The Last Stand of the Reciprocating Steam Engine*

Startling Picture of the Inefficiency of the Steam Locomotive

By A. H. Armstrong

DURING the year 1920 the people of the United States will pay out for automobiles, not commercial trucks nor farm tractors, but pleasure vehicles, a sum of money considerably greater than the estimated requirements of our steam railways for that year. The railways, however, may find it very difficult and perhaps impossible to secure the large sums needed without government aid, notwithstanding the fact that the continued operation and expansion of our roads is of vital necessity to the welfare and prosperity of the country and all its industries. The will of the American public has always been constructive and undoubtedly, in due time, its voice will be heard and properly interpreted by its representatives in Washington with the resulting enactment of such laws as will permit our railways again to offer an attractive field for the investment of private capital.

The purpose of this paper is not to discuss the politics of the situation nor any necessary increase in freight rates that may be required to make our roads self-sustaining, but rather to offer certain suggestions as to the best manner of spending the sums that must ultimately be provided for new construction and replacements.

During the war period many lessons have been most clearly brought home to us and not the least of these is that there is something inherently wrong with our steam railroads. During the three generations of its development, we have become accustomed to look upon the steam engine as properly belonging to the railway picture and have given little thought to its wastefulness and limitations. It is around the steam locomotive that railway practice of today has gradually crystallized.

During the winter of 1917-18 our railways fell down badly when the need for them was the greatest in their history. It is true that the cold weather conditions were unprecedented and the volume of traffic abnormal, but the weaknesses of steam engine haulage were disclosed in a most startling and disastrous manner. Delayed passenger trains in cold weather can be endured by the traveling public in suffering silence or voluble expression, according to temperament; but the blocking of our tracks with frozen engines and trains, resulting in a serious reduction of tonnage in cold weather and a prohibitive delay in transportation of freight in times of great stress, is quite another thing and plainly indicates the inability of the steam engine to meet overloads and adverse climatic conditions.

In marked contrast to the adjoining steam engine divisions, the 440-mile electrified section of the Chicago, Milwaukee and St. Paul Railway continued to do business as usual all through that trying winter of 1917-18. The electric locomotives brought both freight and passenger trains over the electrified tracks in schedule time or better; in fact, it was quite customary to make up on the 440-mile electric run fully two hours of the time lost by passenger trains on adjoining steam engine divisions. While the results obtained upon the Chicago, Milwaukee & St. Paul were perhaps more spectacular due to the greater mileage electrically equipped, other electrified roads contributed similarly attractive records. The reliability and permanency of the comparison between steam and electric locomotive haulage is sufficiently guaranteed, therefore, by the results of several years' operation, to justify drawing certain conclusions regarding the merits of the two types of motive power. The following analysis of the railway situation is therefore offered for the purpose of exposing the fact that railroading today is in reality steam engine railroading and the general introduction of the electric locomotive will permit of fundamental and far reaching changes in the method and cost of hauling freight and passenger trains.

The writer is not proposing the immediate electrification of all the railways in the United States, as many roads of lean tonnage would render no adequate return upon the large capital investment required, but is offering the following table of total operating statistics simply as a measure of the magnitude of the problem confronting us in the future. In this country it should be noted, however, that we have during the past thirty years installed electric power stations equal to twice the estimated capacity required for the electrical operation of every mile of our tracks today.

TABLE I—TOTAL TON-MILE MOVEMENT ALL RAILWAYS IN UNITED STATES—YEAR 1918.

	Per Cent	Ton Miles
1—Miscellaneous freight cars and contents	42.3	515,000,000,000
2—Revenue coal cars and contents	16.23	197,000,000,000
3—Locomotive revenue, driver wt. only	10.90	132,300,000,000
4—Passenger cars, all classes	16.13	196,000,000,000
Total revenue, freight and passenger	85.56	1,040,300,000,000
5—Railway coal	5.00	60,600,000,000
6—Tenders, all classes	6.50	78,800,000,000
7—Locomotive railway coal	0.39	4,700,000,000
8—Locomotive, non-driving wt.	2.55	31,000,000,000
Total non-revenue	14.44	175,100,000,000
GRAND TOTAL (All classes)	100	1,215,400,000,000

