General view of Great Northern three-phase locomotive [Hutchinson]

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THE ELECTRIC SYSTEM OF THE GREAT NORTHERN RAILWAY COMPANY AT CASCADE TUNNEL

BY CARY T. HUTCHINSON

The first three-phase installation on a trunk line railway in the United States was put into operation early in July of this year at the Cascade Mountain tunnel on the Great Northern Railway, in the State of Washington, about one hundred miles east of Seattle.

I purpose in this paper giving a general description of the plant with especial reference to the electric locomotives, together with a brief statement of its operation for the short period since it has been put into service; this record will of necessity be somewhat sketchy, as there has not been sufficient time to accumulate full data for the various conditions of operation that will be met with in service, especially the performance during winter.

In general the plant comprises a hydroelectric generating station, operating under a head of 180 ft., having a capacity of approximately 5000 kw. in generators at 6600 volts and 25 cycles; a transmission system operating at 33,000 volts, delivering energy to a sub-station where it is transformed to 6600 volts, at which pressure it is supplied to the overhead conductors and to the locomotive by way of an overhead trolley; on the locomotive the pressure is reduced by three-phase transformers to 500 volts for the supply of the four three-phase motors with which each locomotive is equipped.

The Great Northern Railway crosses the Cascade Mountains through a tunnel 13,873 ft. long; this tunnel is on a tangent and has a uniform gradient of 1.7 per cent; rising to the tunnel from Leavenworth, on the east, the ruling grade is 2.2 per cent, and

21 per cent of the total distance of 32.4 miles from Leavenworth to the tunnel is on the ruling grade. From Skykomish on the west to the summit the ruling grade is 2.2 per cent, and 44 per

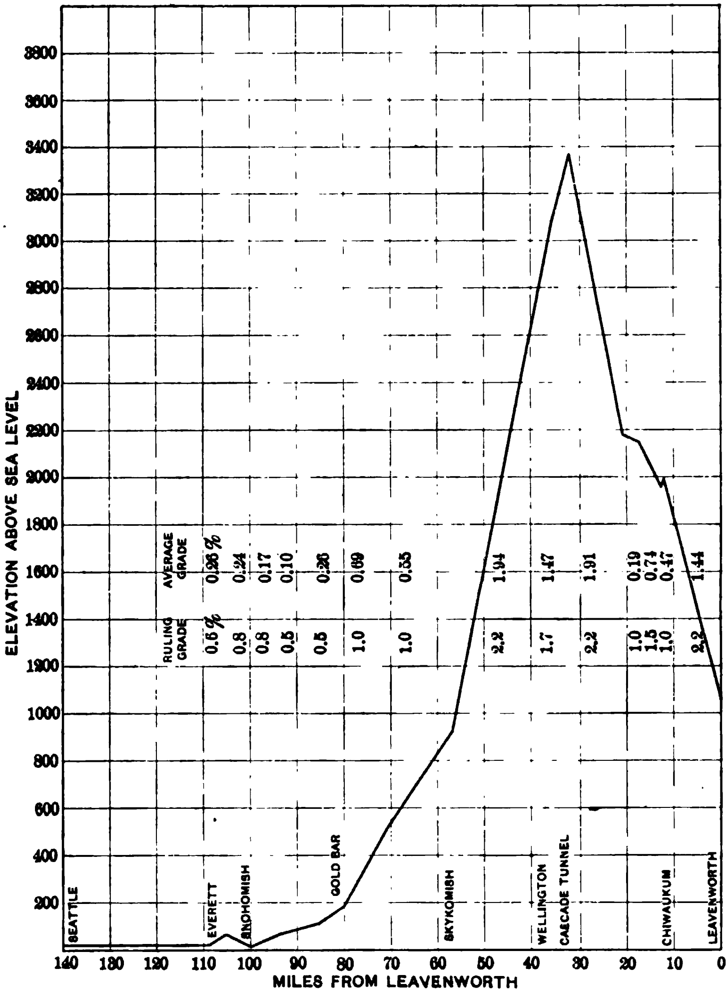


Fig. 1.—Profile of Great Northern Railway—Leavenworth to Seattle

cent of the distance of 24.8 miles is on the ruling grade. Fig. 1 shows a condensed profile of this section of the road; the average up grade from Skykomish to Wellington is 1.94 per cent and from Leavenworth to Cascade, 1.37 per cent.

The operation of the tunnel with steam locomotives was at all times difficult and frequently very dangerous on account of the heat and smoke from the locomotives. Crows Nest coal, which is exceptionally free from sulphur and gas-forming materials, was used for the tunnel service. It was the custom to clean the fires of each locomotive and to put on just sufficient coal to carry it through the tunnel. In the tunnel the rails became very wet from condensed steam, and were frequently covered with a layer of coal soot and ground sand, making them very slippery. The temperature in the locomotive cab was almost unbearable, rising at times as high as 200 deg. fahr. Under ordinary circumstances it required from twenty minutes to an hour for the tunnel to clear itself of gases, but on days when the wind was changeable, the passage of the gases from the tunnel would be stopped by the change in the direction of the wind, and they would pocket. Under such circumstances, work in the tunnel was very dangerous. There are refuge chambers containing telephones every quarter of a mile, but it was a difficult matter to keep these instruments in order, on account of the gases, smoke, and moisture.

The tunnel is lined with concrete throughout its length, and is in good condition. The roof is practically dry. The entire tunnel drips more or less from condensed steam just after the passage of a train, but is comparatively dry at other times. The temperature changes at the top of the tunnel are very rapid, varying from atmospheric temperature to several hundred degrees fahr. from the heat of the locomotive exhaust. For these reasons this tunnel is the limiting feature to the capacity of the Great Northern Railway for hauling freight across the mountains.

Mallet compound engines are used on this division, one at the head of the train, and one pushing. The mountain section as a whole also fixes a limit to the capacity of the road, on account of the slow speed necessitated by heavy traffic; it is impossible for steam locomotives to haul heavy trains on the mountain at a greater speed than seven or eight miles per hour.

The plant described herein is designed for use over the entire mountain division, by extending the system of conductors and building additional stations; it was not designed for the operation of the tunnel alone, although even if the problem had been the handling of the traffic through this tunnel and its approaches only, the three-phase system would in all probability have been selected, on account of its greater simplicity and less cost. The choice of the system to be used was under consideration for more than a year; the three-phase system was finally decided on, plans were prepared, bids obtained, and the contract for the four locomotives let on June 22, 1907.

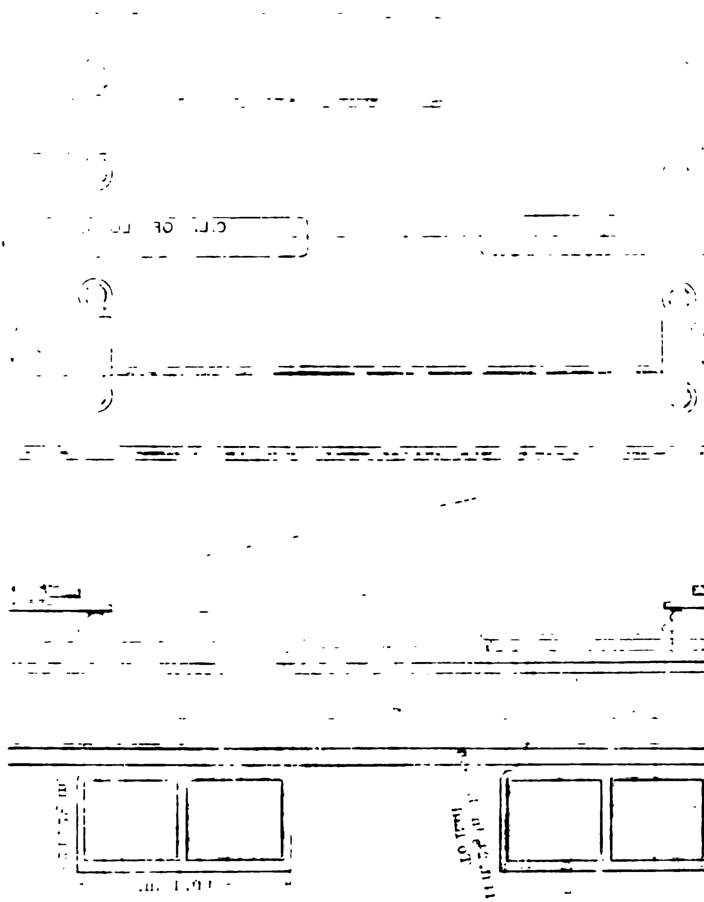
The original problem was to provide equipment to handle a train having a total weight of 2000 tons, excluding the electric locomotives, over the mountain division from Leavenworth to Skykomish, a distance of 57 miles. The system was to be first tried out at the Cascade Tunnel.

The tractive effort required to accelerate a train having a total weight of 2500 tons on a 2.2 per cent grade, using 6 lb. to the ton for train resistance and 10 lb. to the ton for acceleration, making a total of 60 lb. to the ton, is 150,000 lb.; this would require four locomotives of a tractive effort of 37,500 lb. each. The railway company's engineers limited the weight on a driving axle to 50,000 lb.; therefore four driving axles per locomotive are needed, giving a coefficient of adhesion of about 19 per cent. This is a measure of the maximum power required. The locomotive was, therefore, designed to give a continuous tractive effort of approximately 25,000 lb., and it was expected that four would be used with a train maximum weight. But the locomotive as built greatly exceeds this specification.

General Design of Locomotive

The locomotive as built is shown in Fig. 2. The principal data of locomotive are as follows: total weight 230,000 lb. all on drivers; two trucks connected by a coupling, each truck having two driving axles; a three-phase motor connected by twin gears to each axle; gear-ratio, 4.26; diameter of driving wheels 60 in.; synchronous speed of motor 375 rev. per min. giving a speed of 15.7 miles per hour at no load, dropping to 15 miles per hour for a load corresponding to the one-hour rating. The motors are wound for 500 volts and are completely enclosed and air-cooled; clearance between stator and rotor, ⅛ in.; trolley pressure, 6000 volts; each locomotive has two three-phase transformers reducing the pressure from 6000 to 500 volts, arranged with taps so that 625 volts may be used on the motor.

The distribution of the total weight of the locomotive is as follows:



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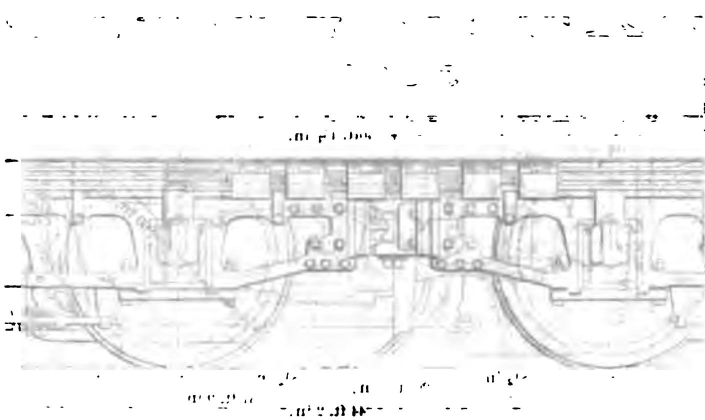

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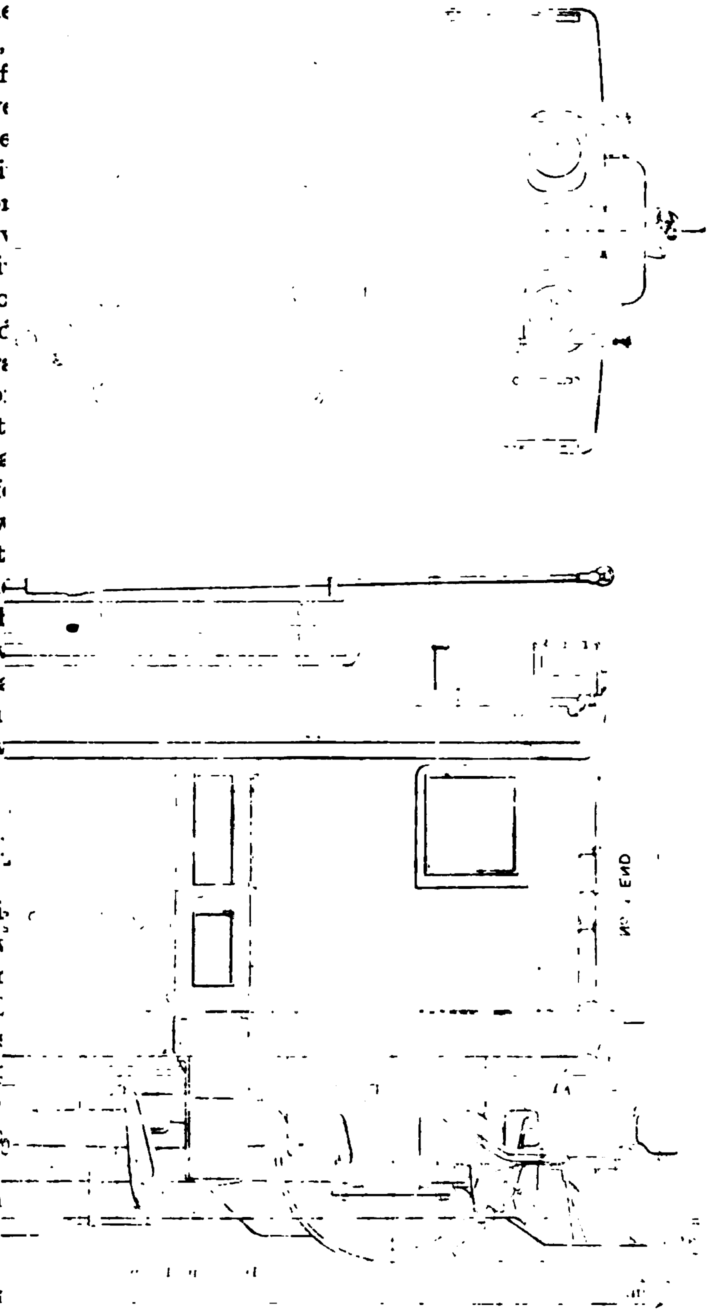

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follows:

2 Trucks	81,500 lb.
1 Cab	30,000 "
4 Motors	48,800 "
8 Gears and gear cases	11,000 "
2 Transformers	20,800 "
2 Air compressors	5,800 "
1 Blower	1,300 "
40 Rheostats	10,200 "
56 Contactors	3,200 "
Miscellaneous	17,400 "
Total	230,000 lb.
That is,	
Total weight per axle	57.500 "
Dead weight per axle	18,500 "

The specification of the motor required an output of 250 h.p. continuously for three hours with 75 deg. cent. temperature elevation, when supplied with not more than 2000 cu. ft. of air per minute. The test results of the motor show a continuous output of 375 h.p. at 500 volts with 1500 cu. ft. and 400 h.p. at 625 volts, with the same air; the one-hour rating of the motor at 500 volts with 1500 cu. ft. of air per minute is 475 h.p.; the ratio of continuous output to the hour-rating with 1500 cu. ft. of air is therefore 79 per cent. The continuous output at 500 volts corresponds to a tractive effort of 9350 lb. per motor and the one-hour output to a tractive effort of 11,900 lb. per motor; the locomotive will, therefore, give 37,400 lb. tractive effort in continuous duty, or 47,600 lb. tractive effort for one hour. Fig. 3 shows the characteristic curves of the motor, at 500 volts.

Calculations from the profile of this section give:

Westbound, Leavenworth-Cascade	
Average up-grade	1.37 per cent
Distance	32.4 miles
Work per ton at the wheel rim	2.15 kw-hr.
Average power per ton at the wheel at 15 miles per hour	1.00 kw.
Eastbound, Skykomish-Cascade	
Average up-grade	1.88 per cent
Distance	24.8 miles
Work per ton at wheel rim	2.16 kw-hr.
Average power per ton at wheel rim at 15 miles per hour	1.31 kw.
Average power per ton at wheel at 15 miles per hour for round trip	1.12 kw.
Maximum power per ton accelerating on 2.2 per cent grade	1.8 kw.

These figures assume the train to be moving continuously and are based on 6 lb. per ton train resistance, as are all calculations herein unless otherwise stated.

The average power of the locomotive when pulling will then be 1.12 kw. per ton, and therefore each motor can carry 250 tons in continuous service on this mountain division, assuming there are no stops and no opportunity for cooling; or each locomotive could haul $(4 \times 250 - 115) = 885$ tons trailing load, if the power requirements were continous; as there are necessarily stops, the rating as determined by heating is somewhat greater than this.

The locomotive has been tested to a maximum tractive effort of nearly 80,000 lb., corresponding to a coefficient of adhesion of nearly 35 per cent; with 60,000 lb. or 26 per cent, each locomotive can accelerate the train of 885 tons trailing on a 2.2 per cent grade, using 60 lb. per ton as the total tractive effort; or, in other words, the train that a locomotive can haul, as determined by the average duty and safe heating limits, is just about equal to the train that it can accelerate on the maximum grade; that is, the average capacity of the locomotive and its maximum capacity are in the same proportion as the average duty and maximum duty. The design is well balanced.

Making some allowance for these figures for the sake of conservatism, the rating of the locomotive on this division can be put at 750 tons trailing load.

Electric Equipment of Locomotive

Each locomotive is equipped with four three-phase induction motors, wound for 500 volts at the primary or stator; the motors are completely enclosed and are cooled by forced air circulation from a large blower. They are suspended from the axles in the standard manner, except that they are geared at both ends of the armature shaft; this was made necessary by the low speed and high torque required, as it was not considered safe to use a single pair of gears. The gear had 81 teeth, the pinion 19 teeth, giving a gear ratio of 4.26. The gears are of specially hardened steel; in order to secure perfect alignment the two pinions on each shaft were cut simultaneously. At first it was the intention to use some form of spring connection between motor and driving wheel, but this was subsequently abandoned, as it seemed that there would be sufficient flexibility in the armature shaft to take out any small differences between the two sets of gears. As far as can be told at present, this assumption appears to be correct, for there has been no difficulty with the gears and no unequal wear. The gears run with little noise and the construction seems satisfactory.

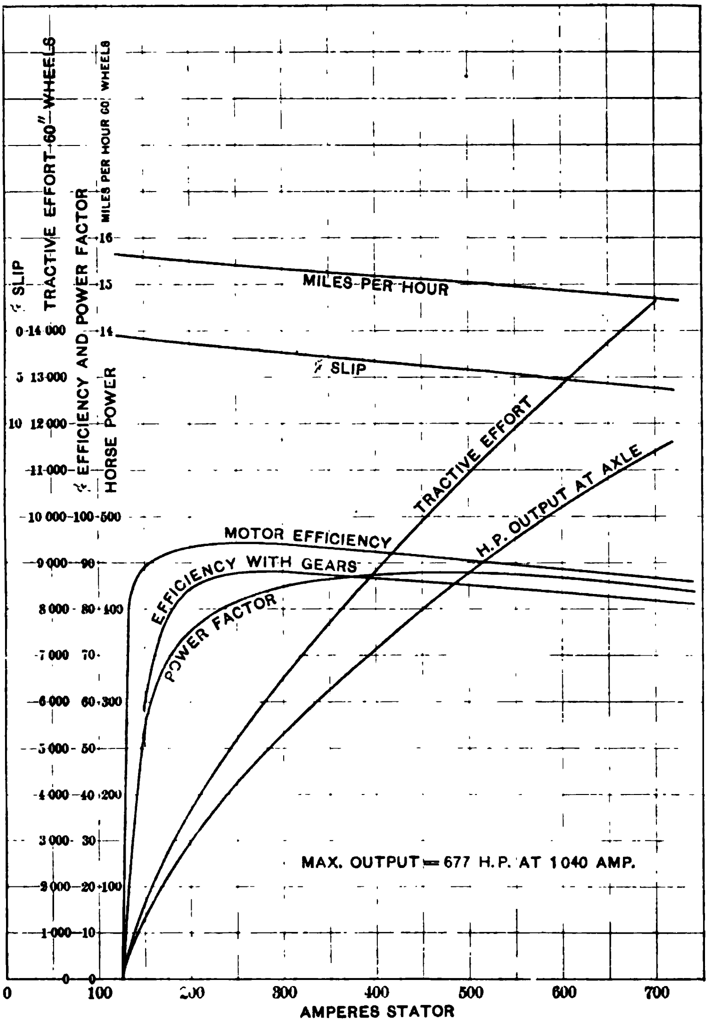


FIG. 3.—Characteristic curves of Great Northern three-phase 475-h.p. 25-cycle, 500-volt motor—gear ratio 4.26; 60-in. wheel

The locomotive carries two three-phase air-blast transformers, having a nominal rating of 400 kw. each, transforming from 6000 volts to 500 volts normally, or to 625 volts by the use of taps. The continuous capacity of the transformer is not as great as that of the motors, although it is fully up to the specification, and it may be that the quantity of air to the transformer will have to be increased when the locomotives are put in continuous service.

Compressed air for the brakes is supplied by two 100-cu. ft.

