts is their dissimilarity. However, in analyzing the past growth of a city and forecasting its future, there are usually five principal influences to be considered:

1. Size and character of its tributary trade territory
2. Its industrial expansion
3. Its attraction as a home center
4. Governmental activities
5. Institutional activities

Study of the trade territory of a city is essential to an analysis of the population supported or likely to be supported by the wholesale, retail, and general office business of a city. This territory usually can be defined with the aid of an analysis of banking relationships, newspaper circulation, and the distribution of sales of representative wholesale establishments.

The trade territory of practically every city is changing, increasing or decreasing in extent and also undergoing changes in the character of the population. In respect to the latter, it should be remembered that the importance of a trade center depends not only upon the number of people in the tributary area but also upon their standard of living. In an analysis of the probable future changes in the trade territory of a city, consideration must be given to the trend in agriculture and industry, including such factors as improved highways, motor trucking, and changes in freight rates.

INDUSTRIAL EXPANSION

It now appears that the growth of most of our cities during the next twenty years will be due primarily to their relative attractiveness for industrial expansion. For purposes of population analysis, it is helpful to classify industries. They may be grouped according to those which attract population,
such as steel mills and automobile factories, and those which result largely from the presence of population, such as bakeries, laundries, and ice cream factories. Again, it is helpful to consider industries from the standpoint of whether they are conservative or exhaustive in nature; that is, whether their supplies are continuous or temporary. The lumber industry as it has been carried on in this country is a striking example of an exhaustive industry; in many places, industries (such as oil refining) based upon the presence of minerals are exhaustive.

If a city has diversified manufacturing plants, its growth is likely to be more uniform or stable than for a city where a single industry is dominant. It is well to note that different industries do not contribute to the population of a city in exact ratio to the number of employees. In a number of industries including the manufacturing of shoes and clothing a large proportion of the workers are girls and women, representing second and third members of a family. Further, one must consider the effects of labor-saving machinery. In the past virtually all industries have been able to increase their output by the application of labor-saving devices without a proportionate increase in the labor required, and it is certain that this tendency will continue.

There are many people who choose a place to live rather than a place to work. Among these are the independently wealthy, the retired, and the adventurers. These people seek
living conditions to meet their desires, and adjust their occupations if necessary to what is attainable where they choose to live. The classes who seek places to live first and occupations afterwards are likely to increase in the future.

In the railroad business, and in most other businesses where advance planning is required, it is important not only to know the probable growth of population, but also its character and distribution, and its division into family units. Future population growth is forecast upon the basis of certain definite factors already cited, including expansion of industry or commercial activities which support population. In estimating the amount of population that probably will be located in high grade, medium grade, and poor sections of the city, it is essential to know rather definitely the class of population supported by the various activities.
Economic Results Due to Electrification

Before the advent of electricity the steam locomotive reigned in an undisputed field. Since, then, however, the electric locomotive, the multiple-unit car, the Diesel oil electric locomotive, and the gas electric car have disputed its rights, on an ever increasing scale. The many operating or economic advantages of these more modern transportation units insures their greater application in the steam locomotive field.

During the past thirty years, and especially in the last half of this period, the basic costs of fuel and labor have been constantly rising. These fact, in themselves, have stimulated economy.

The trains are larger and heavier, the speeds faster. To meet these conditions, the weight and capacity of steam locomotives have constantly increased; the weight of the largest one with tender now exceeding 1,000,000 lbs. and with a capacity of more than 4,000 H.P. And has been mentioned once before, every device of human ingenuity have been added to promote economy, superheaters, feedwater heaters, mechanical stokers, automatic cut-off regulators, etc. Rails and bridges have been made heavier to carry these larger power units. Each year brings nearer the time when train weights and speeds must remain constant or else another type of motive power must be substituted.
As might be anticipated, the nearer the steam locomotive reaches its natural economic limitations, the more rapidly electrifications are taking place.