The tonnage passing over the tracks of our railways may be subdivided in a most interesting manner as shown in Table I. The first four items, representing 85.56 per cent of the total ton-miles made during the year 1918, may be regarded as fundamentally common to both steam and electric operation. By introducing the electric locomotive, however, the last four items are reduced to the extent of completely eliminating items (6) and (7), reducing item (5) by possibly 80 per cent and item (8) by one-half. Of the total of 14.44 per cent affected, therefore, it may be assumed for purposes of comparison that approximately 12 per cent or 146,000,000,000 ton-miles at present hauled by steam engines over our roads will be totally eliminated with electric locomotive haulage. This ton-mileage eliminated is equal to over 20 per cent of items (1) and (2) representing the revenue producing freight traffic on our railways. In other words, if all our railways were completely electrified they could carry one-fifth more revenue producing freight tonnage with no change in present operating expenses or track congestion.

It is evident that the greater part of the tonnage reduction effected by electrification is included in items (5) and (6), representing the railway coal movement in cars and engine tenders. The steam engine tender will of course entirely disappear, while the railway coal haulage will be largely curtailed by utilization of water as a source of power and the establishment of steam power houses as near the coal mines as an abundant supply of good condensing water and load demand will permit. While water power should be utilized to the fullest economical extent, the greater portion of the railway power must undoubtedly be supplied by coal, due to the unequal geographical distribution of water power available.

Even with coal as the source of power, it may not be fully appreciated just how enormous is the saving made by burning fuel in large modern power stations under the most efficient conditions possible, instead of under the boilers of 63,000 en-

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gines which by necessity must be designed and operated for service rather than for fuel economy. During the year 1918 the fuel used by railways is reported to be as shown in Table II.

TABLE II—RAILWAY FUEL 1918.

Total coal production (all grades)	678,211,000 tons
Used by steam railways	163,000,000 tons
Percentage of total	24 per cent
Total oil marketed in U. S.	355,927,000 bbl.
Used by steam railways	45,700,000 bbl.
Percentage of total	5.8 per cent
Coal equivalent of oil at 3½ bbl.	13,000,000 tons
Total equivalent railway coal	176,000,000 tons

A quarter of all the coal mined in the United States is consumed on our railways and the following analysis will point out some features of this extreme wastefulness which are inseparable from steam engine operation.

During the year 1910, exhaustive tests were made upon the Rocky Mountain Division of the C., M. & St. P. Ry. to determine the relation existing between the horse-power-hours work done in moving trains and the coal and water consumed on the steam engines in service. Table III gives the results of these tests:

TABLE III—C., M. & ST. P. RY.; ROCKY MOUNTAIN DIVISION. COAL AND WATER USED.

	Water per H.p.-hr.	Water per Lb. Coal	Coal per H.p.-Hr.
Three Forks-Piedmont	39.6	5.08	7.75
Piedmont-Donald	35.4	4.70	7.54
Deer Lodge-Butte	39.7	4.85	8.31
Butte-Donald	40.4	4.86	8.74
Harlowton-Janny	38.0	4.09	8.90
Janny-Summit	44.2	4.65	9.48
Three Forks-Piedmont	41.4	6.51	6.37
Piedmont-Donald	40.2	5.63	5.78
Average of eight tests	39.86	5.04	7.86

The records were obtained during the portion of the runs that the engines were doing useful work in overcoming train and grade resistance, that is, all standby losses were excluded. The through run, however, included such losses in the magnitude shown in Table IV:

TABLE IV—STANDBY LOSSES.

	Coal per hour
Fire banked in roundhouse	150 lb.
Cleaning fires for starting	800 lb.
Coasting down grade	950 lb.
Standing on passing track	500 lb.

Adding standby losses to the average of 7.86 lb. per h.p.-hr. obtained in the preceding eight tests, the total actual coal consumed under the engine boiler in twenty-four hours divided by the actual work performed by the engine is found to be 10.18 lb. per h.p.-hr, at the driver rims.

As the result of this particular series of tests it was determined that the coal consumed while doing useful work was raised 30 per cent by standby losses. It should be appreciated in this connection moreover that this value was obtained on through runs with no yard switching service or adverse climatic conditions. It may be concluded therefore, that under all conditions of service fully one-third the coal burned on our steam engines today is absolutely wasted in standby losses of the general nature indicated above.