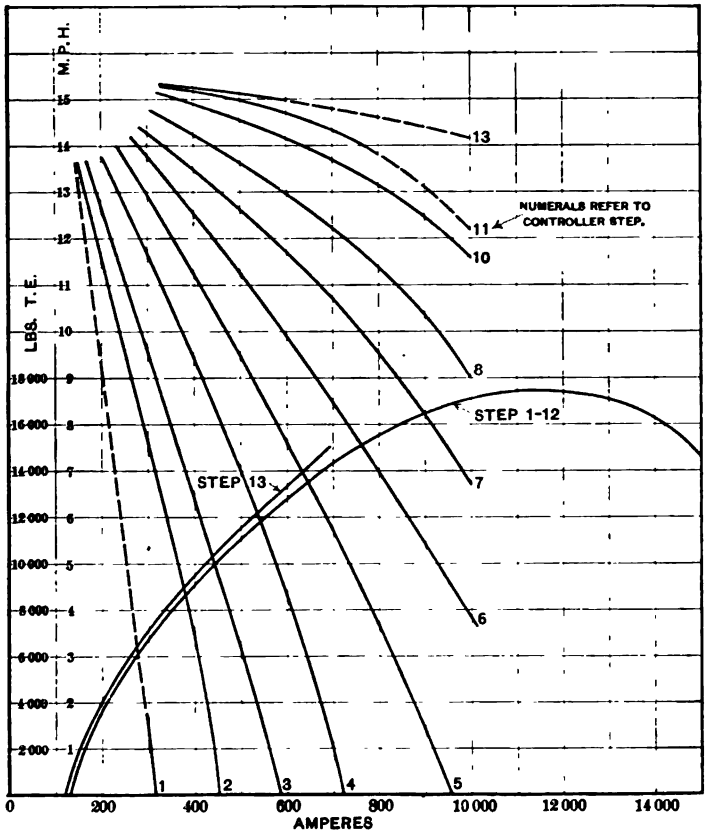


FIG. 4.—Speed-torque curves of Great Northern three-phase motor on the various control steps

induction-motor-driven compressors; the cooling air is supplied by a 9400-cu. ft. motor-driven blower. The locomotive is equipped with a combined straight and automatic air-brake system.

Control system. The control system of each motor is separate; the circuits branch from the transformer and are independent through the resistances. There are 14 contactors in each motor circuit, 56 in all. The pilot control is in duplicate, one switch at each end of the locomotive. There is a clear aisle on each side of the locomotive from end to end, all of the apparatus being assembled in the center of the cab.

At first I intended to have two running speeds by changing the number of motor poles, but this led to many complications; every effort was made to keep the equipment as simple as possible, and I finally decided to use resistance

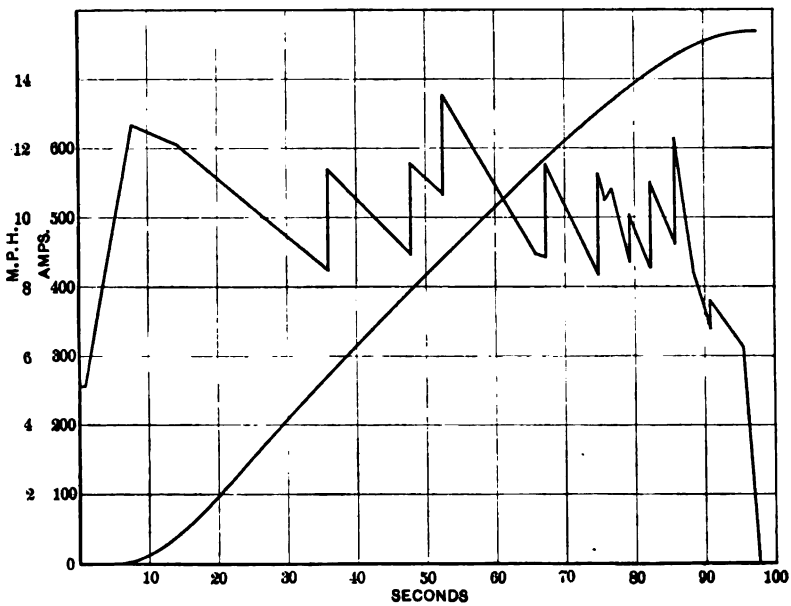


FIG. 5.—Acceleration curves
Tractive effort for locomotive—44,400 lb.
Acceleration—0.177 miles per hr. per sec.
Equivalent to a trailing load of 555 tons on a 2.2 per cent grade

control in the rotor of the motors and to have a single-speed unit.

Iron grid resistances are provided for each motor; there are thirteen steps in the control, but in order to reduce the number of contactors to the lowest possible point an unsymmetrical system is used. A change is made in the resistance of one phase only, in passing from step to step. This arrangement in effect treats the three-phase circuit as a single-phase circuit; on each step of the control the torque is the average of the three values of the torque of the separate circuits. The principal advantage of this is that 56 contactors do the work that would otherwise require 128, thus effecting a great gain in the simplicity of the control apparatus.

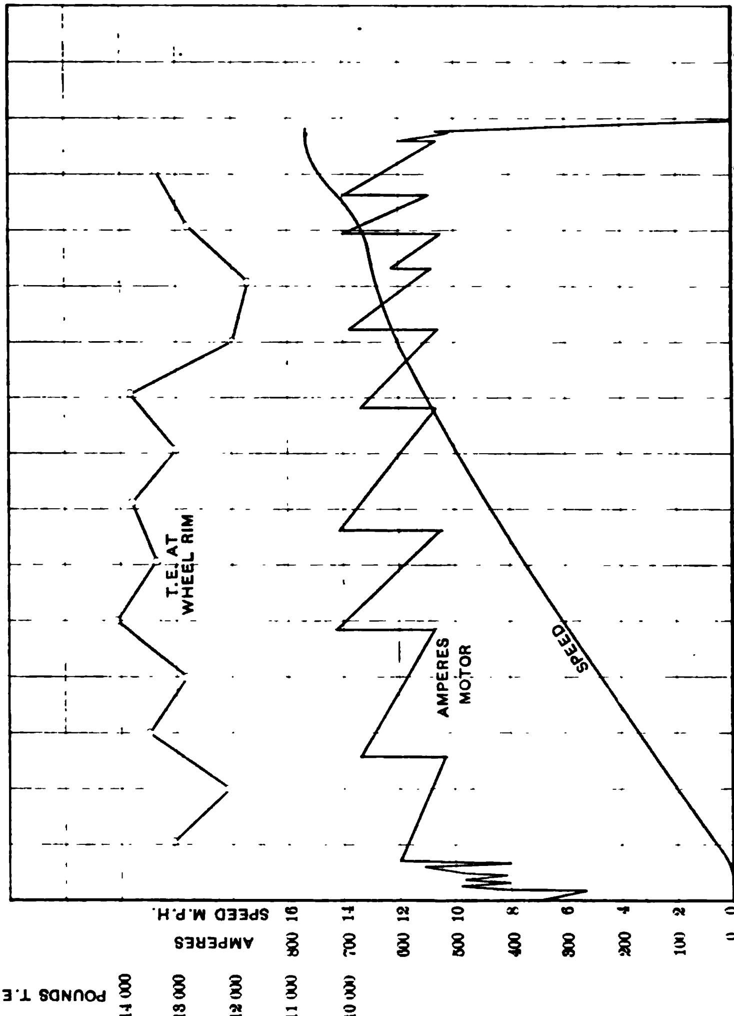


FIG. 6.—Acceleration curves
Tractive effort for locomotive—52,000 lb.
Acceleration—0.12 miles per hr. per sec.
Equivalent to a trailing load of 735 tons on a 2.2 per cent grade

Experience with the locomotive in service indicates that the initial torque, which is approximately 20,000 lb., is somewhat high, and I am now having the control changed so that on the first step two motors only will be thrown in circuit, and on the second step all four motors. This change is readily made by eliminating step 12, which tests have shown to be of little or no value. Fig. 4 shows the speed and tractive effort of the motor on the different control steps, with unbalanced circuits, and on the final step, without resistance.

Many acceleration tests were made at Schenectady, generally using one motor. Fig. 5 shows the result of one of these tests, in which the average tractive effort was 11,100 lb. per motor, corresponding to 44,400 lb. for the locomotive. Fig. 6 shows a similar test in which the average tractive effort was 13,000 lb. per motor, corresponding to 52,000 lb. for a locomotive. Fig. 5 is equivalent to accelerating a train of 555 tons on a 2.2 per cent grade at the rate shown on the curve; that is, 0.177 miles per hr. per sec. Fig. 6 represents the acceleration of a train of 735 tons on a 2.2 per cent grade at the rate there shown, that is, 0.12 miles per hr. per sec.

Mechanical Design of Locomotive

The locomotive is of the articulated or hinged type, having four driving wheels on each half of the running gear and is without guiding wheels. The running gear is not two independent trucks coupled together, but is more nearly comparable to the Mallet type of steam locomotive, in that the hinged sections are so rigidly connected that they tend to support each other vertically and guide each other in taking the curves, although the hinges are designed to offer minimum resistance to lateral flexure. There are no springs to prevent this flexure, and the wheel base is free to accommodate itself to any curvature; the effect of this guiding action is to minimize the flange wear, as in the Mallet locomotive.

The equalization system takes advantage of the vertical rigidity of the truck to distribute the spring stresses over groups of springs instead of concentrating them on single springs; the truck section on the one end is side equalized, but the section on the other end is carried on a three-point suspension. The springs are thereby equalized in groups and the groups are so arranged as to eliminate all skew or twisting stresses in the truck frame.

The framing of the running gear is of substantial steel castings annealed and held together by body-bound taper bolts in reamed holes. Side-frames are castings of truss pattern; end-frames and bolsters are steel castings of box-girder type; the end-frames and all parts are designed for buffing stresses of 500,000 lb. Bolsters are hollow castings and form part of the air reservoir for the motor ventilation; the air is supplied to the motors through a hollow center pin. The wheels are 60 in. in diameter with removable steel tires 3.5 in. thick. The wheel-centers are steel castings. The gears are shrunk on an extension of the wheel-hub, thus eliminating the torsional stresses from the locomotive-axles. The motors are connected through gears at both ends; that is, they are twin-geared to the driving wheels; this has the advantage of maintaining accurate alignment between axles and armature shaft.

The cab is carried on the trucks through center pins on each bolster, the center pin on one end having a slight longitudinal sliding motion to allow for variation in the distances between truck center-pins in taking curves. The cab extends the entire length of the platform and is made of No. 10 steel plates which carry a monitor that supports the trolley base and has a ventilated opening running through the center and perforated side plates to permit the escape of air from the interior of the cab. The greater part of the control apparatus, the rheostat, the transformers, contactors, etc., is placed in a separate compartment 60 in. wide and 22 ft. long, enclosed by steel partitions extending directly up to the monitor roof. This leaves two open operating spaces at the ends of the locomotive, connected together by two side aisles 30 in. in width. This center compartment is divided into three parts by steel-plate partitions, the middle part contains the high-tension apparatus, including switchboard; the end parts are duplicates, each containing one transformer and the contactors for two of the motors. The rheostats are placed in the monitor at the top of the cab. The air for ventilation, after passing through the transformers, cools the rheostats and then escapes to the atmosphere. Placing these rheostats at the top of the cab has also the advantage of raising the center of gravity of the locomotive, which is nearly 60 in. above the rail head, higher than is usual with electric locomotives.

Generating System

The energy supply for the locomotive is derived from the Wenatchie River, which flows along the line of the railway for a distance of some 20 miles. The power house is located about 2.5 miles west of Leavenworth. There is a low concrete diverting dam in the river at a point about 12,000 ft. west of the power house, and from this dam a wood-stave pipe of 8.5 ft. interior diameter runs for a distance of 10,908 ft. and continuing this stave-pipe line is a steel-pipe line for a distance of 962 ft. The pipe line has substantially the same gradient as the railway line, and gives a static head at low water of 203 ft. and in ordinary water of about 200 ft. The operating head at rated load is 180 ft.

The crest of the diverting dam is 400 ft. long; it has three head gates, a log sluice, and a fishway. The pipe line ends in a surge tank at the corner of the power house, having a total height of 183 ft. above its foundation. The tank proper is 30 ft. in diameter, and with a storage height of 54 ft. above its hemispherical bottom gives a storage capacity of approximately 38,000 cu. ft.

The pipe line leads directly into the upright pipe of the surge tank, which is 8 ft. in diameter; within the upright pipe is a waste pipe having a diameter of 3 ft. 2 in., extending 7 ft. above the level of the crest of the dam; in the tank the waste pipe is expanded uniformly to a diameter of 7 ft. 6. in, thus affording a circular weir of 23.5 ft. in length.

The power house is designed for three main units and two exciter units. There are now installed in the power house two main units, each turbine rated at 4000 h.p., directly connected to a three-phase alternating-current generator.

The two main units now erected, with the exciter, require approximately 500 cu. ft. of water per second when operating at full load of 8,000 h.p., giving a velocity of flow in the penstock of 8.7 ft. per sec.

The extreme low flow of the river at the dam is estimated to be 380 sec-ft. The small pond formed by the dam has a storage capacity equivalent to 8000 h.p-hr., for a depth of one foot; it is possible to draw the water in the dam down three feet. There are two other power sites in the canyon, each affording a head of 200 ft., available for subsequent developments.

The entire hydraulic installation was designed and constructed under the direction of J. T. Fanning, of Minneapolis.

Electric Equipment of Power House

The electric equipment in the power house at present consists of two main generating units, each for a nominal capacity of 2500 kilovolt-amperes at 375 rev. per min., 6600 volts and

25 cycles; these machines are designed to have very large overload capacity, and operate at a low flux density.

There are two exciter units, each having a nominal capacity of 100 kw. at 750 rev. per min. These units also have a large overload capacity; they frequently carry 150 per cent overload, on account of the very poor regulation of the water wheels. A third unit, identical with the first two, has been ordered.

The power house also contains four transformers for raising the pressure to 33,000 volts, each of a nominal capacity of 833 kw. but guaranteed to operate 100 per cent overload for one hour, with a low rise in temperature. Three of these units are in service, the fourth is kept as a spare.

The switchboard apparatus is of the usual type, having panels for the generators and the feeders, and is provided with the usual measuring instruments.

One reason leading to the use of the three-phase system was the possibility of regeneration; that is, of returning energy to the system on down grades. With the present installation it is obviously not possible to make any use of the energy so returned, but in order to prove this practically an automatic rheostat controlled by the speed of generator was installed in the power house; when a train on the down grade reaches a little more than the synchronous speed, the electrodes of the water rheostat are automatically lowered by an amount proportional to the difference between synchronous speed and the speed of the generator; this throws a load on the system and acts as a brake to the train. The operation of this apparatus is entirely effectual.

The nominal capacity of parts of this equipment, in particular of the transformers, may seem unusual; but it must be remembered that the plant is intended to operate on a load having extreme fluctuations, the entire load being on for, say, 15 minutes and then off for two or three hours, and consequently the transformers can be made small.

This plant has operated satisfactorily with the exception of certain troubles with the water wheels; in particular, the generators have shown ability to hold their rated pressure under extreme variations of speed, due to the effective control of the Tirrill regulators. The generator fields, designed for 125 amperes, have frequently carried 300 to 350 amperes, and the regulators have held the pressure normal, in spite of fluctuations of 35 to 40 per cent in speed.

Transmission Line

The transmission line extends from the power house at Leavenworth to the sub-station at Cascade, a length of approximately 30 miles, following the railroad all the way; part of the distance it is on the same side of the river as the railroad and part on the opposite side. Figs. 7 and 8 show the general appearances and the details of the construction of the line.

Fig. 7.—General view of transmission line

The line carries two circuits each of No. 2 B. & S. gage stranded hard-drawn copper wire; each circuit is in a vertical plane at one side of the pole, thus permitting the use of short cross-arms; the upper cross-arm was placed some distance below the top of the pole in order to leave room for a ground wire, which has not as yet been installed. The poles are 40 ft. long, placed 6 or 7 ft. in the ground, the tops being 10 in. to 12 in. in diameter; these poles

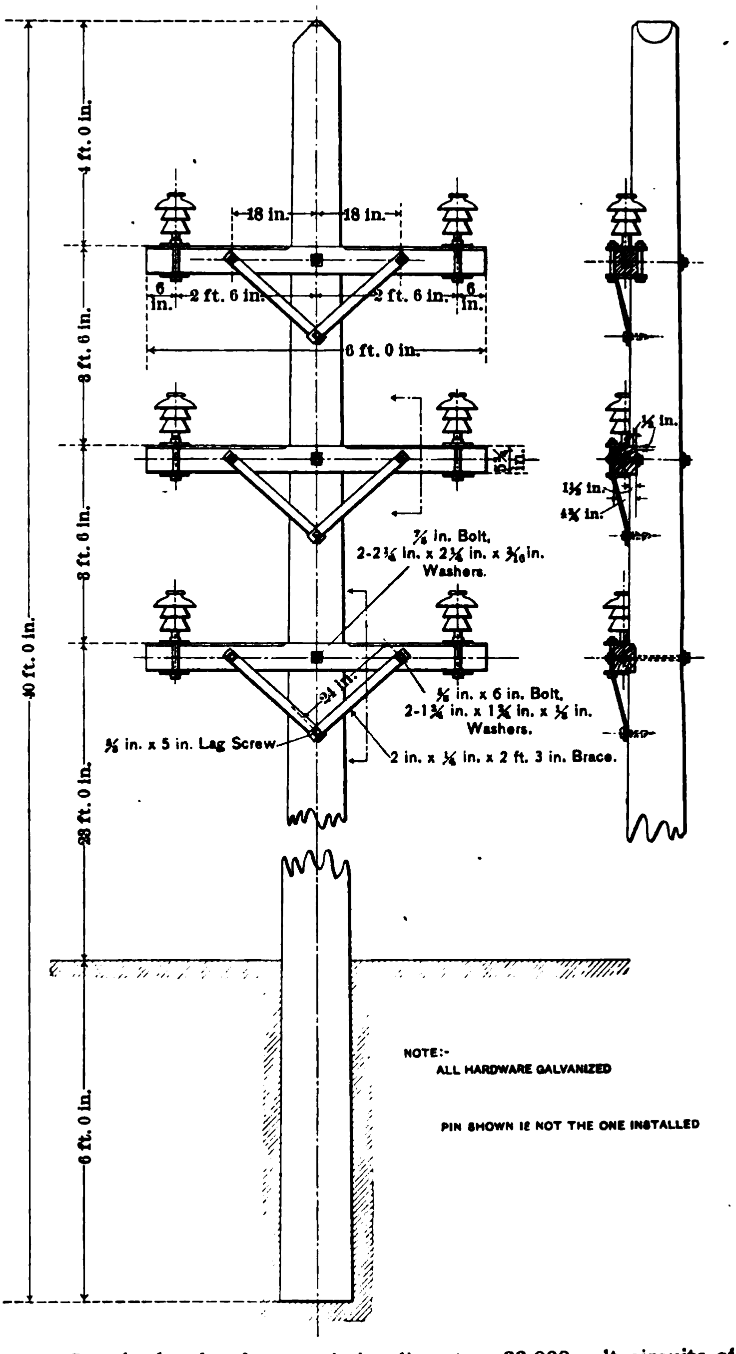


FIG. 8.—Standard pole of transmission line: two 33,000-volt circuits of No. 2 B. & S. gage wire

Wellington yard showing tracks. The main track through the sn[illegible]

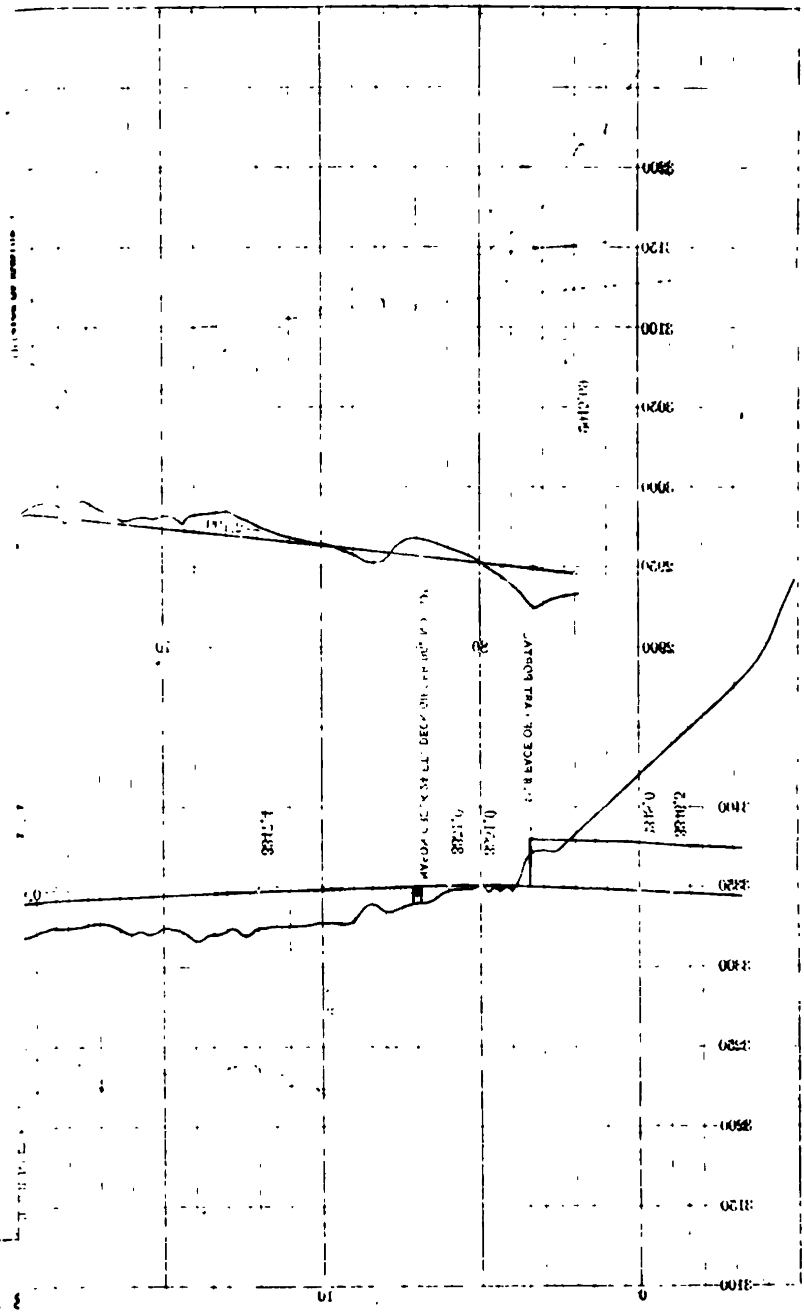


FIG. 8

are unusually sturdy, and it was owing to the fact that timber of this kind could be obtained cheaply in the West that this type of construction was adopted. The line is divided into three sections by two out-of-door switches operated by means of a pole deposited with a station agent; each switch is near a station.