The primary reasons for substituting electricity for steam have been analyzed here before. Unfortunately railroad statistics are not sufficiently flexible to permit, in every instance, the comparison of steam and electric actual operating costs, especially where the section under consideration is comparatively short as in this case, and the expenses thus only form a part of those applying to a railroad division. It can hardly be said that economic considerations were entirely controlling in the electrification of the Baltimore and Ohio Railroad Tunnel, which was the first installation of this kind in the United States, the same thing being true for many other electrifications such as the terminal electrification of New York and Philadelphia. The departure from steam, with its attending smoke, gases, and noise, in some cases made possible the desired form of access to city depots, and met the requirements of public ordinances.

On the long and heavy grades the steam locomotive first demonstrated its limitations both physically and economically. True the weight of the trailing train was not limited, if sufficient weight was placed on the locomotive driving wheels, but the speeds with the heaviest engines available, of which two or three were coupled together in a single train were insufficient to meet the schedules desired. The railroads were therefore confronted, in many cases, with the problem
of substituting a form of power unit with a greater output for a given weight or increasing the number of tracks.

The following tabulations shows the savings effected by a 3000 volt D.C. electrification.

<table>
<thead>
<tr>
<th></th>
<th>Steam</th>
<th>Electric</th>
<th>Percent Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel and Power</td>
<td>315,235</td>
<td>164,509</td>
<td>47.81</td>
</tr>
<tr>
<td>Repairs</td>
<td>124,788</td>
<td>92,278</td>
<td>26.05</td>
</tr>
<tr>
<td>Enginemen’s Wages</td>
<td>104,461</td>
<td>71,225</td>
<td>31.81</td>
</tr>
<tr>
<td>Trainmen’s Wages</td>
<td>147,632</td>
<td>116,486</td>
<td>21.10</td>
</tr>
<tr>
<td>Engine House Expense</td>
<td>29,908</td>
<td>18,638</td>
<td>37.68</td>
</tr>
<tr>
<td>Water</td>
<td>4,954</td>
<td>1,194</td>
<td>75.90</td>
</tr>
<tr>
<td>Lubricants</td>
<td>9,751</td>
<td>4,942</td>
<td>49.30</td>
</tr>
<tr>
<td>Other Supplies</td>
<td>5,823</td>
<td>4,552</td>
<td>21.83</td>
</tr>
</tbody>
</table>

The above figures show the savings in every item attributable to operation. The savings on this represents approximately 22.4 percent on the gross investment without taking credit for the increased tonnage handled.

Generally speaking, electrification has lagged in the United States since the World War. But undoubtedly the reason is the plentiful fuel supply at comparatively low cost, which eliminates to some degree the possibility of the saving effected by electrification in other countries.

Today a new era has arisen, insofar as electrification in the United States is concerned. The Pennsylvania Railroad has completed its plans for electrifying from Washington
to New York. The Delaware, Lackawanna and Western Railroad has completed work on its New York suburban electrification. The New York Central Railroad is now making studies for the completion of its main line electrification to Buffalo, involving over 3000 miles of track. Thus in a few years the electrified mileage of railroads in the United States will grow rapidly.

To meet the requirements introduced, it is anticipated that the electric energy for operating the trains will be acquired at suitable distribution points from large power companies. The transmission companies will deliver such energy to the railroad trolley. The railroad will thus be able to concentrate on transportation.

From the operating viewpoint, the motor car train in comparison with steam operation possesses many advantages. Its freedom from objectionable smoke and steam permits the operation underground and in terminals without restriction. The reversible feature permits faster handling and a reduction of the number of train movements. The high emergency capacity of its motors permits an acceleration far in excess of a train handled by steam locomotion. The electrically operated units cost less to maintain, and have a greater number of hours of service throughout the year. In practically every installation the substitution of motor cars for steam handled trains has resulted in an improvement in the balance sheet due to increased riding. Many roads have for many years been a financial burden, has been made to pay. In addition a substantial improve-
ment in property values has been obtained as a by product of electrification.

A comparatively recent rapid transit line which has been converted to electric operation is that of the Boston Revere Beach and Lynn Railroad handling a heavy suburban traffic between Boston, Lynn, and intermediate suburban residential sections. According to the officers of this road which began operation in November 1928 the passenger revenue for May, June, and July, 1929 showed an increase of 10.2 percent over the same period for the previous year. There was also an increase of 1.58 percent in number of car miles operated.