Supplementing these tests, a 30-day record was kept of all coal used on the entire Rocky Mountain Division and the total engine, tender, and train movements reduced to horse-power hours, resulting in a value of 10.53 lb. coal consumed per horse-power-hour at the driver rims. Both the above values were based upon constants of 6 lb. per ton train resistance at all speeds and 0.7 lb. per ton per degree of curvature as determined in part by dynamometer car tests and representative of general railway operation. Reducing the average coal values of the test runs and the 30-day record per horse-power-hour to electrical constants, we arrive at the data shown in Table V:

TABLE V—COAL EQUIVALENT PER KW-HR.; STEAM OPERATION.

Coal per h.p.-hr. at driver rims	10.27 lb.
Coal per kw-hr. at driver rims	13.75 lb.
Coal per kw-hr. at power supply on basis 55 per cent efficiency	7.56 lb.

It is this last figure of 7.56 lb. of coal burned on steam engines to get the equivalent tonnage movement of one kilowatt-hour delivered from an electric power station that is of special interest to this discussion. Comparing coal and electrical records on the Butte, Anaconda & Pacific Railway before and after electrification results in arriving at a value of 7.17 lb. of coal previously burned on the steam engines to equal the same service now performed by one kilowatt-hour input at the substations, a figure comparing favorably with 7.56 lb. above arrived at by an entirely different method.

TABLE VI—ANALYSIS OF ROUNDUP COAL USED.

Fixed carbon	49.26 per cent
Volatile carbon	38.12 per cent
Ash	7.74 per cent
Moisture	4.88 per cent
B.t.u.	11,899

Making due allowance for the fact that roundup coal is somewhat low in heat units, it is nevertheless within the limits of reasonable accuracy to assume that the steam engines operating over all our railways are consuming coal at a rate closely approximating 12.75 lb. per kilowatt-hour of useful work done, as measured at the driver rims or 7 lb. per kilowatt-hour as measured at a power station and including for convenience of comparison the transmission and conversion losses inherent to electrical operation.

An electric kilowatt can be produced for so much less than 7 lb. of coal that we are now in position finally to forecast the approximate extent of the coal economy that would result from electrification.

TABLE VII—RELATION BETWEEN KW-HR. AND TON-MILES, CHICAGO, MILWAUKEE AND ST. PAUL RAILWAY, AVERY-HARLOWTON—YEAR 1918.

	Passenger	Freight
Average weight locomotive	300 ton	284 ton
Locomotive miles, 1918	651,000	1,431,500
Locomotive ton-miles	195,000,000	407,000,000
Trailing ton-miles	434,406,000	2,903,099,000
Total ton-miles	629,406,000	3,310,049,000
Kilowatt-hours	24,890,000	105,287,000
Watthours per ton-mile	39.6	31.9
Ratio locomotive to total	31 per cent	12.3 per cent
Watthours per ton-mile combined movement		33.2
Ratio locomotive to total combined movement		15.25 per cent

All power values in Table VII are given at the point of supply from the Montana Power Company at 100,000 volts and include deductions made for the return of power due to regenerative braking of the electric locomotives on down grades, amounting to approximately 14 per cent of the total. Owing to the excessive rise and fall of the profile of the electrified zone of the C., M. & St. P. Ry., its operation is materially benefited by regenerative electric braking and the value of 32.2 watthours per ton mile for combined and passenger movement should possibly be raised to the round figure of 40 to make it apply more nearly to conditions universally obtaining on more regular profiles.

Hence referring again to the ton-mile values of Table I:

Total ton-miles, 1918	1,215,400,000,000
Watthours ton mile	40
Kw-hr. total movement	48,700,000,000
Coal required at 7 lb. per kw-hr	170,000,000 ton

The actual equivalent coal consumed on our steam railways for the year 1918 is given as 176,000,000 tons, closely approximating the figure of 170,000,000 tons estimated above from the operating results obtained on the C., M. & St. P. electrified zone. These several values check so closely as to justify the completion of the fuel analysis of the railways as shown in Table VIII.

TABLE VIII—COAL SAVING BY ELECTRIFICATION

Total ton-miles steam	1,215,400,000,000
Reduction by electrification	146,000,000,000
Total ton-miles electric	1,069,400,000,000
Kw-hr. electric at 40 watts	42,776,000,000
Coal on basis 2½ lb. per kw-hr.	53,500,000 tons
Equivalent railway coal 1918	176,000,000 tons
Saving by electrification	122,500,000 tons

The startling conclusion arrived at is that approximately 122,500,000 tons of coal, or more than two-thirds the coal now burned in our 63,000 steam engines, would have been saved during the year 1918 had the railways of the United States been completely electrified along lines fully tried out and proved successful today. This vast amount of coal is 50 per cent greater than the pre-war exports of England, and twice the total amount consumed in France for all its railways and industries. Moreover, the estimate is probably too conservative as no allowance has been made for the extensive utilization of water power which can be developed to produce power more cheaply than by coal in many favored localities.