In the design of the line, as in all other features of the work, the aim was to secure apparatus and types of construction giving promise of the greatest reliability, in order that there should be as few links as possible in the chain from the power house to the locomotive that would be liable to derangement; for this reason a comparatively low line pressure is used.

The telephone line is carried on the same poles; the transmission line is not transposed, but the telephone line is transposed at every fifth pole.

The construction of this line was completed a year ago, and it has stood through one winter, during which there were more than thirty snow and rock slides; only one of these slides caused damage to the line, and in this case only one of the two circuits was interrupted; it could have been repaired within an hour. The same slide interrupted the operation of the railroad for eight to ten hours.

Substation. The substation is at Cascade, practically at the east portal of the tunnel. Three single-phase transformers are in service and a fourth in reserve; these transformers are duplicates of those in the power house. The equipment of the substation is along the usual lines and calls for no special comment. The low-pressure bus-bars at the substation are connected to the overhead wires in the Cascade yard and also to the Wellington feeder, which runs through the tunnel to the extreme end of the Wellington yard.

Tracks electrified. Fig. 9 and 10 show plans of the two yards. In both yards the main track and two side tracks are electrified, together with the necessary crossovers, etc. The total length of the track equipped, including the tunnel, is about six miles. Fig. 11 shows profile of the yards; the tunnel grade is 1.7 per cent.

The length of the several parts of the overhead structure is as follows:

Substation to east portal of tunnel	200 ft.
East portal to west portal	13,900 "
West portal to end of electrified track	6,960 "
Total, substation to rear electric locomotive	21,060 "

or, practically 4 miles.

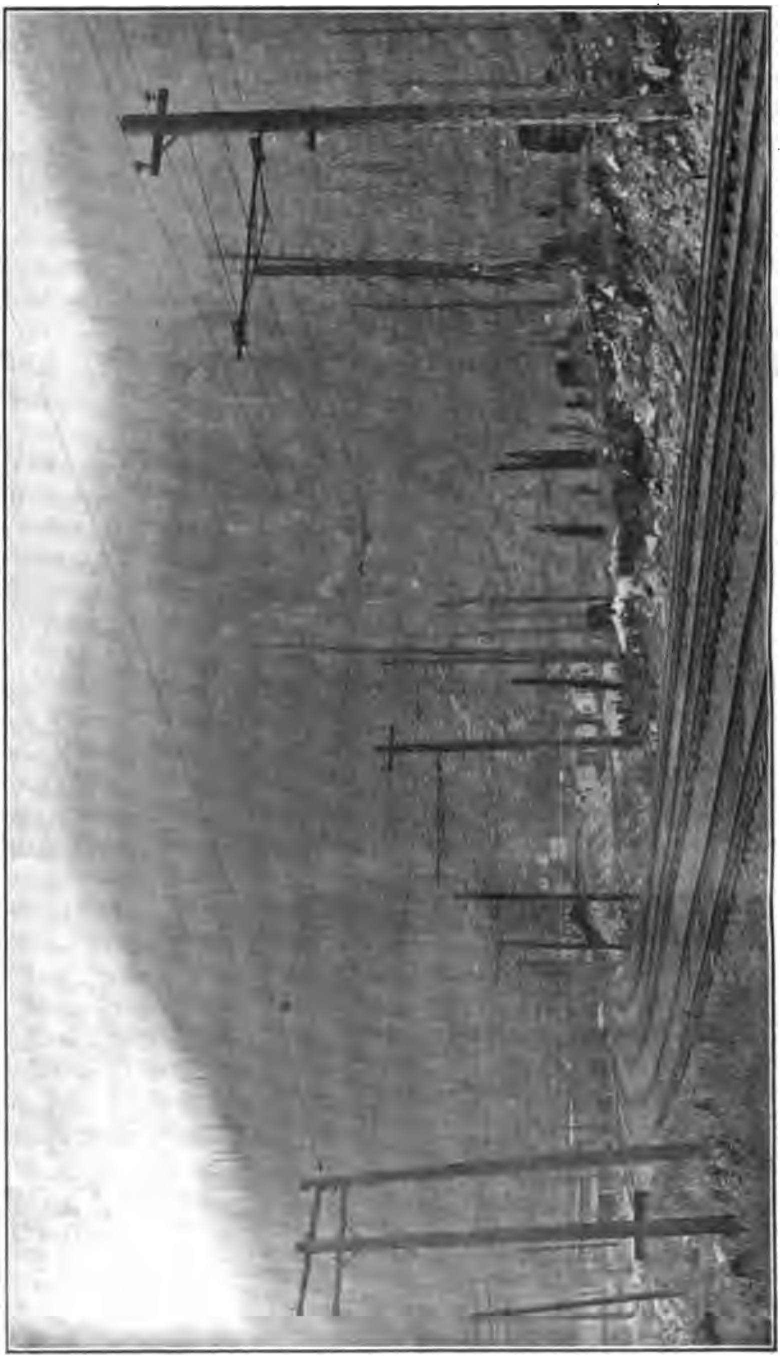


Fig. 12.—Overhead construction in Cascade yard, showing bracket construction at curve

Overhead Construction in Yards

Figs. 12, 13, 14, 15 and 16 show the general type of bracket and cross-catenary construction used in the yards. Figs. 17, 18 and 19 show details of the cross-catenary suspension. Fig. 20 shows details of the bracket construction. The wires are 24 ft. above top of rail and 5 ft. apart; for single tracks a bracket type of construction is used, and for multiple tracks a cross-catenary type, supported by very heavy wooden poles located about 8 ft. from center-line of outer tracks, thus leaving unobstructed the space between adjacent tracks. The wires are supported at intervals of 100 ft.

Multiple track supports consist, for each phase, of a steady span supported by and insulated from a cross-catenary span, both spans being secured to cross-arms on the poles by means of porcelain petticoat strain insulators; the spans for the two respective phases are three feet apart. The wires of the same phase, for the different tracks, are insulated from each other by means of wood breaks and porcelain link insulators, in series.

In the case of brackets, each phase is insulated from ground by means of a wood break in series with a porcelain petticoat strain insulator.

Where wires of opposite phases cross at turn-outs, they are insulated from each other by section insulators made of wood and about five feet in length; four insulators are used, each connected at one end to a special 8-deg. crossing pan and at the other end to one of the four wires converging toward the crossing. Except for one track whose wires are cut straight through the crossing pans without section insulators, it is necessary to switch the controller to the off position when the trolley wheel passes under the insulators; methods of avoiding this have been considered and are being tried out.

Heavy steel bridges, Fig. 14, forming anchorages for the trolley wires are located in both yards at intervals of 1000 ft. Lightning protection, though thunder storms are rare, is afforded by arresters connected to the wires at the ends of the tunnel and yards.

Both rails in the tunnel and one rail in the yards are bonded, with cross-bonding at frequent intervals. A single 4/0 exposed bond is used at each joint, having a length of 36 in. in the tunnel, and 36 and 50 in. in the yards.

In my opinion the use of double insulation everywhere is the reason for the almost total freedom from troubles of any

FIG. 13.—Cross-catenary construction in Wellington yard at switch point.

kind originating on the overhead structures; two separate pieces of insulation of any given strength are much better than one piece of four times that strength. The only troubles experienced up to the present have been at the section breaks and turn-outs, and have been caused by the trolley wheel leaving the wire. There has been no failure of the wires at any point of the overhead structure nor any breakdown of insulation.

Overhead Construction in Tunnel

This construction is shown in Fig. 21, 22 and 23. Fig. 21 gives a cross-section of the tunnel and shows the location of the trolley wires, trolley feeder, the wires for the lighting circuits, and the telegraph and telephone cable. Fig. 22 shows a cross-section of the method of supporting the trolley wires, and Fig. 23 shows a longitudinal view of the trolley suspension scheme; this, however, does not show the swiveled connection of the stud to the clamp holding the trolley wire at the lower end. The necessity for adding this swivel connection was shown by the breakage of several studs.

In the tunnel the wires are 17 ft. 4 in., above the top of the rail and 8 ft. apart; the latter spacing enables train-men to operate the hand-brakes, or walk on the tops of freight cars, the construction being such that head-room in not interfered with. Each wire is supported every 50 ft. by means of a 14-in. Detroit clamp attached by swiveled connection to a stud which is in turn swiveled to the middle point of a turnbuckle. The two eyes of the latter, by means of strand wire, connect each to a link and petticoat strain insulator arranged in series, the two petticoat insulators being secured to the roof of the tunnel by means of two expansion bolts, about 5 ft. 6 in. apart. Anchors and side-braces for the wires in the tunnel are located at intervals of 3000 ft.

Practically all metal work in the tunnel supports is copper or bronze, but experience has shown that galvanized iron, soon becoming protected by a slight coating of soot, would have been satisfactory. The insulators, when first put in service, were covered by a very thick coating of wet soot, but, even under these conditions, it was found possible gradually to bring the voltage up to normal without breakdown. Volumes of smoke and steam issuing from steam locomotives caused only a slight surface leakage, and one rough cleaning sufficed to put the insulators in reliable working condition.

Fig. 14.—Anchor bridge in Wellington yard, showing three tracks electrified

Spacing the wires 8 ft. in the tunnel was necessitated by the requirement of the railroad company that there should be no construction in the roof of the tunnel which could possibly interfere with a brakeman's walking on the top of a freight car. This change in the location of the wires complicated the construction somewhat and was one of the principal reasons leading

FIG. 15.—Construction at switch point, Wellington yard

to the use of a trolley wheel in place of a bow collector. It has, however, caused no material inconvenience and is satisfactory as long as the trolley wheels are in use, but if a change is made to a bow collector, which is not impossible, there may be difficulty in adapting the bow to this location of the wires.

Electric lighting. It is intended ultimately to clean and whitewash the tunnel and light it electrically, and for this purpose a lighting system has been installed. Five transformers of 4 kw. capacity each are placed in refuge chambers; incandescent lights are spaced 50 ft. apart and are connected four in series of a 500-volt system. Several plans were worked out for this lighting system, but taking into account maintenance costs, it seemed best to use a standard 110-volt carbon filament lamp.

Telegraph lines. The telegraph wires, ten in number, as shown in Fig. 21 run through the tunnel in a cable; this

FIG. 16.—Bracket construction at curve Wellington yard

service was thrown entirely out of commission when the electric locomotives began running. There is no interference with the telegraph wires due to the transmission lines paralleling them for thirty miles; the entire interference seems to originate in the tunnel. In order to eliminate this interference, a neutralizing transformer has been installed and adjustments are now in progress. There has been little difficulty in making the ordinary single-wire telegraph service satisfactory, but considerable difficulty has been experienced in

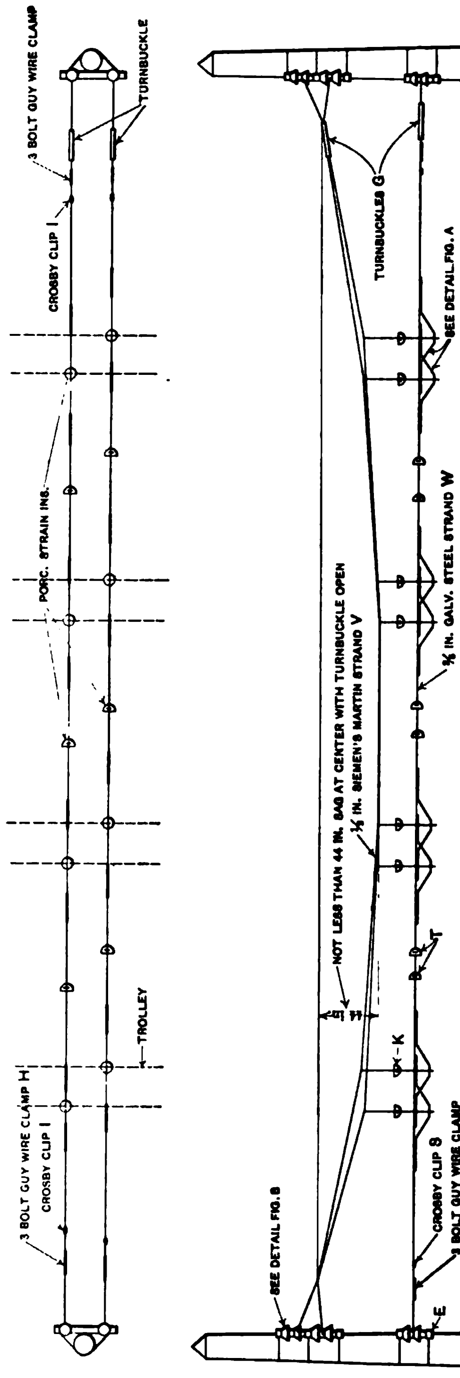


Fig. C.

Fig. 17.—Cross-catenary suspension, general scheme]

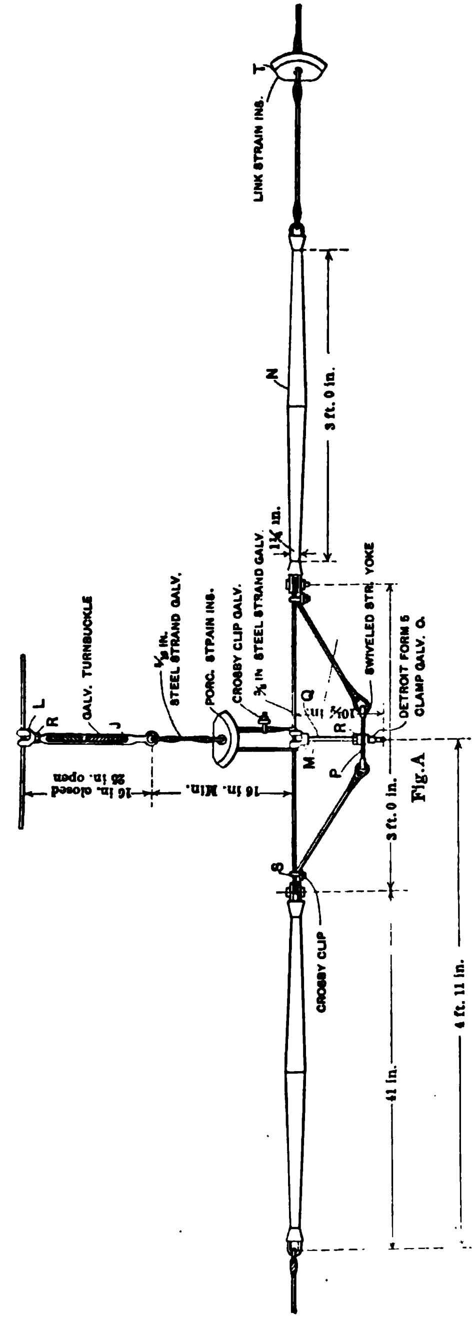


FIG. 18.—Detail *A* of Fig. 17 showing method of holding trolley wire.

getting the quadruplex to work satisfactorily; this matter is still unfinished.

Operation of the System

The electric service was started on July 10, although one or two trains had been handled previously. From that time to August 11, practically the entire eastbound service of the company has been handled by electric locomotives.

During this period of 33 days there have been 212 train movements of which 82 were freight, 98 passenger, and 32 special. In each case the steam locomotive was hauled through with the train. The tonnage handled was as follows:

Freight tonnage	171,000 tons
Passenger "	88,500 "
Special "	15,500 "
Total	275,000 tons

This is an average of 8350 tons per day, all eastbound.

The average freight train weight has been as follows:

Cars	1480 tons
One Mallet locomotive	250 "
Three electric locomotives	345 "
Total train weight	2075 "

The maximum weight of cars was 1600 tons; the minimum 1200 tons.

The representative passenger train handled is made up as follows:

Coaches	426 tons
Two steam locomotives	347 "
Two electric locomotives	230 "
Total train weight	1,003 tons

The maximum was about 125 tons greater.

Frictional resistance of steam locomotives. The power required to haul these trains seemed greater than it should be; investigation showed that the difference was accounted for by the unexpectedly high frictional resistance of the steam locomotves, as a trailing load; tests were made on several engines with the following results:

TABLE III

1 Test No.	2 Engine classification	3 Total weight with tender Tons	4 Weight on drivers Tons	5 Total resistance on 1.7 per cent grade lb.	6 Equivalent weight of freight cars Tons
1	Mallet No. 1904. 2–6–6–2	250	158	19,340	482
2	" No. 1911. 2–6–6–2	250	158	17,500	432
3	" No. 1905. 2–6–6–2	250	158	24,200	602
4	Consolidation.... 2–8–0	159	90	10,080	255
5	Pacific.......... 4–6–0	188	70	10,270	257

The tests were made by towing an engine through the tunnel behind an electric; the electric was fitted up with test instruments and the total tractive effort was thereby obtained. An allowance of 6 lb. per ton was made for the resistance of the electric and the difference is the draw-bar pull in column 5. Column 6 is the equivalent load in cars, taking car resistance as 6 lb. per ton. Each test given is the average from six to twelve separate readings. The average for the three Mallets is more than 20,000 lb.

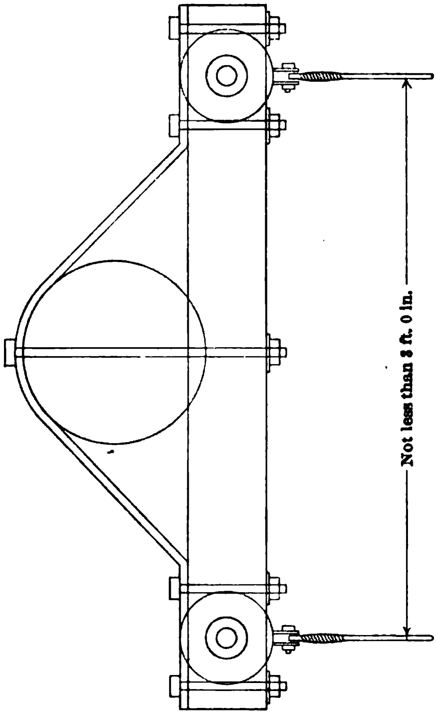
If the grade resistance be deducted from the total pull, and the difference lumped as "lb. per ton" for the locomotive and tender, there results:

TABLE IV

1 Engine classification	2 Frictional resistance of locomotive	3 lb. per ton
Mallet No. 1904.......	10,840 lb.	43.0
Mallet No. 1911.......	9,000 "	36.0
Mallet No. 1905.......	15,700 "	63.0
Consolidation..........	5,480 "	34.5
Pacific................	3,870 "	20.7
Electric...............	1,500 "	13.0

The average for the three Mallets is 47.0 lb. per ton for the frictional resistance on a straight level track.

The figure for the electric was obtained from tests made by



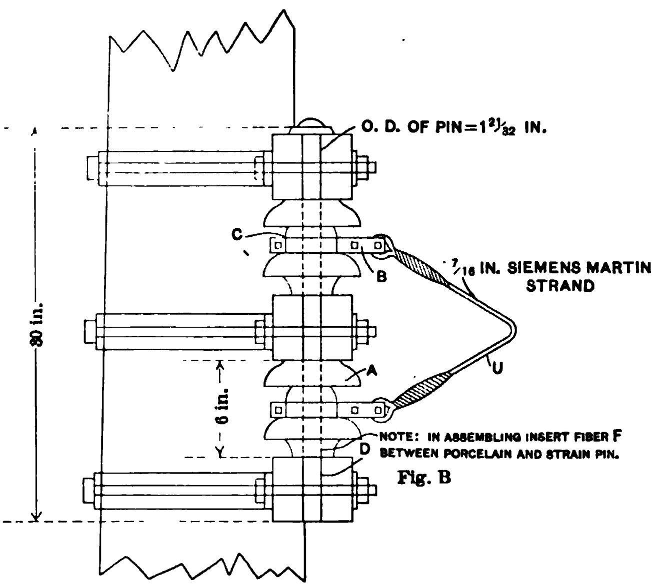


Fig. 19.—Detail *B* of Fig. 17 showing method of attachment of cross-catenary to pole

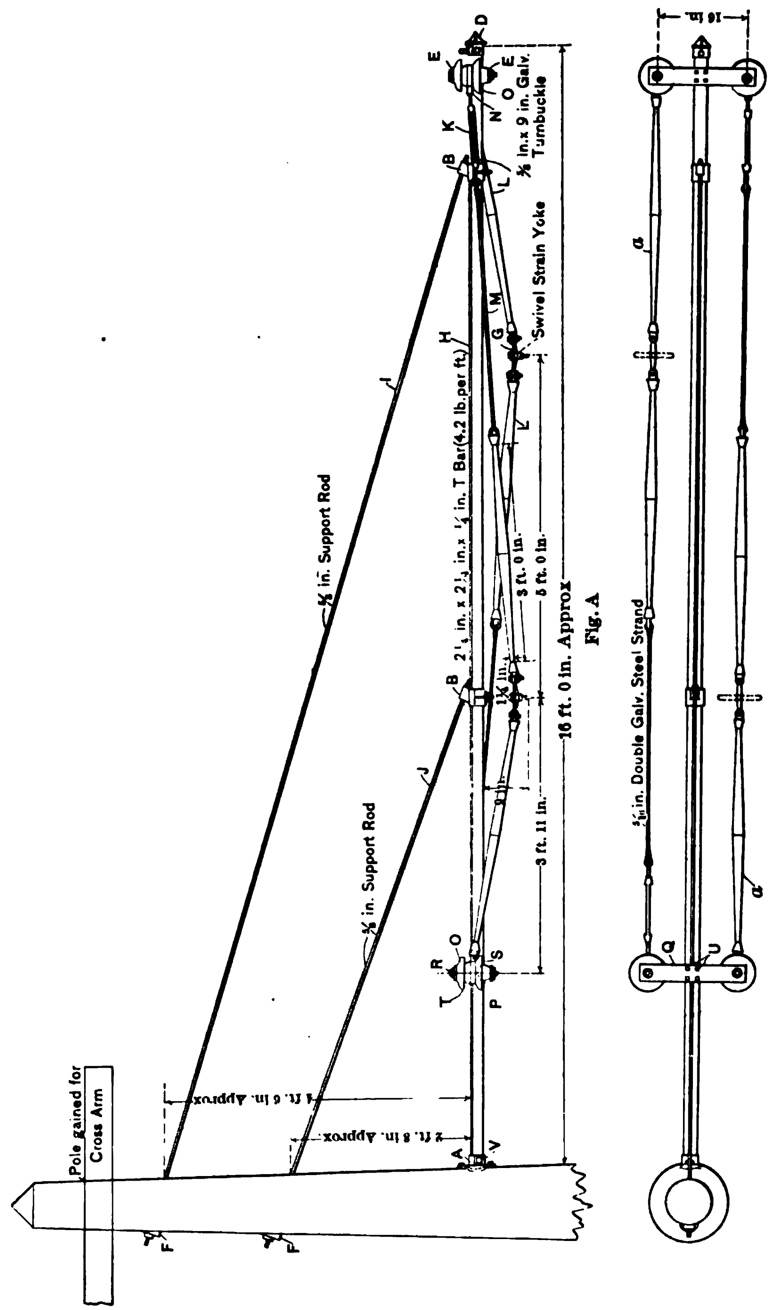


FIG. 20.—Bracket construction in yards

towing it by a motor car on straight level track; this test was made at Schenectady. Included in it is the resistance of gears and bearings of motors.

Using 20,000 lb. as the pull required for a Mallet on the 1.7 per cent grade, the approximate average from Table III, the total tractive effort for the average freight train, is:

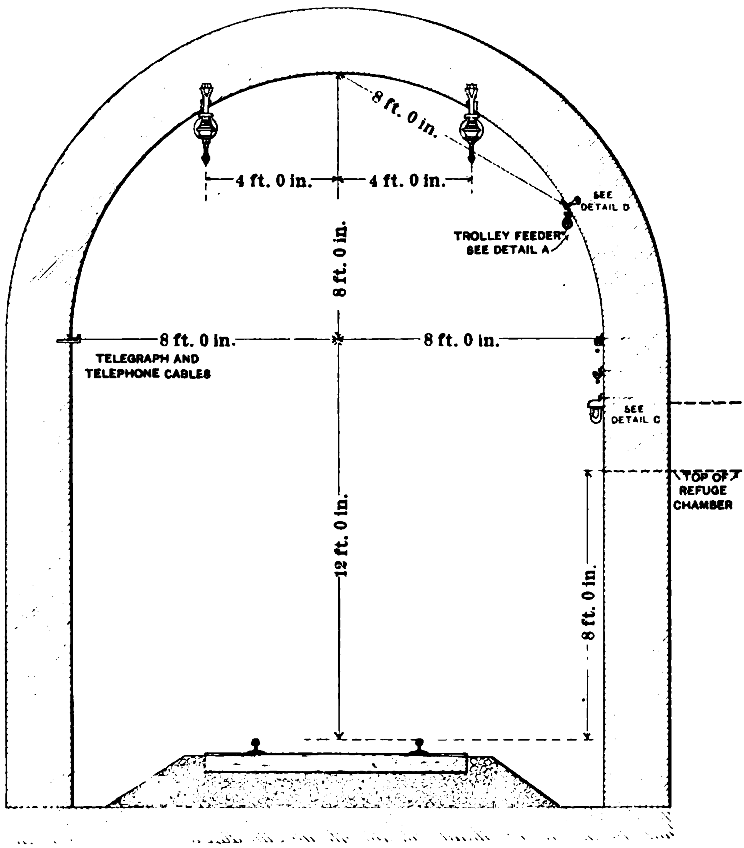


FIG. 21.—Cross-section of Cascade tunnel, showing location of trolley wires, trolley feeder, lighting and telegraph cable

Cars	1480 tons × 40	= 59,200 lb.
One Mallet	250 tons × 80	= 20,000 lb.
Three Electrics	345 tons × 40	= 13,800 lb.
Total tractive effort		93,000 lb.

This is equal to 31,000 lb. for each electric locomotive.

On account of the very high frictional resistance of the Mallet engine as a towing load, this representative train is equivalent to 1980 tons, excluding the three electric locomotives, or a total of 2325 tons, on the 1.7 per cent grade. This is on the assumption that the draw-bar pull required for the Mallet is replaced by freight cars at 6 lb. to the ton; this represents the average freight train handled.

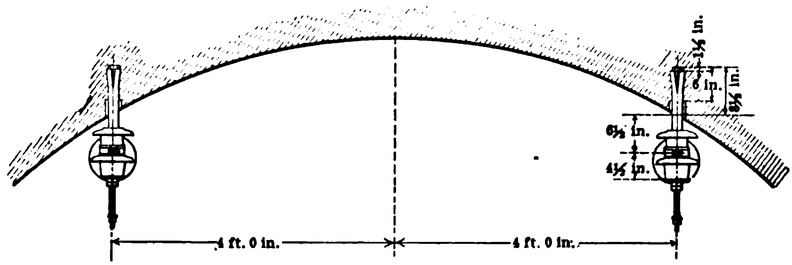


FIG. 22.—Cross-section showing trolley wires in tunnel

The tractive effort for the passenger trains varies from 40,000 to 50,000 lb., depending on the number of steam locomotives taken through; two electrics are ordinarily used, although one would answer in nearly all cases.

During this period there have been no delays due to failure of the electric locomotives, and but two trifling delays due to

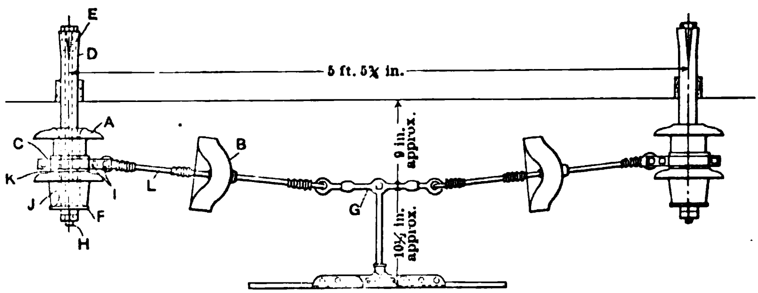


FIG. 23.—Longitudinal view of the tunnel suspension scheme—these supports are spaced 50 ft.

failures of the electric plant, both chargeable to the transmission line and both caused by accidents beyond the control of the operating force.

On August 11 the electric service was discontinued, owing to failure of both water wheels. Service was resumed on Sept. 9 and has been continued regularly since. The plant was taken over by the operating department of the railroad late in September.

The westbound service was not at first handled by the electrics regularly, as there is nothing in particular gained by braking the trains electrically on this short stretch, but now westbound passenger trains are so handled, for the benefit of the passengers.

Regenerating. A number of tests have been made to determine the power returned when regenerating; the following is typical:

TABLE V

TRAIN: MALLET ENGINE, 1550 TONS CAR WEIGHT, TWO ELECTRICS ON 1.7 PER CENT GRADE

Force due to grade		Frictional Resistance	Remainder for acceleration
Mallet	8,500 lb.	11,500 lb.	− 3,000 lb.
1550 tons in cars	52,500 "	9,300 "	+43,200 "
Three electrics	11,700 "	2,070 "	9,630 "
	Total for acceleration		49,830 "

This is equivalent to 1495 kw. delivered to the gears of the motors at 15 miles per hour.

The efficiency of the locomotive is approximately 80 per cent—hence the power returned to the line, should be 1200 kw. The test of this train gave 950 kw.; this difference is due to the standard practice, not yet abandoned, of keeping a certain number of car pressure retainers set on down grade.

The Mallet, instead of adding to the delivered power is an additional load that has to be carried by the train.

A similar test on a ten-car passenger train weighing 950 tons gave

Delivered power, calculated .... 590 kw.
" " measured .... 597 "

In this case there was no added resistance of pressure retainers.

These tests merely confirm the calculations, as they should. On a 1.7 per cent grade, then, one ton, descending at 15 miles per hr., will deliver 0.67 kw. to the system; on a 2.2 per cent grade it will deliver 0.91 kw.

Efficiency. The losses in the system when delivering 4000 kw. to the locomotive, at the west end of the Wellington yard are:

Place	Power Kilowatts	Per cent.
Power house low-tension bus-bars.............	4740	100
Substation " " "	4250	89.8
Trolley wheel of the locomotive..............	4000	84.5
Driving axles " " "	3320	70.

The average efficiency is somewhat higher than 70 per cent.

Handling of Trains

The maximum duty was imposed upon this equipment from the outset. On account of very poor regulation of water wheels, steam has been used in one of the Mallet engines in starting the freight trains in the Wellington yard; an attempt has been made to use just sufficient steam to enable the Mallet engine to turn itself over. Steam is shut off at the portal of the tunnel; in addition to this, in order to provide smoother starting, a slight air pressure has been maintained on the locomotive at starting, which is gradually reduced.

On several occasions trains have broken in two, due to the trolley wheel on the rear locomotive leaving the wire and thus cutting off part or all of the power supply to the rear locomotives. This throws a greatly increased draw-bar pull on the front locomotive, and the consequence is that the train is jerked apart. This happened in the early stages of the work, and was due to the fact that the turn-outs were not in the best order, and also that the engineers had not sufficient experience in handling trains. Another means taken to avoid the broken draw-bars was to use the rear Mallet engine to assist the train over the trolley crossings in the Wellington yard; this was a temporary measure and has been discontinued.

Economy of Mallets. It is interesting to compare the performance of a Mallet compound locomotive under the same operating conditions as this system. The data for this are given by Mr. Emerson, superintendent of locomotive power of the Great Northern Railway Company, in a discussion before the American Society of Mechanical Engineers on locomotives of this type;* as an excellent performance he gives these data:

> Recent performance shows that on a round trip over this division the L-1 engines handled 1600 tons with a total of $43\frac{5}{8}$ tons of coal, or equivaent to 25.13 lb. of coal per 100 ton-mile.

* Transactions of the American Society of Mechanical Engineers Vol. 30, page 1031.

The division referred to is from Leavenworth to Everett, 108.7 miles. The work done per ton for a round trip over this run is readily calculated; from the profile I find,

Total rise, westbound	2212 ft.
" " eastbound	3440 "
	5652 ft.

and $5652 \times 2000 / 2.65 \times 10^6 = 4.26$ kw-hr., at the rail; this is the work done per ton in lifting the train; the work done against train resistance, assuming resistance to be 6 lb. to the ton, for 108.7 miles, is 1.3 kw-hr; the total work done in round trip per ton 5.56 kw-hr. There should be a negligible addition to this for starting the train.

The average train weight is:

Cars	1600 tons
One engine, 109 miles	
Second " 58 "	
Equivalent engine weight	380 "
Total	1980 tons

The coal used was 43⅝ tons, equal to 87,660 lb.

Coal per ton	44.3 lb.
Coal per killowatt-hour	8.0 lb.

A modern steam station can deliver one kilowatt-hour for 3 lb. of coal, at the bus-bar, which, with an efficiency of 70 per cent to the rail, gives a consumption of 4.28 lb. per kilowatt-hour at the rail; in other words, the Mallet compound requires nearly twice as much coal per kilowatt-hour at the rail as would be used in a modern steam station in the place of the hydroelectric station at Leavenworth.

Advantages of Three-Phase System

This plant has demonstrated, in my opinion, that the three-phase induction motor has certain very marked advantages over any other form of motor for heavy traction on mountain grades; these advantages may be stated somewhat approximately.

1. *Maximum electrical and mechanical simplicity.* This point is of great importance and was one of the principal reasons for using three-phase system; the motors will stand any amount of abuse and rough use.

2. *Greater continuous output within a given space than can be obtained from any other form of motor.* This, I believe, is

shown by comparison with other electric locomotives; it is due to the fact that the losses can be kept lower in a three-phase motor than in any other type. As Fig. 3 shows, the electrical efficiency of the motor is high for a wide range of load.

3. *Uniform torque.* This is important, particularly at starting. I believe that a three-phase motor will work to a three or four per cent greater coefficient of adhesion than a single-phase motor at 15 cycles.

4. *The possibility of using* 25 *cycles.* This is important, as it leads to a less cost and a better performance of power station apparatus; moreover, it is standard and the power supply can readily be used for other purposes, as well as for traction; a commercial supply can be provided.

5. *Constant speed.* This is ordinarily stated as a disadvantage of the three-phase motor; but in my opinion it is a distinct advantage in mountain service, particularly the limitation of the speed on down grades. It has also the advantage on up grades that meeting points can be arranged with greater definiteness. There is a general notion that the impossibility of making up lost time with the three-phase motor will be a decided drawback to its use. This would be true if there were the same liability to lose time with three-phase motors; but when a train can be counted on to make a definite speed, without regard to conditions of tracks or of its load, there is less liability to lose time. Although I am not prepared to state that a three-phase motor is suitable for cases where the profile is very variable, yet it is by no means certain that it would not work out well; the question is merely one of making a given schedule between two points with greatest regularity.

6. *Regeneration on down grades.* This matter has been discussed since the earliest days of electric traction, but, as far as I know, has not been, up to the present, put into practice. Although this result can be attained with other forms of motors, yet it is most perfectly attained by three-phase motors, there being no complications involved. This is of importance in reducing the power-house capacity required for a given service; although, no doubt, the saving in power-house capacity will not be as great as indicated by theory, owing to the various emergencies that must be provided for, nevertheless there will be a material saving. A 2500-ton train on the average down grade of 1.5 per cent will deliver about 1400 kw. to the system. The equivalent power house capacity would cost at least

$200,000; hence if only 20 per cent of this can be utilized the saving will equal the cost of one locomotive.

7. *Excessive short-circuit current is impossible* and consequently destructive torque on the gears and driving rigging is eliminated. There will be no necessity for the complication of a friction connection between the armature and driving wheels, as in the design of recent large direct-current electric locomotives.

8. *Impossibility of excessive speeds.* Even when the wheel slips the speed remains constant. Therefore, the maximum stresses put on the motor are less and are more accurately known than with any other form of motor.

DISADVANTAGES OF THREE-PHASE

On the other hand, the principal disadvantages of three-phase motor, for traction use, are commonly stated to be:

1. *The constant speed.* This is rather an advantage for this class of service.

2. *Constant power.* The fact that the motor is a constant-power motor and therefore requires the same power at starting and while accelerating as at full speed. While this is true, it is not a matter of any particular consequence in a service where the stops are very few, and consequently the proportion of total time spent in acceleration is small, and where the additional power required to accelerate the train is a small percentage of the power used by the train at full speed. In this particular case on the 2.2 per cent grade, when accelerating at the rate of 10 lb. to the ton, the power required during acceleration is only 20 per cent greater than that required at full speed; this is not a serious matter.

3. *Small mechanical clearance.* In this particular motor the clearance is ⅛ in., which is ample for all practical purposes.

4. *Inequality of load on several motors of a locomotive due to differences in diameter of driving wheels.* To meet this an adjustable resistance is included in the rotor of each motor, the motors are then balanced up and no further attention is required as long as the wear on the driving wheels is approximately the same. If, at any time, the load becomes badly unbalanced it is a simple matter to readjust the resistances.

5. *Low power-factor of the system.* This does not seem to be borne out by practice. The power-factor, as shown by the switchboard instruments in the power house, is 85 per cent. This is a good result and is much higher than the power-factor

of a well-known single-phase system that I recently had occasion to visit.

6. *Two overhead wires*. There is no doubt that two wires will cause more trouble than one, and in case of complicated yard structure it might not be practicable to use two overhead wires; but where the problem is that of a single track with an occasional turn-out or crossing there is, practically speaking, no more difficulty in maintaining two wires than one.

In brief, in service, of this character the three-phase motor has marked advantages in capacity, reliability, simplicity, and general trustworthiness, when compared with any other motor.

Some Minor Advantages of Electric Traction

In the many discussions of electric traction which have recently taken place, I do not find several minor advantages sufficiently emphasized. One of these advantages lies in the fact that with electric traction the exact performance and condition of the locomotives and of all elements of the system is accurately known at each moment; on the other hand, with steam locomotives neither the engineer nor the motive power man can have any clear knowledge of the conditions of operation at the moment; he can only ascertain the performance of the locomotive by elaborate tests, which, as a matter of fact, are seldom made. The ratings and performance of steam locomotives are made up largely by " authority " based on a few tests from time to time, and take no cognizance of the actual condition of the locomotives. The importance of this, I think, is clearly brought out by the tests of the steam locomotive cited herein.

With electric locomotives the operation on a heavy grade becomes as simple as on the level; the engineers and train men feel much greater confidence in the electric locomotives and consequently the mountain division ceases to be a terror to them.

Electric traction will permit the use of very long tunnels, which are not now possible on account of difficulty of ventilation. There is no particular reasons why tunnels of ten or twelve miles should not be operated as easily as those of one mile.

The great increase possible in the speed of trains with electric traction and the consequent increase in the capacity of a single track will operate to postpone for a long time the necessity for double tracking. This double tracking on a mountain is a very expensive piece of business and this saving alone will, in some cases, more than offset the cost of electrical equipment.

A word in closing: the construction work in the tunnel and yards was carried out under great difficulties, owing to the necessity of not interfering with the regular service of the road. At times it was not possible to work in the tunnel for more than one hour a day, and for days at a time two or three hours was all that could be allowed, but in spite of this the work was carried out with very satisfactory speed, due particularly to the skill and ability of my assistants, R. Beeuwkes and W. S. Skinner, and the unstinted assistance of the engineering department of the road.

Discussion on "The Electric System of the Great Northern Railway Company at Cascade Tunnel." New York, November 12, 1909

President Stillwell: We are to have the pleasure this evening of listening to the presentation of a paper by Cary T. Hutchinson on "The Electric System of the Great Northern Railway Company at Cascade Tunnel." It is certainly a fact of great interest that in this year, 1909, a three-phase railway installation of magnitude has been completed and put in commercial operation in the United States. Polyphase motors were brought to this country in 1888. Those which arrived in that year were rated about one-quarter horse power, but none of them, I think, ever succeeded in developing that output. At that time serious efforts were made by American engineers associated with one of our manufacturing companies to adapt this type of motor to railway purposes, but they reached the conclusion that the constant-speed characteristic of the motor rendered it unsuitable for such service. A number of years later DeKando, in Europe, undertook to adapt polyphase motors to traction purposes, and it is a pleasure to have an opportunity to record the admiration that I feel, that I think all American engineers feel, for DeKando's exceptionally able and original work in that development.

The three-phase system has been in use in Italy, and in Switzerland, for a number of years, and, since 1904, on what may be called a large scale on the Valtellina line. From 1890 until recently but little attention was paid in the United States to the practical application of the polyphase motor to railway purposes. It received during that period, it is true, careful study; but the conclusions reached were negative, so it was not introduced in commercial service in this country.