Perhaps no nation can be justly criticized for lavishly using the natural resources with which it may be abundantly provided. In striking contrast with the picture of fuel waste on the railways in this country however is the situation presented in Europe at this writing.

Faced with a staggering war debt, with two millions of its best men gone and an undetermined number incapacitated for hard labor, and with so much reconstruction work to do, France has to contend also with the destruction of half its coal producing capacity. Before the war, France imported twenty-three million of the sixty-five million tons of coal consumed. It is estimated that the full restoration of the coal mines in the Lens region will take ten years to accomplish, which means materially increasing the coal imported into France if pre-war consumption is to be reached, as the relief rendered from the Saar District will not compensate for the loss in productivity of the mines destroyed by the Germans. This situation is being promptly met in part by France in the appointment of a Commission to study the feasibility of the general electrification of all its railways with special reference to immediate construction in districts adjacent to its three large water-power groups, the Alps, the Pyrenees, and the Dordoyne or Central plateau region. It is proposed to electrify 5200 miles of its total of 26,000 miles of railways during a period covering twenty years. If this work is accomplished at a uniform rate of 260 miles a year, it is a most modest program considering the extreme necessity for the improvement.

In even worse plight is Italy with practically no coal of its own and compelled to import its total supply of 9,000,000 tons. The war has brought home to these countries what it means to be dependent upon imported fuel for their very existence and both Italy and Switzerland are also proceeding with extensive plans for railway electrification. Contrary to general understanding, the mines of Belgium are not destroyed, but the need of fuel economy is very acute and this country also has broad plans for railway electrification with immediate construction in view.

Recognizing the many advantages of electric operation of its railways, Europe furthermore considers this a most opportune time to start the change rather than to spend its limited funds in replacing worn out and obsolete steam equipment in kind. Also in marked contrast to the American attitude is the sympathetic interest and constructive assistance rendered by the Governments abroad in regard to the vital matter of rehabilitation of its railway systems. It would not be without precedent if the next decade witnessed England and the Continent outstripping this country in the exploitation of another industry which, while possibly not conceived here, has certainly been more fully developed and perfected in America than elsewhere.

From figures given, the conclusions in Table IX are arrived at in the matter of power station capacity required for complete electrification of the railways in the United States.

TABLE IX—RAILWAY POWER REQUIRED.

Kw-hr. electric operation, 1918	42,776,000,000 kw-hr.
Average load, 100 per cent load-factor	4,875,000 kw.
Power station capacity at 50 per cent load-factor	9,750,000 kw.

It appears therefore that approximately 10,000,000 kw. power station capacity would have been sufficient to run all the railroads for the year 1918, or one-half the station capacity which has been constructed during the past thirty years.

TABLE X—ESTIMATED POWER STATION CAPACITY, UNITED STATES, YEAR 1918.

Central stations	9,000,000 kw.
Electric railways	3,000,000 kw.
Isolated plants	8,000,000 kw.
Total	20,000,000 kw.

In the order of magnitude, therefore, it is not such a formidable problem to consider the matter of power supply for our electrified railways and it becomes evident also that the railway power demand will be secondary to industrial and miscellaneous requirements.