In the United States there are to-day three different systems operating electric traction of the heaviest kind; namely, the direct-current system, the single-phase alternating-, and the three-phase alternating-current systems. All of these systems, I think it may fairly be said, are doing their work not only successfully, but in a manner that shows a marked improvement over the steam locomotive operation that they have superseded.

The steam railroad managements of the country are beginning to awaken. They are asking which is the best system for general railway work, and that question must be answered by the electrical engineer. A member of the committee of the American Railway Association said to me this morning that he felt the art was not sufficiently advanced to justify his railroad in considering seriously the application of electric motors. Now, the fact is that we have a variety of methods, and it is important to accelerate the process that ultimately is to result in the survival of the fittest.

It is here, I think, that one of the functions of this

Institute comes in. In this country there is no government commission to decide general standard specifications and to pass on the claims of various systems before adoption, as is done, for example, in Germany. With us, the evolution of a system is not directed, except so far as commercial interests may influence it, or the consensus of opinion of the members of this Institute affects it. I am always glad, therefore, to have this subject presented, because there is nothing within the scope of the American Institute of Electrical Engineers that is of greater technical interest, or that compares with it in commercial importance.

Cary T. Hutchinson: I shall not attempt to cover the entire scope of the paper, but shall merely emphasize a few of the features of the work. The first is that this system was installed with the expectation that it will form part of a larger system, having a length of from 60 to 100 miles. At present it is merely a shuttle service through a tunnel from a yard on one side to a yard on the other, the distance being about 4.5 miles.

If nothing further than this were contemplated, it would seem that such electrification would constitute a very serious additional expense, and this doubtless would be true, although owing to the peculiar conditions under which the steam service has been handled there is an actual saving in operating expenses over this stretch of about $100 a day. The fundamental reason, however, was increase in capacity. This tunnel formed the congested point of the railroad system; under some conditions it was almost impossible to get the tonnage through the tunnel.

A short description of the method of handling the traffic under steam will indicate the difficulties that were encountered. Trains east-bound from the Pacific coast were from 1400 to 1500 tons trailing load with two Mallet compound engines. At the west end of the tunnel, at the foot of the grade, all trains were stopped, fires were hauled and cleaned, the engines took on a special high-grade coal, new fires were built and the engines remained in the yard for an hour or more, coking these fires in order to get rid of superfluous gas. In addition, a helper engine was kept in the yard, which used the same grade of coal and with the same precautions. The train was divided into two parts, the helper engine taking about 400 tons through and the two Mallet engines afterwards taking the remainder of the train, say 1000 tons.

When weather conditions were bad it was almost impossible to get trains through the tunnel; sometimes it was necessary to wait two or three hours after the passage of one train before it was safe to send a second train through. Frequently the steam pressure in the rear Mallet engine would fall from 200 lb. to 70 lb. or less, owing to the impossibility of maintaining fires on account of the exhausted condition of the air in the tunnel. The train would then have to stop and be split into two sections, and it would be necessary to back the rear engine out with part of the train.

These conditions also had a very bad effect on the train crews. Good engineers would not stay on the division; it was considered dangerous service.

Under these conditions Mr. James J. Hill, finally determined, after several years' consideration, to try out an equipment at the tunnel with the express intention of using it on the entire mountain division, if it proved to be satisfactory. These were the conditions that led to the adoption of this particular system.

W. S. Murray: As a single-phase man in other fields I wish to say that as far as the Cascade Tunnel *per se* is concerned, I am heartily in agreement with Dr. Hutchinson's chosen method of electrification. It is my belief that the physical conditions call for this method. Assume any piece of trackage, either one mile or 300 miles in length, at constant grade, whether zero or such a percentage that admits of adhesion of the locomotive driving wheels, and with no stops in the schedule (or if inclusive of stops then with exceedingly low train acceleration). Under these conditions, particularly where single track is involved, thus eliminating any complication of overhead construction, it is my belief that the three-phase system would be correctly applied.

Dr. Hutchinson says that traction developed by motors of the three-phase type admits of 3 per cent or 4 per cent greater adhesion than in the case where single-phase motors are used. Now, the single-phase motor is admittedly heavier than the three-phase motor of the same capacity, and, therefore, if it lack adhesion in its torque developing characteristic—which statement is by no means accepted by all—the deficiency is taken care of by its excess weight, thus illustrating the old adage, " It is an ill wind that bloweth no man good."

Though the subject treats of a three-phase installation, I am sure that Dr. Hutchinson will not object to an effort at drawing the line between the application of three-phase and single-phase apparatus. Dr. Hutchinson speaks of the advantage of a frequency of 25-cycles. This frequency is also applicable to single-phase installations, but it is true that the use of three-phase apparatus assures less costly generators. This saving, however, is offset in the case of single-phase installations by less costly switchboards. It is interesting to note that it is not much more expensive to use three-phase generators for single-phase distribution, as the new type of dampened field cuts down the rising voltage on the idle phase, making it possible to develop and use three-phase current for commercial requirements.

Concerning the speed of trains propelled by three-phase or single-phase motors. Infrequently it is said that a train under three-phase propulsion is more certain of making its schedule, on account of its constant-speed characteristics. Now, there is no desire on the part of the single-phase motor not to go. If we should place impress 500 volts on the terminals of one of Dr. Hutchinson's three-phase motors, and on one of the New

Haven locomotive single-phase motors, subjecting neither to any load, the former, if a frequency of 25-cycles were used, would arrive at 300 revolutions and go no higher, while the single-phase motor would, in a very short interval of time, arrive at a speed far in excess of that of the three-phase motor. The speed of the single-phase motor depends simply on the balancing resistance of the train, at the voltage applied to the motor. If the required balancing speed is 60 miles an hour, there is a voltage that corresponds to this on the transformer; it is simply for the engineer to see that the controller is on the right notch to supply it. Speed is a direct function of voltage, and the single-phase motor receives its voltage without the interception of resistance. Resistance, both within and without the circuits of the motor, means loss. In the case of the three-phase motor, except cascade connection, resistance has to be inserted for all speeds below the normal slip-speed of the motor.

The true speed-torque traction curves for railway motors were given by the direct-current series motor long before the alternating-current motor, either of the induction or the single-phase type, put in an appearance. In general it may be said that this type of motor conserves the apparent necessity of a service having a motive power which, at high efficiency, will take care of variable-speed requirements made necessary by accelerations, slow-downs, and stops. Horse power is directly proportional to speed and torque. On a grade the series motor admits of a lower speed, which, taken with the increased torque requirements, tends to keep the horse power constant; in the case of the polyphase motor, the speed remaining constant with the increase of torque required, due to grade, the horse power rises. It is thus clear that the single-phase motor, with speed characteristics similar to those of the direct-current series motor, admits of maintaining nearly constant load upon it under varying conditions of grade: with the three-phase motor, the load, for the reasons stated, must vary over exceedingly wide limits. For example, Dr. Hutchinson's locomotive, when hauling a train up a 2.2 per cent grade, has to develop six or seven times as much power as when hauling the same train on a level. A constant load-factor cannot fail its appreciation, be it in a power house or an electric locomotive, and the illustration previously made is an attempt to bring out the just reason for Dr. Hutchinson's application of the three-phase motor to special conditions of constant grade, no stops or low acceleration, and that of the single-phase motor in the field which admits of great variation in grades and higher acceleration.

To exemplify more concretely the point made in the previous paragraph, Dr. Hutchinson says that the Cascade Tunnel electric locomotive requires only 20 per cent more power in accelerating a train in the tunnel grade than in running the same train on the same grade at full speed. This is interesting, and convincing as to the ability of an electric locomotive of this design to take care of the concrete conditions cited.

It is also interesting to analyze this conclusion. To accelerate a train on grade it is necessary to overcome three classes of resisting forces:

1. The inertia of mass.
2. The resistance of frictional parts.
3. The resistance of gravity.

At an acceleration at the rate of 0.1 of a mile per hour per second, the resisting force due to inertia of mass is 10 lb. per ton. The friction per ton in a freight train, inclusive of the locomotive, may be estimated at 8 lb. per ton, though this is high. The grade is stated to be 2.2 per cent. Gravity offers, therefore, at 20 lb. per ton, a total of 44 lb. Thus, the total resistance per ton to accelerating on the grade in question is 62 lb. After the train has been accelerated to speed, 10 lb. of this 62 lb. drops out, due to the disappearance of mass inertia. The ratio of 62 to 52 is practically 20 per cent, as Dr. Hutchinson points out. Under this analysis it is not difficult to see, however, why the ratio is so small. If we drop the acceleration to 0.05 of a mile per hour per second, then the difference would have been only 10 per cent. The two things that cause this ratio to be so small is the low acceleration and the high grade.

Exactly opposite conditions exist in high-speed suburban passenger service, where the acceleration is exceedingly high and grade is practically eliminated. As an example, under the conditions of no grade, a passenger train being accelerated at 0.7 of a mile per hour per second will require 70 lb. to the ton, and assuming the average friction per ton up to 60 miles an hour to be 10 lb., the total pounds per ton required is 80. After the train has arrived at the balancing speed of 60 miles per hour, mass inertia disappears; the remaining resistance, train friction, may be 15 lb. per ton. Now, it is seen that the ratio of the torque required to accelerate this train to the torque required to keep it at 60 miles an hour is 80 to 15, or the increase instead of being 20 per cent is 530 per cent. An acceleration of 0.7 mile per hour per second is not unduly high for a suburban service on trunk lines, and this analysis is an attempt to bring out the great difference between the case cited and the duty requirements of the Cascade Tunnel locomotives.

I agree with Dr. Hutchinson that in regard to mechanical clearance, ⅛ in. is ample for all practical purposes. The method suggested for dividing up the load uniformly on the motors by the insertion of resistance would seem to be practical. As these resistances must be continually in series it would be interesting to know what percentage of loss is incurred; doubtless it is low.

The single-phase system, such as, for example, that of the New York, New Haven & Hartford Railroad Company cannot claim any higher power-factor than that mentioned by Dr. Hutchinson in the case of the Cascade electrification. Power-factor in a system is an interesting detail. It is possible to be misleading. The New Haven road is a large user of single-phase power, and its power-factor seldom rises above 85 per cent. Indeed, it is more frequently below 80 per cent. It is well to know, however, exactly what power-factor stands for. A high-voltage system primarily stands for very low transmission losses. Let us assume, for example, that the actual transmission losses of the New Haven systems are between 5 and 10 per cent at unity power-factor. Even should the power-factor sink as low as 75 per cent, this would mean that the line loss, instead of being from 5 to 10 per cent, would be from 6.7 to 13.3 per cent. Remembering that many systems have a normal loss of 25 per cent, it would seem that the fluctuation of power-factor, even within wide limits, is not serious.

I am in agreement with Dr. Hutchinson that the yard proposition on two overhead wires is not practicable, and I also believe that this is true of main-line tracks where high speeds and many switches are involved. I wish to support Dr. Hutchinson's views in regard to simplicity, capacity, and reliability of the induction motor. I have always had the greatest respect for this kind of motor. It is my great regret that its electrical characteristics do not, in my belief, conform to those required by the general traction problem. It is to the alternating-current series motor what the direct-current shunt motor is to the direct-current series motor. The direct-current shunt motor has disappeared forever on all traction lines, and I do not believe that it can reappear under the cloak of alternating current.

E. B. Katte: Sometime ago I had the privilege of seeing one of the electric locomotives in the works of the manufacturing company and believe it will be hard to improve upon either the electrical or mechanical design for the speeds for which the engines are intended.

The reasons for adopting a three-phase system over the whole mountain division are quite obvious, but I am surprised to note that this same system would probably have been used if only a four-mile tunnel section was to have been considered. Without going into figures, it would seem that a direct-current system with storage batteries would have made unnecessary the use of steam locomotives in starting electric trains, and at the same time would have relieved the power station from the sudden inrush of current, thus securing better regulation at the water wheels. And further, by adopting multiple-unit control for the locomotives, two or more at the head end of a train could have been operated with one-half the number of men.

Dr. Hutchinson describes the ground-wire, provision for which has been made on the top of the transmission-line poles, but states that it has not yet been installed. I wish he would explain why the ground-wire was finally omitted. When the transmission line of the New York Central was designed, similar provision was made for a ground-wire, but after further consideration it was left out; for the reason that the poles were of steel and each carefully grounded to a large copper place set in permanently wet ground, and it was believed that each pole would act as a lightning rod and thus protect the line. However, on the Great Northern line the poles are wooden and the insulator pins do not seem to have been grounded, consequently if a ground-wire is ever necessary, these would appear to be conditions under which it would be most valuable.

The fact that wooden poles are used through forests leads me to ask if any special protection against destruction by fire was adopted. Last year when estimates were made for the information of the "up-state" Public Service Commission, covering the cost of electrifying railroads through the state forest lands, it was considered necessary to use steel poles because of the danger due to forest fires.

The experience with insulators covered with soot from steam locomotives is similar to that on the New York Central system. At first we were much perturbed because of the soot which was accumulated upon the 11,000-volt insulators in yards used by steam locomotives through which the transmission line passed, but after careful tests on several insulators which were well covered with soot it was found that the flashing-over point was several times the normal voltage even when the soot was well saturated with water.

Among the minor advantages to be derived from electric traction, brought out in this paper, is the possibility of knowing at any instant, by the direct reading of meters, the exact operating condition of any element of the system. I believe this to be more than a minor advantage and think it of very great importance and help to those charged with the safe and reliable operation of trains.

Bion J. Arnold. During the last summer I rode through the Cascade tunnel several times on the electric locomotives described by Dr. Hutchinson. I was interested in the operation of the system. It seemed to perform its work as satisfactorily as any direct-current or single-phase installation I have ever seen. It had the objectionable double overhead conductor, and the yard was necessarily somewhat complicated on that account. I agree with Mr. Murray that for a railroad with many yards—and many yards are the rule with steam railroads if an overhead conductor is to be used—the single-phase installation is preferable. That is one of the principal reasons why the single-phase system was used for the tunnel of the Grand Trunk Railway system between Detroit, Michigan, and Sarnia, Ontario—a tunnel installation similar to this, terminating at each end in a vast yard with a number of tracks, and located in a climate where snow and ice were likely to cover tracks—over which the train movements were infrequent. I concluded that under such conditions a third-rail might become iced or covered with snow, making it difficult at times to move trains. These and other conditions impelled me to adopt the single-phase system, and at a time when such a system had not been tried on heavy traction work. The Grand Trunk installation has been in successful operation for some years, and so far as I know there is no desire to adopt any other system.

We all know that both the direct-current system on the New York Central and the single-phase system on the New York, New Haven and Hartford are operating successfully. Mr. Sprague and others are advocating a high-potential, direct-current system, and I have no doubt that within moderate limits that system will be equally successful. All of this tends to show that while we may individually believe in some particular system, none of us can prove conclusively that his is the ideal system—and that when conditions arise which call for the development of a new system, such a system will be properly developed and applied.

I am surprised at the excessive friction of the Mallet compound locomotives. Dr. Hutchinson gives it as an average of 46 lb. per ton. Ordinarily the friction load for steam railway trains is estimated at 6 lb. per ton on level straight track. This excessive friction is probably due to the greater number of cylinders, reciprocating parts, and extra weight of the valve motion of these engines; and it indicates that some of the advantages of these immense engines are offset largely by this excessive friction, especially when they become a trailing load. What is the friction of these engines when running under steam? I assume that this table gives the friction when the engines are being pulled as trailers by the electric locomotive.

Dr. Hutchinson says he adopted a method which gave him a single speed, for his electric locomotives and that resistance was used when starting. He also says that one of the reasons for doing this was to obtain simplicity, giving as an additional reason that the power cost was nothing, being developed by water power, consequently he could afford to waste it in starting the locomotives. But such practice would not do in case the power were produced by a steam power plant on a railroad of any great magnitude. I think, therefore, that a different conclusion would have to be drawn as to the method of control to be adopted, in case the three-phase system were made applicable to a large railway system. In this respect Mr. Murray has pointed out the superiority of the single-phase system, as far as economy of operation and securing of variable speed is concerned.

F. N. Waterman: As one who has advocated the consideration of three-phase motors for railway work, I am particularly gratified by the evidence of its advantageous application as set forth in the paper of the evening. There is one interesting property of induction motors which is not exhibited in the present instance, because only one train is operated; namely, the action of moving trains as fly-wheels to keep down the peaks or to minimize the fluctuations of output of the central station. This was illustrated by the operation of one of the electrified divisions of the Italian state railways, known as the Valtellina line. The traffic comprised freight and passenger service, with an average of from four to six trains running simultaneously. With only one train running, as occurred at the extremes of the day, the ratio of maximum to average ordinate of the output curve was about 3.5 to 1. The average run was short, requiring frequent accele ation. With a number of trains on the line, the ratio of maximum to average output fell to 1.7 or 1.8 to 1, giving a load-factor of 55 to 60 per cent. The reason why the ratio of maximum to average was as favorable as 3.5 to 1 with single train operation, was the employment of the cascade control for most of the trains. The freight was handled at that time, in the manner adopted by Dr. Hutchinson, by rheostatic control with a low rate of acceleration. The remarkably favorable results on the Italian state railways was unquestionably due to the peculiarity of induction motors, that they cease taking current if the frequency falls by the amount of their slip, and return current if it falls to a greater extent. The water wheels driving these generators fell off in speed some five per cent, as full load came on, while the average slip of synchronously running trains was less than one per cent. Hence, as the shock of starting a train came upon the power house, the frequency fell, and it had to fall only one per cent entirely to relieve the station of other loads. A further fall would cause the moving trains to return energy to the line and help supply the starting current. This momentary relief of the station resulted in the high load-factor noted. It would appear that this property of induction motors should be of great value where a small number of trains is operated.

Of course, relief of the power house by this means is only momentary. Whether it would be of consequence at all in such a proposition as Dr. Hutchinson is dealing with is perhaps problematical. The starting of a 1600-ton freight train is a very different matter from the acceleration of a 125- or 150-ton passenger train, and the time-interval during which the fly-wheel action is effective might very readily be so small that the advantage would not be realized to anything like the same extent, but it is a property resulting from the constant speed characteristic of the motor, which in many cases is of large consequence, and in any case is extremely interesting, as being not merely a theoretical deduction, but as proved out in the practice of the Italian State Railways. The tandem control, which has been spoken of as " messy ", is employed by the Italian state railway, even on a recent installation, which is like this Cascade installation in being a through haul on a constant grade.

I had some calculations made a short time ago showing the effects of tandem control of three-phase motors in comparison with the series-parallel control of the New York Central locomotives. It was impossible to include a computation for the single-phase locomotive, because sufficiently accurate information regarding the performance of single-phase locomotives was not available. Table I shows that the tandem control with two speeds—a method that leaves the entire equipment available for either kind of running—is at least not inferior to the New York Central locomotives, employing four motors and their three groupings, in respect of maximum draught on power house or total energy consumption, but is rather better. If handled on the basis of constant-current input, which is not the custom in direct-current practice in this country, I believe the three-phase locomotive will show rather a noticeable advantage when the application of the three-phase motor to railroad work has received the same thorough study and development as given to the direct current motor. If experience abroad may be taken as a criterion it will be found superior for many purposes, to any other form of motor.

COMPARISON OF THREE-PHASE AND DIRECT CURRENT LOCOMOTIVES.

Type of locomotive	Total train weight tons	Net train weight tons	Distance in feet	Time in sec.	Speed maximum miles per hour	Kilowatt maximum	Kilowatt hours	Watt-hours per ton-mile gross	Watt-hours per ton-mile useful
New York Central (weight 95 tons)..	435	340	27300	426	58.4	1920	110	49.4	62.8
Valtellina 2 speed type (weight 68 tons)	408	340	27300	426	58.5	1660	104	49.1	59.4
Valtellina 3 speed type (weight 68 tons)	408	340	27300	425	58.5	1660	91.5	43.5	52.3
New York Central..	265	170	29800	403	60.5	1800	82	54.9	85.5
Valtellina two-speed type............	238	170	29800	404	59.5	1660	71	52.8	74
Valtellina three speed type............	238	170	29800	402	59.5	1660	60	44.7	62.5

Notwithstanding the use of cascade control on the Valtellina locomotives, the control apparatus is much more free from complicated or messy apparatus than that of any electric locomotive in use here. This results from the use of liquid rheostats with compressed-air control. A limit relay is used to maintain the rotor current constant, and the rate of acceleration is determined merely by the notch in which the handle of the controller is set. In the simplicity and small space requirements of the control apparatus there is a great contrast in the appearance of these Valtellina three-phase locomotives and that of the large locomotives in use in this country.

From a mechanical point of view I was much interested in the motors of the Italian state railways. The clearance used there between rotor and stator is 2 mm., about

$\frac{1}{16}$ in., and the wear of the bearings, in some 60,000 miles of operation on these locomotive motors, was about 0.3 mm. The reason for such a result is that the collector rings are outside the bearings, leaving it only necessary properly to proportion the spiders to have virtually the entire interior of the rotor for bearings and lubricating means. While the three-phase motor, particularly if arranged for cascade operation, requires an air-gap as small as $\frac{1}{12}$ in. the remedy is present in ample bearing space. Dr. Hutchinson points out some of the advantages of the three-phase motor; the foregoing seem to me to be further advantages.