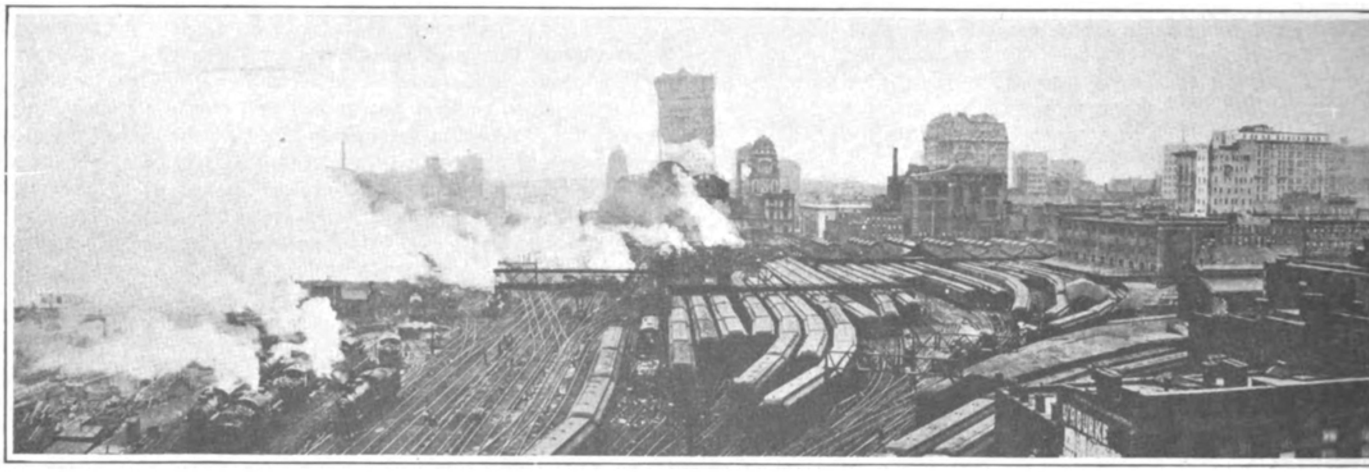
Such being the case, the question of frequency of electric power supply becomes of great importance, if full benefit is to be obtained from extensive interconnected generating and transmission systems covering the entire country. Indeed with the full development of interconnected power systems supplying both railway and industrial load from the same transmission wires, the above assumption of 50 per cent load-factor for the railway load can be materially bettered.

In this connection a method of limiting the troublesome peak load hitherto considered inherent to railway power supply has been in successful operation on the electrified C., M. & St. P. zone for the past year. With unrestrained peaks, the load-factor was approximately 40 per cent, but this low value has been raised to nearly 60 per cent by the installation of an inexpensive and most satisfactory device known as the power limiting and indicating apparatus.

TABLE XI—LOAD-FACTOR RECORDS, C., M. & ST. P. RY.

	Per Cent Duration of Peak	Per Cent Load-Factor
April	6.4	59.3
May	4.6	56.1
June	1.6	56.5
July	0.7	55.6
August	4.1	54.7
September	9.5	58.8

The readings in Table XI cover the performance on the 220 miles of the Rocky Mountain Division supplied by seven substations controlled as a unit. A load-factor of nearly 60 per



SMOKE CONDITIONS AS THEY EXISTED AT THE GRAND CENTRAL TERMINAL, NEW YORK, IN 1906

cent brings the electric railway within the list of desirable customers and makes it possible for power companies to quote attractively low rates for power.

Returning again to the question of power supply, it is instructive to note the general trend toward a higher frequency. It is quite evident that 60 cycles is rapidly becoming the standard frequency in America; and many instances are on record where it has replaced lower frequencies, principally 25 cycles. This fact in no manner handicaps the future development of electric railways, as entirely satisfactory power can be obtained from 60-cycle transmission lines through rotary converters, or synchronous motor-generator sets, depending upon the direct-current trolley voltage desired. Indeed a growing appreciation of the declining importance of 25-cycle power generation in this country contributed largely to the demise of the single-phase system, as its chief claim for recognition is wiped out with the introduction of the motor-generator substations required with 60-cycle supply.

While America apparently has adopted 60 cycles as its standard frequency and can look forward to unlimited interconnection of its large power systems, European practice is evidently crystallizing on 50 cycles. The situation abroad is as yet, however, not clearly defined. In such a small compact country as Switzerland for instance, where so much electrical development is taking place, there is much conflict of frequencies. Apparently there is little appreciation of the advantages resulting from interconnected power stations; in fact the Loetschberg Railway is supplied with power from 15-cycle waterwheel-driven generators placed in the same power station with 42-cycle units supplying industrial load while in the same immediate district there is a 50-cycle transmission line and no tie-in frequency changer sets as yet installed to interconnect any two frequencies. The power company, power consumer, and electrical manufacturer pay heavily for the complication imposed by maintaining three frequencies where only one is needed, and growing appreciation of this fact may lead to the standardization of 50 cycles in Switzerland and thus swing that country in line with its neighbors and ultimately bring about a more economical ratio of installed generator capacity to average load demand for the country as a whole.