J. H. Davis: The system described marks an epoch in the history of heavy railroad electrification in the United States. It is the first attempt in this country to use the three-phase induction motor for handling heavy passenger and freight trains on a trunk line railroad.

I am especially impressed with the importance of the electrical engineer's decision in recommending the adoption of a certain system of electrification. His decision is second in importance only to that of the engineer locating the railroad. A decision to use this or that system of electrification for a certain purpose, as, for instance, handling heavy traffic over a mountain division, will, of necessity, have great weight in determining the system of electrification to be used when other divisions of the road are electrified. The system thus adopted may or may not be that which is best suited for the desired extension. If the entire road is eventually electrified, one system of electrification should be used throughout, although this system may not be best adapted to all of the various conditions to be met. Therefore the system adopted should be that which is best adapted to the requirements of the road as a whole. The necessity for interchange of equipment from one division to another is well known, and in meeting this requirement the electrical engineer can best obtain simplicity of equipment by confining himself to one system of electrification. The gain in this direction will be more than sufficient to offset the loss due to the adopted system not meeting in the best way some of the conditions.

Inasmuch as the conditions at Cascade Tunnel are very similar to those encountered on the Belt Line Railroad of the Baltimore & Ohio, where direct-current electric traction has been used for 14 years—this being the first installation of electric locomotives for heavy traction purposes in the United States—a comparison of the physical conditions, train weights, tonnage handled, equipment used, etc., may be of interest. This comparison I give in the subjoined Table I.

It might be added that the working conductor on the electrified section of the Baltimore & Ohio was originally placed overhead, its design, however, being very different from that used at the Cascade tunnel. The low working voltage on the Baltimore & Ohio necessitated the collection of a large amount of current, and a rather complicated overhead construction was necessary. Serious trouble was experienced in maintaining this overhead structure, and for this reason it was abandoned and the third-rail installed.

TABLE I.

Physical conditions:	B. & O. R.R.	G. N. Ry.
Length of electrified section	3.7 miles	4.0 miles
Ruling grade	1.5%	2.2%
Average grade	1.0%	1.7%
Length of longest tunnel	7,400 ft.	13,873 ft.
Train weights:		
Freight, including steam and electric locomotives	1928	2075
Passenger " " " " "	990	906

Tonnage handled per day:	B. & O. R.R.		G. N. Railway	
	No. of train	weight	No. of train	weight
Passenger	21	6,630	3	2,690
Freight	28	29,600	2.5	5,290
Special	0		1	470
Totals	49	36,230	6½	8,350

Equipment:	B. & O. R.R.		G. N. Ry.
	Pass.	Freight	Freight
Number of locomotives	5	2.5	4
Weight, tons	90	160 (2 units)	115
Number of motors	4	8	4
Rated horse power	1,100	1,600	1,900
Tractive effect, rated load	26,000	70,000	47,600
Speed at rated load, miles per hour	16	8.5	15

NOTE:—Data on B. & O. equipment based on natural ventilation: Great Northern on forced ventilation.

L. R. Pomeroy: About seven years ago I made an examination of the Cascade Tunnel to determine the possibilities of electrification. At that time it was very difficult to arrive at the actual cost of steam operation, on account of the fact that the motive power statistics furnished were for average and general conditions, complicated by the addition of constructive switching and arbitrary mileage.

Since then I have been furnished with a road test of a Mallet locomotive over the section described in the paper, namely from Leavenworth to the Cascade Tunnel summit, a distance of 32.4 miles, with an average grade of 1.35 per cent and a limiting grade of 2.2 per cent. Also from a neighboring road, having similar physical conditions, an actual coal record; that is, tons of coal used for a period of six months, of individual classes of locomotives, representing 156 locomotives making 1,382,092 miles, and consuming 174,121 tons of coal, as follows:

No.	Class	Engine-miles	Tons of coal	Pounds per 1000 ton-miles	Pounds per engine-mile
55	2-8-2 simple.	291,070	33,418	191	230
6	2-8-2 compound.	81,150	10,275	175	251
24	2-8-0 simple.	299,036	33,931	345	227
71	2-8-0 compound.	710,836	96,479	306	271
156		1,382,092	174,121		

Some figures of the test referred to are as follows:

Distance	32.4 miles.
Running time	4 hr. 0 min.
Time lost in stops	3 " 4 "
Total time	7 " 4 "
Average speed (miles per hour)	8.1 miles.
Pounds of coal used per trip	23,100 lb.
" " " " " square foot of grate, per hour	74.03 "
" " " " " mile	717 "
" " " " " 1000 ton-miles	896 "
Average tonnage hauled	810
Average number of cars per train (all loaded)	21
Average grade	1.35%
Maximum or ruling grade	2.2 %
Indicated tractive force	60,000 lb.
Type of locomotive 2-6-6-2 (L2)	Mallet
Total weight of locomotive	225 tons.

From the foregoing data the writer desires to present a few deductions.

A train with a trailing load of 2500 tons over the section of road on which the test was made will require about 5750 kw-hr. at the rail per trip.

Assuming a modern steam generating station, the coal used per trip at 15 miles per hour would be about 5 lb. per kw-hr. (at the rail) or a total of 28,750 lb. With the same tonnage per train under steam conditions at 15 miles per hour, three steam locomotives would be necessary.

Increasing the speed of the steam train from 8.1 miles per hr. to 15 miles per hr., reduces the tonnage about 30 per cent per locomotive. 810 tons trailing load plus 225 tons, the weight of the locomotive, times 70 per cent, equals 725 tons per locomotive. The coal consumption of the steam train then becomes 32 miles times 717 lb. per mile times three locomotives, equals 68,832 lb. Percentage of difference in favor of electricity:

$$1 - \frac{28,750}{68\,832} = 58 \text{ per cent.}$$

Going back to the coal used by the 156 steam locomotives—these locomotives are used on two mountain divisions—for six months; namely, 174,121 tons. For a year the amount would equal 348,242 tons. At the rate of $2.00 per ton for Crow's Nest coal, the cost of coal equals $696,484. Also the cost for water used would be about $25,000. It has been shown that the coal saving amounts to 58 per cent. Calling this one half or 50 per cent, the saving would equal $348,242. It is claimed that the Mallet type of locomotive is 30 per cent better than the types composing the 156 locomotives referred to. We will, therefore, reduce this amount to correspond. $348,242 times 70 per cent equals $243,769; add the saving in water, $25,000, and the net saving then becomes $268,769. This amount capitalized at 5 per cent represents $5,375,380. This amount alone, not figuring on other savings, such as train crews, reduction in train-mileage with the same tonnage, and the advantage of a great increase in capacity, would go to show that such a mountain section comes very near being a situation where we can accomplish by electrification what is now impossible under steam conditions.

In the table of test data it will be seen that the time to make the run was 7 hr. and 4 min.; time consumed in stops or laying in side tracks, 3 hr. and 4 min.; time in motion, performing useful work, 4 hr.

Approximate figures from four railroads which give separately in the annual reports the coal per locomotive-mile for freight and passenger service, based on the total coal charged to engines for the year, the consumption per horse-power-hour is as follows:

	Passenger	Passenger and Freight	Freight
Road A	12.30		9.64
" B	12.86		11.20
" C	14.00		10.00
" D		10.63	

while from individual road tests we find the coal consumption frequently is from 4 to 8 lb. per horse-power-hour.

The point that I desire to make is that it is not quite fair to the electric side to base the comparative costs on a road test without adding a liberal amount to cover this "contingent" feature.

In Tables III and IV the resistance of the Mallet locomotives is shown to be in the neighborhood of 50 lb. per ton exclusive of the resistance due to gravity. This is not to be wondered at when the sizes of the pistons are taken into consideration. The L-1 locomotive has cylinders 21.5 in. and 33 in. by 32 in. stroke and the combined area of the four pistons is 2436 sq. in. If atmospheric pressure of 15 lb. per square inch is figured against the low-pressure pistons only, the thrust equals 25,659 lb. A large share of this piston resistance is by-passed, but the fact that these locomotives cannot drift freely down a hill without a slight opening of the throttle, and from the tests shown in the paper, it would seem that the by-pass valves should be supplemented by some form of drifting valve which would result in materially reducing the resistance found in towing the locomotive with closed throttle. It is customary with some railroads to base the value of saving due to elimination of curves and grade reduction, not on the increased capacity, but on the money value of a reduction in train-miles. For example, on a division of 225 miles having seven freight trains per day the value of each one per cent in reduction of train-miles is about $3000 per annum, the capitalized value of this amount at 5 per cent per annum equals $60,000 for each one per cent of saving. The rate per train-mile being 50 cents, which represents the costs directly affected; that is, transportation expense not general expenses. This being the case, figures representing costs of electric service on this basis will directly appeal to railroad managers; whereas figures based on increased capacity are more or less problematical and open to doubt.

W. N. Smith: Although for a dozen years or more the three-phase system has been firmly established as the standard for general power transmission, certain disadvantages incident to its use have until now deterred engineers in this country from undertaking to avail themselves of some of its inherent advantages in heavy electric traction. It has been reserved for the author of the paper to be the first in the United States to reduce theory to practice and to place before us a general description of the construction and performance of a type of electric locomotive which, so far as this country is concerned, has never before emerged from text books and technical papers.

It seems to me that in the case here treated, operating conditions are such that the advantages of the three-phase system are of maximum importance, and the disadvantages of minimum importance. The relative advantages are clearly stated by the author and need no further comment. On the other hand, the chief disadvantages of the three-phase system, reduced to their lowest terms, are the harnessing of the inherently constant-speed motor to variable-speed duty, and the necessity of two trolley wires instead of one.

The first objection is largely minimized in this electrification by the nature of the train service and the character of the railroad line itself, both of which favor maintaining a constant speed. Whether or not there is any valid objection to maintaining a constant speed on a long railway line on the surface, there can certainly be none to doing so in a tunnel; and the speed is so moderate that the relatively inefficient performance during acceleration is not of long duration in proportion to the entire length of the run. In this case the acceleration seems to last about 1.5 min. out of the 12 to 14 min. that would be required to make the tunnel run.

The objection to two trolley wires is partly obviated in this case by the slow speed of 15 miles per hr. In my opinion this is the salvation of the wheel-trolley contact system here adopted. But even slow speed cannot mitigate all the disadvantages of two trolley wires of opposite polarity.

I have somehow received the impression that our European friends operate their railroads under some conditions that seem inapplicable to our roads. They appear to have a somewhat different view-point, to which both the employes and the public are accustomed: they pay strict attention to methodical detail all down the line, and subordinate the results thereto; while in this country the aim is more toward the final result and all possible time-consuming details are regarded as secondary to that result. This is the only way I can account for the favor with which the Europeans apparently regard the use of two trolley wires. They seem to have tackled this phase of the problem with remarkable freedom from the prejudice against it that has always existed in this country.

In a long straight tunnel taken by itself the double-trolley construction adopted by the author does not seem to present any unusual difficulties in maintenance. It seems to have been experienced in long-tunnel electrifications that the transition period from steam to electric power is the time when insulation is most likely to fail. The worst difficulty with the double-trolley wire seems to me to be at track intersections where moving contact must be made at will, upon intersecting wires of opposite polarity, without risk of short-circuit, and without danger of temporarily checking headway and injuring draft-gear by losing power for a few seconds when accelerating a heavy train at slow speed. The first of these considerations is all-important. The second depends on how many chances it is safe to take by temporarily cutting off or reducing the locomotive torque while starting a heavy train. Under the conditions of the Cascade Tunnel electrification, with main and side tracks at tunnel portals on a two per cent grade, it would seem necessary to have two sets of trolleys in contact, one set at each end of the locomotive when passing switches, at least whenever conditions make steady acceleration difficult, as with snow on the rails and journals stiffened by frost, and excessive train weight.

The paper betrays some dissatisfaction on the part of the author as to results so far accomplished with the double-trolley system as here developed. In working out improvements he will have the sympathy and encouragement of all who realize that, after all, the mechanical reliability of the moving contact system is the very foundation of successful electric railway operation, regardless of the kind of current employed. It is this feature that appeals to me as being susceptible of the greatest improvement. It is in respect to the trolley problem that the single-phase system is likely to be regarded as superior for some time to come.

It seems to me that future development in the perfection of the moving contact will be in the way of the wide roller type with pantagraph mounting, as distinct from the narrow trolley wheel or the sliding shoe; for the sliding shoe, widely used for high-speed work at the present time, seems susceptible of further betterments, if wear and tear at high speeds and heavy currents are to be overcome.

It is quite conceivable that ultimate speeds of 20 to 30 miles per hour may sometimes be thought advisable for some classes of train service on a mountain-grade line of this type instead of the 15-mile speed chosen for the heavy freight service of this installation. This refers more particularly to fast passenger and light freight trains. Train-speeds that operating economy may demand in the future ought not to be rendered impossible by the limited reliability of the time honored trolley wheel for high speed in such heavy service, particularly when passing switches.

The same considerations of speed prompt the opinion that the next locomotives to be built for this electrified section, or a similar one, will be fitted either with pony wheels or with side-rods for coupling to motors placed on top of the frames, or possibly with both of these contrivances. There seems to be no mistaking the tendency that has set in during the last two or three years, for electric locomotive construction to be guided more and more by the experience gathered during the two generations of steam locomotive practice. The boasted simplicity of the geared or gearless motor hung directly on the locomotive axle has proved disadvantageous in some other respects. The increased flexibility of locomotive design from the mechanical standpoint, which is consequent upon placing the motor on top of the frame and using side-rods and jack-shafts, and the general mechanical uniformity with the frames and running gear of existing steam locomotives, will make an electric locomotive appear more like a standard piece of machinery to the railroad operating man than has hitherto been the case. The great advantages will be the raising of the center of gravity, the ready standardizing of mechanical parts independently of electrical equipment, and the ability to use the same arrangement of frames and running gear for either direct-current, single-phase, or three-phase motors. With such construction safe speeds are not limited to 15 miles per hour. Without it, track maintenance and liability to derailment would likely continue to be as disadvantageous to the electric locomotive at high speeds as they have in the past.

One feature of the author's description of the performance and rating of the locomotive motors which is of particular interest is that emphasis is put upon the continuous capacity, as well as the one-hour rating and the maximum tractive effort. In spite of the objections that have been urged against the term "continuous capacity" as applied to railway motor specifications, the author apparently takes it for granted that it is bound to survive; and it is to be hoped that its evident applicability to the specification of locomotive motors will lead to a more universal recognition of its appropriateness in specifying the smaller sizes of railway motors.

The author's estimate of the power station fuel consumption of these electric locomotives as compared with the Mallet compound steam locomotives, while interesting, would be more convincing from an economic standpoint if submitted in greater detail. The chief advantage of electric traction, demonstrated by the paper, is the increase of the capacity of the tunnel and adjacent mountain section, by doubling the speed possible with steam locomotives of the most economical type. Moreover, there are still other operating features, such as the location of passing sidings, and the signalling and train-dispatching system governing the physical possibilities of getting the trains past each other at the increased speed, which have need of full consideration in order to determine the economic value of the increased speed made possible by the electric system.

F. S. Denneen: The chief reason for selecting the direct-suspension type instead of the more elaborate catenary type, now so popular, was the greater mechanical and electrical simplicity of the former. It is at once evident that with two wires over each track, with 6600 volts between them and between either wire and the ground, the problem of insulating the catenary type of construction would be a difficult one. With several tracks having numerous switches and intersections the problem would be greatly complicated. Within the tunnel the available head-room and side-wall clearance were so small that the catenary suspension was not desirable. With the speed limited to 15 miles per hour, many of the advantages of catenary construction over the direct-suspension type would be lost. A careful study of the entire situation then led to the conclusion that the direct-suspension type would fully meet all operating requirements, and, at the same time, because of greater simplicity, repairs could be much more quickly made, thereby reducing the danger of appreciable delays in the service.

The overhead structure in the yards on single track consists of the bracket shown in Fig. 20. It will be seen that each phase is supported by an independent span, and that auxiliary insulation is provided in every case; that is, the major insulation may be said to consist of the two heavy porcelain strain insulators marked *E* and the auxiliary insulation, the wood break strains marked *A*. The porcelain strains are rated for 10,000 volts, while the wood break strains might be rated at 3300 volts, or more. If I remember rightly in certain parts of the yards it was necessary to provide overhead construction for as many as six tracks; the details of the design work have somewhat slipped away from me, because it is more than a year and a half since I had anything to do with it. It was not possible to place any supporting means between the tracks and the entire overhead structure had to be carried on cross-span construction, which, because of its flexibility, made the insulation a difficult matter.

Fig. 17 shows that wires of the same phase are carried upon one cross-catenary, while those of the opposite phase are carried upon another one, also that there is insulation between the wires of the same phase over different tracks. This was done in order to make the tracks entirely independent, and to make it possible to cut out any one track or any set of tracks. Fig. 18 shows a unit system, that is, it is arranged so that by removing one or two bolts a new piece or a new unit can be quickly inserted without serious interruption to service. Adjustment by means of suitable turn-buckles is provided at every point where necessary.

Within the tunnel, the end-section of which appears as Fig. 21, the details of the overhead construction appearing as Fig. 22 and 23, bronze fittings were used in most cases. There was a great deal of moisture and drip, but it was not known how much of the moisture was due to the steam from the locomotives and how much from the drip through the tunnel roof. To provide against corrosion, bronze was largely used. Dr. Hutchinson says it is possible that malleable iron and steel properly galvanized would have done as well.

Dr. Hutchinson refers to the trouble experienced at the intersection of lines due to the trolley leaving the wire, this trouble occurring as the trolley wheel crossed the pan-casting. At the time the layout was originally made, a scheme was considered for automatically turning the tongue portion in the pan so as to carry the wheel across in the proper direction, but this scheme complicated the arrangement and was not used.

When the original tunnel layout was made, the trolley wires were set 5 ft. apart, but after the designs had been worked out and approved by the railway engineers, the officials of the road decided that they wanted the entire central part of the tunnel clear, so it was necessary to set the trolley wires out to a separation of 8 ft. within the tunnel, which added a number of difficulties. The clearance between the side walls and the trolley on either side was only approximately 14 in., and as it was necessary to prevent the trolley from swinging, it was somewhat difficult to put in steady members with double insulation. The steady device used consists of two porcelain insulators of the ordinary skirt type of about 22,000 volts rated capacity, placed in series; the insulators are fastened together in a vertical position by means of a U-shaped casting with the ends cemented into the insulator pin holes. Each insulator carries a malleable iron cap, one of which is attached to the trolley wire and the other to the side wall of the tunnel. The connecting U casting is provided with a flanged portion all round, to protect the porcelain from blows from the trolley wheel. The large strain insulators used in the tunnel are capable of working at 20,000 volts, and the porcelain links at 10,000 volts; either could be broken,therefore, without interrupting the service.

It was the aim to provide against the likelihood of failure due to electrical or mechanical trouble with the insulation; for this reason heavier insulation was used than heretofore, for lines of this voltage.

W. I. Slichter: It is to some of the minor features and problems of the designing engineer, that I would like to call especial attention. The principal characteristic which differentiates American from European railway installations is size. Our trains are about three times as heavy as the European trains, and our heavy traffic over single-track roads requires that every operation must be performed with the utmost reliability to prevent costly blockades.

In the locomotives under consideration it was necessary that there should be developed a tractive effort about three times as great as that developed by the foreign locomotives, and the practice of pushing a 2000-ton train up a 2 per cent grade required that this tractive effort should be applied gradually, steadily, and continuously, as any sudden variations in a tractive effort of this large value would almost certainly result in breaking a train in two and possibly in causing a wreck. Thus the control system of such a locomotive is a most vital feature. There can be no reduction in the tractive effort after it is once applied, and there must be sufficient control-steps so that successive increments of tractive effort are not so great as to slip the wheels or strain the draw-bars to a dangerous extent.

These conditions rendered any scheme of double-speed connection, such as concatenation or changeable poles, undesirable, as in these it is necessary to cut out at least a portion of the motors while the change is being made. In this particular case the character of the service and the low speed of the locomotive eliminated the necessity of having more than one running speed. The problem was then to provide a control system which would give a steady acceleration and yet provide for running at fractional speeds for short intervals of time such as 15 min., as contrasted with continuous running.

This is accomplished by using plain rheostatic control in the secondaries of the motors, varying the resistance by contactors and providing sufficient capacity in the rheostats to permit of running for 15 min. at full load. Of course this means that the locomotive takes full rated power from the instant of starting; but the percentage of power wasted in this way is not great, as the running time is long compared with the time occupied in starting.

The control system consists of fourteen contactors per motor, five of which are in the primary, there being one contactor on one phase and two on each of the other two phases to provide for reversing the motors. This leaves nine contactors in the secondary to give thirteen steps, which is accomplished by a scheme of dividing the resistances into two or three groups, each having its contactor; and these groups are brought into different combinations so that each group is used over and over again, some times in series, some times in multiple with the others, and not left idle after being used once.

Of course this involves increasing the resistances unequally in the three phases, but this unbalancing has been kept within such limits that the torque per ampere is never less than 90 per cent of that with balanced resistances on all steps, and this loss is of far less importance than the inconvenience that would result either from increasing the number of contactors or decreasing the number of steps. As Dr. Hutchinson has said, an additional step has been obtained by closing the circuit at starting on two of the four motors before the circuit of the remaining motors is closed, thus the tractive effort on the first step is about 10,000 lb. and on the second 20,000 lb. and while accelerating at an average tractive effort of 37,500 lb. the tractive effort may be kept within the limits of 41,000 lb. maximum and 35,000 lb. minimum.

A separate and independent set of resistances is provided for the secondary of each motor to avoid the tendency of the motors to exchange current and " buck " when they are all connected in multiple to one set of resistances. If the driving-wheels were of exactly the same diameter, this multiple connection would act as a side-rod and tie the motors together; but as there are apt to be inequalities in the diameters of the different driving-wheels, a considerable load might be put on the motors in merely slipping the wheels to make them revolve at the same speed. As it is, the only effect of the existence of driving-wheels of different diameters is to cause a slightly unequal division in the load on the motors, which may be cared for by the auxiliary resistance referred to by Dr. Hutchinson. At the same time the natural tendency of the wear is corrective, tending to wear most on the larger wheel.

The advantage of the induction motor, due to its peculiar adaptability to regeneration, is best illustrated in this instance by considering the amount of energy which is regenerated and which would otherwise have to be dissipated in rheostats. To hold a train having a gross weight of 600 tons on a 2.2 per cent grade would require a resistance capable of absorbing 650 kw. per locomotive for the time during which the braking occurred. This corresponds, in size of rheostats, to the condition of running continuously at a speed of 4 miles per hr. with an input of 460 amperes per motor and a tractive effort per locomotive of 37,500 lb.

A very prominent feature of regeneration with the polyphase induction motor is the simplicity of its operation. As the greater part of the train gradually passes the summit and comes upon the down grade the speed gradually increases from 15 miles per hr., to 16.5 miles per hr., and without any attention on the part of the motorman the locomotives change their function from motoring to generating and from taking 1000 kw. from the line to giving back approximately 600 kw. Meantime there has been a tendency on the part of the generators in the power house and the water wheels to increase in speed with the speed of the motors on the locomotive.

This tendency is made use of by means of a centrifugal device to throw in circuit the water rheostat mentioned by Dr. Hutchinson, and located just outside of the power house. This rheostat takes the energy generated by the motors and holds the speed and frequency of the system down to normal. The water box is controlled in such a way that with a very slight increase in speed of the water wheels or generators the resistance is thrown across the generator bus-bars. When the speed has become constant the resistance in circuit remains constant, and, conversely, as the speed decreases the resistance is drawn out of circuit. With a growth of the system and increase in the number of locomotives operating at once, this rheostat in the power station would be used less and less and more of the regenerated energy would be usefully employed.

E. F. W. Alexanderson: Looking at the design of the motors on the Great Northern locomotive as an induction motor, nothing new is to be found except in the proportions. In order to meet practical railroad requirements the mechanical clearance is three times as large as is usually made in a stationary motor of the same type, and twice as large as it has been made in certain well known three-phase European locomotives. As illustrating that the predetermination of the characteristics of induction motors has become almost an exact science, even when the proportions do not allow their derivation from other existing machines, it may be mentioned that the characteristic curves and overload capacity of the motor from test agree within the errors of measurement with the data submitted with the contract.

The interesting part of the problem in this case is the adaptation of the induction motor to railway requirements. The motor, as mentioned in the paper, considerably exceeds the specifications of capacity in continuous operation for a given temperature rise. In the case of a stationary motor of the ordinary kind, such a result would be a criticism of the design. With a locomotive motor it only emphasizes a fact borne out by experience in several instances, that the success of an electric locomotive depends more upon a certain balance of design than the ability to meet a definite service requirement; in other words, the maximum tractive effort of the motor must have a certain relation to the weight on drivers, and a locomotive motor that lacks overload capacity would be unsuitable even if it should meet the specified requirements in the most creditable way. Railway motors of the ordinary type are in most cases limited in capacity by the temperature-rise in service; this is substantiated by the fact that there is allowed a higher temperature than that found economical with stationary machinery.

The continuous capacity of such motors of the closed type is usually about one-third of the capacity for one hour, whereas, the continuous capacity of the Great Northern motors with forced ventilation is 79 per cent or 74 per cent of the hourly capacity at 500 volts and 625 volts respectively. In attempting to meet the Great Northern requirements, it was immediately apparent that a motor of any reasonable size would run too hot unless forced ventilation were used. It was naturally attempted to make the artificial cooling as efficient as possible by taking advantage of the structure of an alternating-current motor with distributed windings, thus bringing the air into intimate relation with the active parts. In order not to waste space in the length-direction of the motor—which had already been encroached upon by the double gearing—the air is led through holes or channels running longitudinally through the core. This system of ventilation proved successful, and the tests show that the continuous capacity with forced ventilation is practically the same as the hourly rating on a standard basis without ventilation. It is most gratifying to see in Dr. Hutchinson's analysis of operating conditions that the design is well balanced, and that the continuous capacity is in proportion to the maximum work the locomotive may be called upon to do with a given weight on the drivers.

The weight-efficiency of the three-phase railway motor is often referred to. It might, therefore, be of interest to compare the Great Northern motor with two other well known locomotive-motors—the Detroit River tunnel locomotive (a freight locomotive of the same weight and mechanical design provided with four motors of the double geared type), and the Simplon, a well known three-phase locomotive. In the same table is shown the comparative figures for a stationary three-phase motor of the same dimensions. All three induction motors have practically the same armature peripheral speed, and the weight per horse-power is favorable. The Simplon motor is favored by a small air-gap, but handicapped by being wound for high voltage. No data are available for another three-phase railway motor with forced ventilation, but the capacity at 40 degrees rise of the Great Northern and the stationary motor gives a sufficiently good comparison. As might be expected, the weight per horse power in this case is somewhat greater for the railway type of motor on account of the air-gap being more than twice as large. The comparison of the four-motor types shows a relative consistency and also indicates the great possibilities of the inductive motor for high continuous output.

	Detroit River tunnel 600-volt direct current	Great Northern 625-volt three-phase	Simplon 3000-volt three-phase	Stationary motor 550-volt three-phase
Weight	8330	12200	22000	11500
Air-gap		0.125	0.059	0.050
Peripheral speed in feet per minute	2450	3440	3250	3550
Horse-power hourly—75 degree rise	300	550	1100	——
Weight per horse-power	29.5	22	20	——
Horse-power continuous—75 degree rise	—	400	—	——
Weight per horse-power	—	30.5	—	——
Horse-power continuous—40 degree rise	—	260	—	330
Weight per horse-power	—	47	—	35

C. L. de Muralt: I am one of those who desire that each system shall have a fair show. I do not propose to advocate that any one system shall be used exclusively. The three-phase system has advantages which have already been thoroughly appreciated, and which will be more appreciated the more it is used, and I think it will be used extensively. But the other systems have also their advantages, and these systems will no doubt be continued to be used. It is for the broad-minded man to understand and realize and appreciate the advantages and disadvantages of each system. Engineers, in considering the electrification of steam railroads, must decide which system presents the greatest number of advantages and the least number of disadvantages in each particular case. There is no such thing as a universal system. There is no universal steam locomotive now. We might as well put forward one type of steam locomotive to haul all of our steam trains, as to put forward any one electrical system for hauling all our electric trains.

What Dr. Hutchinson brings out principally, to my mind, is that the efficiency of the three-phase system is extremely high. I have claimed that for some time, but have met many doubters. We have now an American example which shows conclusively that I actually underestimated the efficiency of the three-phase system. There is no other system that will show the same efficiency under the same conditions.

The recuperative feature has also been rather underestimated by me. Dr. Hutchinson's paper shows conclusively that the regeneration of the trains on the down grade is fully up to the calculated results. There is, of course, no reason why actual experience should disagree with calculations on this subject. But the full commercial value of recuperation has not been brought out. It cannot, because this is too limited an application of electricity. When the road is extended and operates over a longer distance it will show this also. In Europe, where roads are operating over long distances, with several trains on the line at one time, good use is made of the recuperative feature. Many mountain roads in Switzerland do not need any thing like the amount of energy that would ordinarily be required to propel the trains up-grade, because the power returned by the trains descending the grade helps out the power station.

Some engineers claim it is not good practice to use two trolleys. Unquestionably, one would be preferable; but two are used, and have been used for years, under conditions where switches are placed as close together as the tracks will permit, and these trolleys have been operated successfully. It is not an operating feature at all; it is a matter of suitable design, and proper location of overhead line. Once these are taken care of, the road will operate with two overhead wires just as well as with one. There is hardly any difference in maintenance either, because the maintenance cost is made up of labor rather than of material, and the same track-gang that must be kept waiting to take care of an occasional break on a one-trolley line will also take care of an occasional break on a two-trolley line.

The constant-speed characteristic is of course an engineering question, a question that needs to be carefully investigated in each particular case. It will not do simply to say that the series characteristic is advantageous. It may be so in many cases but not always. Sometimes it is disadvantageous, and for main trunk line operation I think it generally is disadvantageous. It is all very well to say that the constant-speed characteristic means increased power when the train runs at full speed up-grade. But those who have ridden up hill in an automobile, and watched the automobile slow down until it stopped, will want a constant-speed machine for grade work, and not a variable-speed machine. Of course when the locomotive does not do its work, it does not use any power. But the amount of energy consumed by a train running at slow speed and using small power, is not one whit smaller than the energy consumed by a train running at high speed and using big power, because the big power will be used for a shorter period only.

Calvert Townley: One point has not had as much emphasis as its importance deserves. The advantages of electric over steam traction and the possibilities of using mountain streams to supply electric power to the Western railroads have been much discussed on paper. Here is a case where the installation has actually been made. A large steam railroad, backed by abundant capital, and officered by men of high professional standing has electrified a section of its line at heavy expense. The type of apparatus selected, its performance, and characteristics, in which we, as electrical engineers, are natually much interested, important though it may be, is really secondary. The greatest importance attaches to the adoption of electricity to replace steam in this sort of service for the first time. It means more than any mere question of the electric system selected. We hope that this installation will be successful; that it will be extended; that the road will find the substitution of electricity for steam has been to its advantage; and that not only because of operating economies but also on other and broader grounds the value of this installation will prove to be so great that a distinct advance toward the electrification of important trunk lines will have been made.

I am personally pleased that we have at last in this country a three-phase installation for heavy railroad service, and from which we get such an encouraging report of early performances. The service requirements are well selected to favor this system, which certainly should do well here, if anywhere. It would be extremely unfortunate, both for those immediately concerned, as well as for every one else interested in the electrification of steam roads, if such an installation should partly or wholly fail. The railroad world is quick to note success or failure, but slow to differentiate between systems or to accept explanations from interested parties.

Some matters in the paper are not entirely clear. First, what is the actual capacity of this locomotive? I note that the guaranteed performance of the motors before they were built was 250 h.p. each under continuous load, while after construction the tested capacity was 375 h.p., an increase of 50 per cent. In making this statement the author permits us to infer that there is a corresponding increased locomotive capacity. In another part of the paper, however, the transformer capacity is said to be smaller than that of the motors. The transformer rating is given at 400 kw. each, there being two supplied. If the transformer is limited to its rating, the continuous output of the motors cannot exceed 200 h.p. each, due allowance being made for losses; that is to say, 7.64 h.p. per ton total weight of locomotive. Even if the transformers can be made to carry 25 per cent overload continuously, and thereby permit the motors to be rated at their guaranteed capacity of 250 h.p. each, the horse power per ton becomes only 8.7, not as great as can be obtained with, for example, 25-cycle, single-phase motors. In view of this fact the author's second advantage of a greater continuous output than with any other type of motor would fail of demonstration. Further, if the tested capacity of the motors, 375 h.p. each, is to be made available, apparently the transformer capacity must be very materially increased. Additional or larger transformers probably mean a larger cab, heavier framing, and so on, and this of course changes the weight and upsets any direct comparison. It is not stated that the control apparatus, switches, and resistance are large enough to handle the current for motors rated at 375 h.p. each, or that the blowers have sufficient capacity to furnish additional air to the transformers. If these matters have been covered by tests, a statement regarding them would afford a better understanding of the claim for great power per small weight.

The claim for maximum electrical and mechanical simplicity is valid as applied to the induction motor, which should receive full recognition. However, the control apparatus, compared with that required by direct-current or by single-phase motors, is much more complicated. It is necessary to break twice as many circuits as with direct-current or single-phase motors. Instead of being more simple, therefore, the control part of the three-phase equipment would naturally be somewhat more complicated.

With reference to uniform torque, I ought perhaps to say that our observations on single-phase locomotive performances do not support the view that the so-called pulsating torque of that motor is practically in evidence.

Since practically all the single-phase installations in this country use the 25-cycle current, the author's claim that the three-phase system has an advantage because it alone can use this frequency is somewhat puzzling.

The comment of a prominent steam railroad engineer on the question of constant speed was that the conditions which affect the operation of trains on schedules and which cause delays are many of them entirely foreign to any question of traction. Various and diverse influences cause delays, requiring trains to make up time if they are to be maintained on schedule. Therefore, an inflexible and a uniform speed is undoubtedly somewhat of a disadvantage even though the running time and operating conditions indicate that ordinarily it is desirable to maintain a uniform speed when the trains are running.

Ability to regenerate current by the three-phase system is of an undoubted advantage, and, naturally, will be used to produce a saving as the system is extended beyond its present limitations.

Charles P. Steinmetz: More than 15 years have elapsed since three-phase induction motors were first applied to railway work. Some years previously the single-phase commutator motor had been designed for railway work, but had not been used in practice, because there was no frequency low enough to make that type of motor suitable. A great deal of work was done on three-phase induction motors, a number of equipments were built, and high hopes were entertained that we were at the beginning of important developments in electric railroading. At the same time the synchronous converter was successfully developed and applied, its use enabling the operation of direct-current railway systems over such distances that the direct-current railway motor took care of all railway work for many years. For this reason the three-phase induction motor railway development did not progress in this country as it was hoped it would. The three-phase motor was used only to a limited extent, in mining locomotives, etc. Abroad, where prejudice retarded the introduction of the synchronous converter, considerable work was done in three-phase railroading.

Ten years after the early work the alternating-current railway motor was taken up again and the old single-phase compensated commutator motor was introduced industrially. Meantime it has developed so that to-day the single-phase motor is successfully applied to the solving of electric railway problems. At the same time most of us have begun to understand its limitations; it is not a universal motor, as its application is seriously circumscribed. The need of a frequency lower than the present standard as claimed by many designing engineers, limits the use of this type of motor. If it requires a system that differs from standard in all its parts—generators, transformers, etc.—this motor will be handicapped, because the economic development of the electrical industry must be towards uniformity in methods of generation, transmission, and distribution of power.

It seems now that the three-phase induction motor also has reappeared and found successful application. The advantage of this type of motor is its simplicity and reliability, its uniform torque, and greater output for its weight. These are the characteristics of polyphase machinery. The main characteristic of the three-phase induction motor, however, is that it is a constant-speed motor. From this feature follow most of the other characteristics: the relatively low efficiency of acceleration; that it consumes the same power in turning round slowly as when running at full speed at the same torque. A result of the constant-speed feature is the automatic regeneration of power above synchronism. We can improve the acceleration by concatenation, or, as it is called abroad, cascade connection, or by changing the number of poles. The repulsion motor or any alternating-current commutator motor can be made regenerative, but this means additional complication, which to my mind is undesirable in railway work.

The constant-speed feature limits somewhat the general application of the three-phase motor to railway work. It is well suited for mountain divisions, for running continuously with heavy torque, positive or negative. The successful application described by Dr. Hutchinson is on a mountain division. Another application would be for very high speed passenger service. At speeds of 50 or 60 miles an hour, or more, the air friction produces a considerable part of the train resistance; there is a decrease of the difference between the power required to run on a level track at a constant speed and the power of acceleration, and, therefore, an approach to the same conditions as running on a mountain division.

For general railway work, however, as at present carried out in this country, the three-phase locomotive is not as well suited as the direct-current locomotive or the single-phase locomotive, for the reason that the direct-current series motor or the alternating-current commutator motor can directly replace the steam locomotive in present railway operation, while the three-phase induction motor locomotive is not at its highest efficiency, when operating on a railway system under existing conditions. The method of operation must be rearranged to a constant-speed service. Whether the constant-speed operation of the railway would be disadvantageous, or advantageous, over the present variable-speed method, requires further consideration. At present we are inclined to consider it as a disadvantage; the present varying speed method as preferable. If the steam locomotive slows down on an up-grade, or loses time at a station, it can make it up on the level track by speeding. At the same time, if the traffic is unusually heavy, the steam locomotives cannot make schedule and all schedules are upset, and just when we need the full capacity of the railroad system most, the operation of the railroad is at its worst, as we have seen more than once.

In a broad study of the railway problem we have to investigate whether the method now in use is really inherent in the problem, a necessary requirement of the desired results, or whether it is an incidental feature of the particular apparatus we use. The steam locomotive is a constant-power motor. It gives approximately the same power irrespective of the speed, the power as limited by the steaming capacity of the boiler. Whether there is a heavy grade or a run on a level, there is a definite power limit, and this condition has brought about the present method of railway operation. It was the necessity of making up for lost time, as the locomotive has to slow down on up-grade, because it can not keep up steam when running as fast on a grade, as on a level track. With a different type of motive power, however, it would be well to investigate whether there would not be an advantage in rearranging the method of operation to suit the characteristic of the new motive power. It is quite likely that the capacity of any railway system could be greatly increased if we could get really constant-speed operation irrespective of grades, loads, etc. Possibly at constant speed much greater passenger traffic and much greater freight traffic could be handled. All these problems require impartial investigation by engineers that are not in favor of any one type of motor, or of the steam locomotive; engineers that would consider the entire railway problem, and find a solution for increasing the capacity of existing steam roads.

As regards the limitation of the shunt motor, I wish to draw attention to one particular feature: when we speak of the shunt motor, or the induction motor, we always exclude the rapid transit service, from its field of use. We consider rapid transit as that class of service where the series characteristic is especially necessary and to which the shunt motor is especially unsuited. The most extreme case of this intermittent service, acceleration at heavy torque and no constant speed running—the most extreme case of rapid transit—is the high-speed passenger elevator. This service is now always operated by the induction motor and the shunt motor, with or without compound field. It is rather interesting to see that where no precedent limited the character of operation, in the extremest case of rapid transit, motors of shunt characteristic have been chosen for the sake of service capacity, reliability, and safety.

Carl Schwartz (by letter): The operating conditions as presented by Dr. Hutchinson seem to indicate that the three-phase system is well adapted to the service, its few inherent disadvantages being overbalanced by its advantages.

In previous considerations of various systems of electric traction considerable attention was given to the design of the locomotive, the characteristics of the motors, and comparatively less to transmission and generating systems. While the locomotive is a very important part of the whole, both the weak and the strong features of an electric traction system are only in part determined by the characteristics of the locomotive. The decision as to which system is best to adopt may be influenced very much by other considerations.

One of the first advantages of the three-phase system in common with the direct-current system is that the generators are not subjected to such extremely heavy strains as are incidental to single-phase operation. In case of the Great Northern Railway Company's electrification current is generated at 6600 volts, transformed at the power house to 33,000 volts, this pressure is reduced at the substation to 6000 volts, and fed to the trolleys and the track rails. The intermediate transformers are a very important element in the system, and, together with the fact that the system is three-phase and not single-phase, explain the freedom from generator troubles.

Under present conditions we understand that one important feature of the three-phase system, the recuperation of energy from trains going down-grade, cannot be taken advantage of. This advantage, of course, exists only if trains are in service simultaneously up- and down-grade, so that there is load to carry at the switchboards for the train going down grade and returning power back to the station. This condition can ordinarily only be met by an installation of sufficient size, unless the schedule is so arranged that trains will travel up- and down-grade simultaneously. If this is not the case the power returned by a train running down-grade will have to be absorbed by automatically regulated rheostats which thus simply replace the mechanical brakes on the locomotive and dissipate the energy.

I investigated in detail sometime ago the merits of the three-phase system for a tunnel electrification in the Middle West where no water power was available. I found that the same conditions eliminated the feature of power recuperation, and, in this case, the only reason remaining for possible selection of the three-phase system. The result was the selection of direct current with a storage battery to equalize the load.

The operating conditions in the generating stations are stated to be very irregular. The generators may carry full load for, say 15 minutes and then run idle for several hours. Outside of bad regulation the objections against such intermittent operation are not great, but the operation would become extremely wasteful in case of a steam generating station and would show results on the coal pile that would exceed the consumption of the Mallet type locomotive.

Dr. Hutchinson calculates the equivalent consumption of a Mallet compound locomotive at 8 lb. of coal per kilowatt-hour. In case of the three-phase system he assumes 3 lb. of coal per kilowatt-hour at the bus-bars, or 4.28 lb. at the rail, taking the total efficiency from the station bus-bars to the rail at 70 per cent. The consumption in a modern steam station is two or three pounds per kilowatt-hour for a load-factor of, say, between 60 per cent and 40 per cent, but not for operating conditions similar to the Cascade Tunnel electrification. I do not desire to predict any figure for coal consumption in this case, but it will be above 8 lb. per kilowatt-hour, as in the case of the steam locomotive, and not below.