A good example of the necessity for improvement in power distribution conditions in Switzerland is provided in the supply of power to the Loetschberg Railway as illustrated in Table XII.

TABLE XII—POWER SUPPLY TO THE LOETSCHBERG RAILWAY, MARCH, 1919.

Total for month	540,180 kw-hr.
Average of six 15 min. peaks	3,489 kw.
Load-factor, basis 24 hours	20.8 per cent

As the railway was operating for only seventeen hours per day, the load-factor during actual operation is somewhat better than 20.8 per cent. On the other hand, the actual momentary peak load greatly exceeded 3489 kw.; and this very fluctuating railway load furnishes a good illustration of the need of combining it with other diversified loads, in order to keep down the fixed investment of power station equipment now set aside for this isolated railway load. For example, the 60 per cent load-factor of the C., M. & St. P. power demand is the ratio of average to momentary peak while the Loetschberg Railway peak load is determined by six 15-min. peaks with momentary peaks greatly in excess of this figure.

Apparently the adoption of a standard frequency of 50 cycles would meet all general requirements in Switzerland, but would necessitate the installation of frequency changing substations to meet the demands for 15-cycle, single phase railway power. If the electrified railways are to benefit, therefore, from the establishment of a common generating and transmission system in Switzerland, the choice of the single-phase railway system might possibly be considered unfortunate, viewed in the light of modern development in power economics and the successful adaptation of the less expensive and more flexible direct-current motor to high trolley voltages.

From the power station standpoint, the electrification of our railways admits but one conclusion. We have some 63,000 engines now in operation and their average combined load amounts to approximately four million horse-power at the driver rims or only an insignificant total of 65 h.p. for each engine owned. It is true that, owing to shopping and for one cause or another, a large proportion of these engines are not in active service at all times, still the average twenty-four-hour output of each engine is less than ten per cent, of its rating. In the case of the C., M. & St. P. electrification, the average load of each individual electric locomotive is only 15 per cent of its continuous rating, but by supplying power to 45 electric locomotives from one transmission system, the average combined load-factor is raised to nearly 60 per cent, a figure which could even be surpassed on roads of more regular profile. Furthermore, when the railway load is merged with the lighting and industrial power of the district and the whole diversified load supplied from the same 60-cycle transmission and generating system, it is quite evident that all the conditions are most favorable for the efficient production of power. In this country such an achievement will probably be governed by the laws of economic return upon the capital required because our vast natural fuel resources are popularly regarded as inexhaustible, but in Europe there is the compelling spur of stern necessity behind the movement to utilize economically the water powers they possess in place of the coal they cannot get.

While the much discussed subject of power generation and transmission is a very vital part of the railway electrification

GRAND CENTRAL TERMINAL FROM 50TH STREET, SHOWING RESULTS OF ELECTRIFICATION

project, chief interest centers in the electric locomotive itself. Few realize what a truly wonderful development has taken place in this connection in a comparatively few years and how peculiarly fitted this type of motive power is to meet the requirements of rail transportation. Free from the limitations of the steam boiler, and possessing in the electric motor the most efficient and flexible known means of transmitting power to the driving axles, the electric locomotive gives promise of revolutionizing present steam railway practice when its capabilities become fully recognized. The only limits placed upon the speed and hauling capacity of a single locomotive are those imposed by track alinement and standard draft rigging. Only questions of cost and expediency control the size of the locomotive that can be built and operated by one man, as there are no mechanical or electrical limitations that have not been brushed aside by careful development. Just what this means in advancing the art of railroading is as yet but faintly grasped, any more than the boldest prophet of twenty years ago could have fully pictured the change that has taken place at the Grand Central Terminal as the result of replacing steam by eelctricity.

Progress in utilizing the capabilities of the electric locomotive has been slow. It is hard to break away from lifelong railway traditions established by costly experience in many cases. In consequence the electric locomotive has thus far simply replaced the steam engine in nearly similar operation. Even under such conditions of only partial fulfillment of its possibilities, the electric locomotive has scored such a signal operating success as to justify giving it the fullest consideration in future railway improvement plans.

On the C., M. & St. P. Ry. 42 electric locomotives have replaced 112 steam engines and are hauling a greater tonnage with reserve capacity for still more. On this and other roads, electrification has set a new standard for reliability and low cost of operation. In fact, although no official figures have yet been published, it is an open secret that the reduction in previous steam operating expenses on the C., M. & St. P. Ry. are sufficient to show an attractive return upon the twelve and a half millions expended for the 440 miles of electrification, without deducting the value of the 112 steam engines released for service elsewhere. As the electric locomotive is destined to leave its deep impression upon the development history of our railways, it is fitting that the remainder of this paper should be devoted to its consideration.