Any other system than the three-phase would under the same conditions not show better results, as the question of coal consumption is influenced more by the load characteristics than by the few per cent difference in efficiency between rails and station bus-bars. The traffic will have to be materially greater to approach a consumption of, say 3 lb. of coal per kilowatt-hour or one-half that of the Mallet compound locomotive.

Dr. Hutchinson has enumerated under the disadvantages "the constant speed of the locomotive" but he himself sees this characteristic rather as an advantage. Constant-speed characteristics of the locomotive motor on a mountain division is apt to accomplish one thing which other systems than the three-phase will not do; that is, allow close adherence to the schedule, which can be made more uniform than for steam service. While there is no possibility of making up lost time there is less possibility of losing time. As the speed is limited by the amount of traffic possible to handle up-grade on the division, the average speed will be increased. This means a proportionate increase in the capacity of the road and may in some cases eliminate the necessity of double-tracking.

Some of our Western roads may find this feature a sufficiently strong impetus to induce them to electrify, even if the power house should not show one-half the coal consumption of the Mallet type of locomotive. Furthermore, this item of energy consumption, as far as station economy is concerned, disappears more or less if water power is used. The only feature remaining is some possible increase in capacity of the power and transmission system, which may not be too expensive on account of the short duration of the peaks.

The three-phase system installed for the Great Northern railway by Dr. Hutchinson is the first three-phase railroad electrification in America, and there seems good reason to believe that this example will go far to secure for the three-phase system in this country the place it deserves.

Frank J. Sprague (by letter): The present is no time for arbitrary statements as to the supremacy of any one electrical system, but rather for that catholicity of view which admits of a variety of effective solutions for many problems, even if for others some one system may offer a preponderance of advantages. I shall, therefore, express no special views on the relative merits of different systems, except that I am glad to note that my efforts in behalf of the adoption of interpole motors and 1200-volt, direct-current operation, with both overhead and third-rail conductors as one of the possible alternatives, have received the practical endorsement of adoption and a rapidly widening application, thus giving the electrical engineer an additional lever for attacking the electrical transportation problem on a large scale.

Without discussing earlier installations, it is of interest to note that so far as at present developed this Cascade Tunnel installation is one of three in this country of almost identical requirements; that is, operation through a tunnel of heavy freight and passenger trains on severe grades at moderate speeds. Each of these is characterized by a different electrical system. Two, the Sarnia single-phase and the Cascade three-phase, are in operation, while the Detroit Tunnel direct-current locomotives have been fully tested. In each case the steam locomotive could only be used under the maximum disadvantages, the very worst possible conditions. Adoption of electrical operation by almost any method offered an effective remedy, and it is an encouraging fact that each of these installations overcomes many difficulties incident to steam operation under certain limitations, and that we have as a result higher speeds, greater capacity, and increased safety and cleanliness.

But none of these installations represents trunk line requirements under conditions which exist on many of our roads. It has been my fortune to have for nearly three years made a study of such a trunk line, presenting what I consider perhaps the most difficult operating problem I have ever encountered. I refer to a stretch of nearly 140 miles on the Sacramento Division of the Central Pacific Railroad, over the Sierra Nevada Mountains. There is much about the investigation of this which it would not be proper for me to touch upon, and I will only refer to it in a brief way.

The section in question is normally single tracked, with sidings every few miles which raise the aggregate trackage to something over 200 miles. The physical conditions are such as to present extreme difficulties to double tracking, although second tracking is being added for a part of the distance. There are nearly 32 miles of snowsheds and tunnels, and in winter the snow sheds form practically continuous tunnels. The grades are severe, there being a rise of about 7000 ft. in 83 miles in one direction, with a ruling grade of 2.4 per cent, and the amount of curvature is startling.

Over this division practically the entire freight and passenger traffic from the Union Pacific Railroad for Central California passes. Freight trains, often over a third of a mile in length, and with 2000 to 2500 tons trailing load, are operated in both directions. These trains require as many as four consolidated locomotives, or two of the heaviest Mallet compounds. The running speed is sometimes as low as seven miles an hour, and the schedule speed for the division is seriously interfered with by opposing traffic. Coupled with this freight operation is passenger operation in both directions, in trains up to nearly 400 tons trailing load, way trains, "limited," Pullmans, and fast-mail trains, operating at double the freight speeds, and with coasting speeds as high as 50 miles an hour.

This division is approaching the limit of steam capacity, especially when considered in relation to the balance of the system, and the question is whether such a division can be operated electrically, and if so, what can be gained thereby. Would the object be economy in fuel? Such alone would not warrant electrification, although the general line of investigation of railroads operated by electricity will show about 50 per cent in coal economy. If carried out, electrification will be primarily for the purpose of increasing capacity, and thereby effecting ultimate economy.

The specifications already issued require operation on this road of 2000-ton trains at 15 miles an hour on a 2.4 per cent grade, and 400-ton passenger trains at twice this speed. This last condition involves a much larger motor capacity at the head of a passenger train than the gratifyingly large capacity exhibited by the locomotives of the Cascade Tunnel, not in tractive effort, but in the product of tractive effort and speed.

The investigation of the possibilities of electrification on this road have been conducted on a plan somewhat different from that ordinarily taken. It was not deemed wise first to decide upon a system, but rather to ascertain the costs of locomotives by various systems which could perform a service determined as essential to effective operation, and then to collate all the facts, advantageous and otherwise, affecting capital cost and cost of operation, after which the best system to meet the existing conditions could be determined.

If asked what system would probably be indicated, I must frankly say that I do not know. That electrification is possible I do know, and that such can be successfully carried out I do not doubt, with increased capacity and general economic results. That it will be so done I also firmly hope and believe, but I am impressed with the absolute necessity that in considering a problem of this character, as well as all problems which are continually confronting the electrical engineer, there is no development which can be reasonably undertaken which should be curtailed, and none which should be disregarded.

We are passing through that inevitable stage of development and elimination essential to final correct decisions and permanency of results. However critical, therefore, I may sometimes feel as to the inadequacy of any system in some particular application, I welcome every installation which promises to further the effective and economic application of electricity to trunk-line operation.

Discussion at Minnesota Section, November 18, 1909.

Edward P. Burch (by letter): The writer made a study of the Cascade Division of the Great Northern Railway, including the Cascade Tunnel, and reported on its electrification to the Great Northern Railway Company, in January, 1904. The report was on the power problem, the mechanics involved, the available water power, the advantages of electric traction to prevent congestion of traffic, and finally on the net saving which was possible. The latter was corroborated by the record made by the general manager. It was recommended that a commission be appointed to study the subject as the responsibility for selecting a definite electric system for the whole division was large. The only precedent for the work was at the Baltimore and Ohio Railroad tunnel, where there were hauled many more freight and passenger trains per day up heavy grades and with great satisfaction, after the third-rail was installed.

The electrification of the Cascade tunnel itself was an exceedingly simple piece of work, but the electrification of the Cascade Division from Leavenworth to Everett, 109 miles, involved many problems not yet solved. The electric system and the locomotives were to be suitable for, and interchangeable on, the entire division, not for the tunnel only.

It was well known that no electric system was offered by American manufacturers for real railroading on these mountain grades; and experimental work was not welcomed on so large a scale. President Hill's decision was that the new Mallet compounds should be tried out.

The great objection to the use of three-phase power for railroad work is due to the necessity of carrying two overhead conductors; nor is this a minor matter in railroading. The delivery of power from a contact line to the locomotive is of vital importance and must be made absolutely perfect. Two overhead conductors in railroading, around freight yards and terminals, do not promote simplicity. It is not possible to carry two overhead wires with a difference of potential of 6,000 to 11,000 volts, above the many switches at yards and sidings which are most common in railroading, and make a rugged construction. Long, expensive, and complicated section-breaks are not desirable.

In practice the alignment of American track is not good. Further, the distance between the rail and the trolley of American roads will be from 22 to 24 ft. as a minimum, where European practice shows from 14 to 18 ft. Track irregularities cause the deflecting force at the upper end of the pantograph or trolley wheel to vary about as the square of the height. In railroading it will not do to have the trolley flop off, partly because it will be dangerous in ordinary operation. When there are two or three locomotive units to a train it is absurd to think that locomotive men will give attention to four trolley poles, turning them when the direction is reversed. A pantagraph is necessary, but it is not possible to run a pantagraph over rough switchwork at good speed without danger of short-circuiting the two trolley wires. A difference of potential of 6,000 to 11,000 volts will be used in heavy electric traction.

Modified systems may be used for mountain grades; namely:

1. The use of two trolleys for slow, three-phase freight locomotives; and the single-phase system, using one of the two overhead trolleys, for passenger service, for simplicity, variable speed, and rapid, efficient acceleration.

2. A single-phase, 11,000-volt trolley line and a rectifier on the

locomotive delivering 600-1200 volts direct current for motors. This would make an interchangeable system.

3. Three-phase generation, single-phase utilization from a single contact line, and the H. Ward Leonard scheme with the high-voltage, high-speed, light-weight, single-phase motor-generator which will drive the axles through intermediate low-voltage motors.

4. The use of the three-phase system with two trolleys for heavy grades, and the use of three-phase motor as a single-phase motor from one trolley at all sidings, yards, terminals, shops, etc., in slow speed and light switching work, for simplicity and safety.

Max Toltz (non-member): In regard to the details of the electric locomotive. Transmitting the power by gears from the motor to the axle is street railway practice and is not as good as side-rod construction. The gear transmission with which the Great Northern electric locomotive is equipped makes it unhandy to inspect the apparatus, or to repair motors or to inspect accessories, because it will be necessary to lift the cab and pull the truck from under and then raise the motor, etc. With the side-rod construction smaller wheels can be used, and, instead of four motors, two motors need only be installed above the locomotive frame. This has also the advantage of locating the collector rings where they can easily be inspected and repaired.

The motors should be wound for at least 3000 volts, instead of 500 volts and the former voltage should be also carried by the trolley wires. In that case the transformers on the locomotive between the trolley wires and the motors would be eliminated—a step towards simplification—and at the same time the electrical losses due to transformers will be cut out.

Instead of trolley poles with wheels, bow trolleys with roller contact for each wire could be used having the advantage of overcoming the present trouble of the trolley wheel jumping trolley wires when going in either direction.

An automatic device similar to the one used on the Valtallina electric three-phase locomotives should control the current supply to the motor instead of the common step-down rheostat.

A single speed in the motors is satisfactory for the tunnel operation, but if the whole Cascade division is to be electrified two speeds will be necessary, so that trains going down grade may run at a higher speed.

The transmission lines between the power house and the sub-station would be more reliable if each circuit had its own pole line, one on each side of the railway, for a slide or a falling tree would not put the line completely out of commission.

Trolley wires suspended from messenger cables would withstand harder usage in heavy operation.

In regard to some of the data given in Dr. Hutchinson's paper, exceptions should be taken. The rail resistance is given at 6 lb. per ton, which under the very best of conditions of rail and equipment is 6.5 lb. Dynamometer tests give 6.5 to 14.25 lb. per ton. In the tunnel with its soot and wet rails the resistance used to be over 10 lb. per ton.

The rail resistance of the Mallet locomotive is stated to be 47 lb. per ton, computed from ammeter readings. This figure is much too high, and is probably due to the air pump action of the pistons in the cylinder. It is assumed, of course, that the throttle valve was closed with the reverse lever being in the forward corner notch. It should be borne in mind the cylinders of the Great Northern Mallet locomotive have no by-pass connection, but are equipped with valves, one at each end of the cylinder.

The following results were obtained from tests in which indicator cards were taken simultaneously on all four cylinders of the Mallet, on a level track:

Type of locomotive	Locomotive weight	Miles per hour	Horse power absorbed	Resistance lb. per ton
Mallet	250 tons	8	57 h.p.	10.8 lb.
"	250 "	10	74 "	11.2 "
"	250 "	12	95 "	12.7 "

If Mr. Emerson had given the coal consumption per 100 ton-mile-hours instead of 100 ton-miles the results would have been somewhat different. The writer assumes, therefore, that Dr. Hutchinson's calculations are based upon a speed of 7 to 8 miles per hour, but calls attention to the fact that the most economical work of the Great Northern Mallet is performed at about 11 miles per hour.

The minor advantages of electrification as explained should be called "major" advantages but to these should be added:

1. The saving in locomotive ton-miles due to the elimination of the tender of the steam locomotive.

2. The mileage of the electrical locomotive will also exceed that of the steam locomotive, because the engine need not go to the round house for boiler repairs and need not be turned.

3. The best showing of the electric locomotive as compared with the steam locomotive will be made during the extreme cold weather when the latter will fail in generating the usual quantity of steam, while the former will not be hampered by any temperature prevailing in this country.

4. Also the elimination of all water and coal stations should not be overlooked.

The steam locomotive cannot expect to equal the record made by the New York Central locomotives of only 14 minutes delay in 80,000 train miles.

E. Marshall (non-member): On down-grade through the tunnel the crews were at first afraid to trust to regeneration by the induction motors to do the braking, but a few trips were sufficient to reassure them. The trip through the tunnel is now entirely devoid of danger from this source.

There have been only a few failures due to the electric locomotives. In one case some of the resistance grids were burned out, but the locomotive could be operated. In several cases of overloaded motors the secondary leads of the motors were melted from the rings. Due to inaccessibility the repair of these motors is a difficult task.

The system of current collection by means of a wheel trolley and overhead wires strung similar to street railway lines is not satisfactory. Trolleys leave the wire, tear down the overhead work, and sometimes are the cause of a train breaking in two, due to relieving the load on the locomotive. In case of change of direction the trolleys must be changed; this is sometimes forgotten and the overhead construction suffers in nearly every case. On account of the 5 ft. spacing of the wires in the open, and 8 ft. in the tunnel, the pantagraph cannot be used. It is probable that the overhead work will be changed to catenary construction and bow collectors used, as there is no question about that design being more satisfactory.

On the whole the operation of this system is most satisfactory. The above remarks are not made as criticisms but are mentioned to show that the defects are no greater than one has a right to expect in a system where precedents are so few. Everyone connected with the operation of this system is anxious to see it extended to take in at least all of the track having the 2.2 per cent grade.

Cary T. Hutchinson: I am gratified to see that there seems to be a very general agreement with me that the three-phase system was well adapted for use in this particular place. I believe nearly all of the speakers have assented to this.

I find in the discussion a number of points in which the various speakers differ from me in regard to details, and it is very probable that they may be right and I wrong. I do not think it necessary to discuss these points, but wish merely to answer the questions that have been asked.

In reply to Mr. Katté. The ground wire was omitted as there is no lightning on this side of the mountain. My reasons for saying that probably a three-phase system would have been used even though only the tunnel were under consideration, was because of the far greater capacity of three-phase motors as compared with direct-current motors in the same space, and the lesser cost of construction and operation. Wooden poles were used, as they could be obtained very cheaply and of extremely good quality.

Mr. Arnold and others question the high frictional resistance of the Mallet locomotives. I can only say that these tests were carefully made by competent observers, and I am sure are accurate expressions of the conditions that existed. I of course do not pretend that the internal losses of the Mallet, when operating under its own steam, are represented by these figures; there is no direct comparison between the two conditions.

I do not think that the method of control used on the Italian State Railways referred to by Mr. Waterman would be satisfactory under the conditions of a Western railroad in this country where it would be fatal to install any apparatus requiring careful supervision of operation and maintenance. Everything must be of the sturdiest character, and as nearly as possible "fool-proof."

Mr. Pomeroy gives some very interesting results of coal consumption of heavy locomotives on mountain grades. It should be noted that Mr. Pomeroy shows the coal consumption to be nearly twice as great as I deduced from Mr. Emerson's statements, amounting to from 13 to 19 lb. per kilowatt-hour as compared with 8 lb. Mr. Pomeroy also brings out the very interesting fact that the coal consumption in operation is just double that deduced from test results. I had also arrived at the same figure by the comparison of records of operation with special test runs made on hills—such runs are practically of no value in determining coal consumption.

I agree with Mr. Smith and with others who state that the collection of the current is a very important factor in deciding the type of machinery to be used. The use of the trolley wheel in this particular case was forced upon me, and was not my deliberate choice, as the officers of the road would not permit encroachment upon the overhead space in the centre of the tunnel. It is not at all improbable that some change may be made in this, particularly if the system is extended, and a pantograph may be used.

I am also glad to see that Mr. Smith, in common with others, approves the rating of an electric locomotive by its continuous duty. This seems to be the only sensible way to rate any piece of electrical apparatus, even though it is used in intermittent service. There will of course be all sorts of intermittent service, and the ratio between the actual service and the continuous capacity must be determined for each particular case. A motor, however, having a greater continuous capacity will, other things being equal, be the better motor for any service. Other methods of rating railway motors serves principally to conceal the facts.

Mr. Denneen has emphasized some of the reasons for the use of special features of the overhead construction. In this, as in other matters, I can only say that all the details of this subject were carefully considered.

Mr. Townley questions the continuous capacity of locomotives on the ground of the lower rated capacity of the transformers. It is true that the rating of the transformers is only 800 kw., continuous, with the quantity of air specified but the transformers have an overload rating of 100 per cent for one hour. For the service that the locomotives are now employed in, the transformers have ample capacity, and there is space enough either to install larger transformers in case they are needed for the extended service under contemplation; or what would be simpler, increase the quantity of air to these transformers. This has been done on test. There would be no difficulty by one or the other of these methods in making the transformers equal in continuous capacity to the motors and rating the locomotive at something over 1100 kw. continuous. The control apparatus has been operating regularly at much greater power, and there will be no difficulty at this point. The motors themselves are the limitation to the capacity of the locomotive—not the transformers, nor the subsidiary apparatus.

Mr. Schwartz is of course correct in stating that the coal consumption of a steam station, operating as the Tumwater station is now operating, would be much greater than 3 lb. per kilowatt-hour and might be almost anything. My comparison was not intended to refer to existing conditions but to the service as it would be when handling the entire traffic of this mountain division, and the traffic so arranged as to secure a reasonably good load-factor at the power station, which I regard as an essential to the electrical handling of any train service. In other words, when a division is electrified, the train dispatching must be conducted in accordance with the exigencies of the power station; the cost of any other method of dispatching will be so great that railroad officials will readily agree to this limitation.

If, however, Mr. Pomeroy's figures represent more nearly the coal used in steam service, as I believe they do, then it is not at all certain that a steam station would not give better coal economy, even if operating under as disadvantageous conditions as now exist at the Tumwater station.

Mr. Toltz gives some interesting figures for the frictional resistance of Mallet locomotives based on the indicated power in the engine cylinder. As I have said above, there is no necessary connection between the power so used and the power required to tow the same locomotive. I do not, however, think that much reliance can be placed on indicator cards, taken under the conditions described by Mr. Toltz. It is to be noted that the figure he gives for the total resistance of the locomotives, of say 11 lb. to the ton, is about the same as he states the rail resistance should be, which he gives at from 6.5 to 14.25 lb. per ton. The 6 lb. to the ton that I used was given me by the chief engineer of the railroad.

Mr. Marshall has referred to some accidents to the overhead structure, due to trolleys leaving the wire. This has been due largely to the impossibility of keeping this overhead structure in proper alignment, owing to the fact that little or no time can be found for working on this structure, on account of the exigencies of the train service.

Parker H. Kemble (by letter): The handling of traffic on railroads has now been a business and a study for some eighty years. Certain broad principles have been laid down and methods developed which are worthy of attention in discussing or selecting a method of electric operation. A change of motive power does not imply an overturn in methods. Electric power does mean larger loads, greater speed possibilities, and greater range in grades without change in weight of train or type of locomotive; in other words, improved tools for the use of the traffic manager. The broad principles remain as before. On a railroad system of varying profile, the present system provides locomotives of moderate weight and high speed for levels, heavier and slower engines (or else lighter trains for the same engine) for the moderate grades, and Mallet specials and pushers for the steepest ridges of the divides.

To handle this traffic, what does electricity offer? In the alternating-current division there are two main systems at present —single-phase and three-phase. These are of essentially opposite characteristics. Neither will fulfil all the requirements of railroad traffic over varying profile. Each is perfectly adapted to handle a particular grade or condition. In combination they fill all requisites.

As regards power stations they are identical; both generate three-phase, 25-cycle current at about 11,000 volts pressure; as regards transmission line, even where all the power would ordinarily be taken from one phase, the combination would require but one more transmission wire with the added advantage of a possible balancing of load. As regards contact line, the extra wire shown in the paper under discussion can be easily installed.

A modification of the single-phase pantagraph would be necessary, but that would be about all the change. On the levels and slight grades the single-phase motor with its high acceleration variable speed, and variable torque, complies with the traffic requirements. On the heavier grades another wire is strung over the track and the three-phase motor comes in to add its valuable grade-climbing abilities and safe down-grade speed control to the other.

It does not seem beyond the possibilities of multiple-unit control to imagine these two motors working together. At any rate, were the three-phase motor to be restricted to the role of pusher, the single-phase motor could surely carry its own weight. With the rapid progress in alternating-current motor design, a combination of types for certain profiles might be available.