Our steam engine construction is unsymmetrical in wheel arrangement, must run single ended, and is further handicapped with the addition of a tender to carry its fuel and water supply. The result has been much congestion at terminals; and the necessary roundhouses, always with the inevitable turn tables, ash pits, and coal and water facilities, have occupied much valuable land; and in addition steam operation has greatly depreciated the value of neighboring real estate. The contrast offered by the two large electric terminals in New York City is too apparent to need more than passing comment, and similar results may be expected on the fulfillment of plans for electrifying the Chicago terminals.

While it has been a simple matter to design electric locomotives to run double ended at the moderate speeds required in freight service, the problem of higher speed attainment, exceeding 60 miles per hour, has presented greater difficulties. The electric motor is however so adaptable to the needs of running gear design that electric locomotives are now in operation which can meet all the requirements of high-speed passenger train running. These results, also, are obtained with less than 40,000 lb. total weight, and 9,500 lb. non-spring borne or "dead" weight on each driving axle, and finally, but not least, with both front and rear trucks riding equally well, a success never before achieved in locomotives of such large capacity.

In connection with the riding qualities of electric locomotives, it is of interest to note the conclusions that the Committee of the American Railway Engineering Association, F. E. Turneaure, Chairman, reached in their report of 1917:

"From the results of the tests on the electrified section of the Chicago, Milwaukee & St. Paul Railway, the tests made in 1916 on the Norfolk and Western, and the few tests made in 1909 at Schenectady, N. Y., it would appear to be fairly well established that the impact effect from electric locomotives is very much less than from steam locomotives of the usual type. Comparing results obtained in these tests with the results from steam locomotives, it would appear that the impact from electric locomotives on structures exceeding, say, 25 ft. span length, is not more than one-third of the impact producted by steam locomotives."

There is as yet no general acceptance of a standard design of electric locomotive. Geared side-rod construction for heavy freight service and twin motors geared to a quill for passenger locomotives appear to find favor with the Westinghouse-Baldwin engineers, while the General Electric Company goes in for the simple arrangement of geared axle motors for freight and gearless motors for passenger locomotives. In both Switzerland and Italy the side-rod locomotive enjoys an almost exclusive field. How much of this preference for side-rod construction is due to the restrictions imposed by the use of alternating-current motors is hard to determine, but the facts available indicate both in this country and abroad the uniformly higher cost of repairs of this more complicated form of mechanical drive.

The electric railway situation in Italy is further complicated by the employment of three-phase induction motors with all the attendant handicaps of double overhead trolleys, low power-factor, constant speeds, and overheating of motors resulting from operation on ruling gradients with motors in cascade connection. In many respects the non-flexible three-phase induction motor is poorly adapted to meet the varied requirements of universal electrification; and in consequence Italian engineers are still struggling with the vexing question of a system, which may, however, be in fair way of settlement through the adoption of a standard of 50 cycles as the frequency of a nation-wide interconnected power supply, thus throwing the preponderance of advantages to high-voltage direct current.

The extreme simplicity of the gearless motor locomotive appeals to many as does its enviable record of low maintenance cost, reliability, and high operating efficiency, as exemplified by its unvarying performance in the electrified zone of the New York Central for the past twelve years. Table XIII shows that the high cost of living did not appear to have reached this favored type of locomotive until the year 1918.

The records on the C., M. & St. P. locomotive are equally remarkable when considering their greater weight and more severe character of the service.

TABLE XIII—MAINTENANCE COSTS, NEW YORK CENTRAL.

	1913	1914	1915	1916	1917	1918
Number locomotives owned	48	62	63	63	73	73
Average weight, tons	118	118	118	118	118	118
Cost repairs per locomotive mile	4.32	4.03	4.45	3.78	4.01	6.26

TABLE XIV—LOCOMOTIVE MAINTENANCE COSTS, CHICAGO, MILWAUKEE & ST. PAUL RAILWAY.

	1916	1917	1918
Number locomotives owned	20	44	45
Average weight, tons	290	290	290
Cost repairs per loco. mile	8.21	9.62	10.87

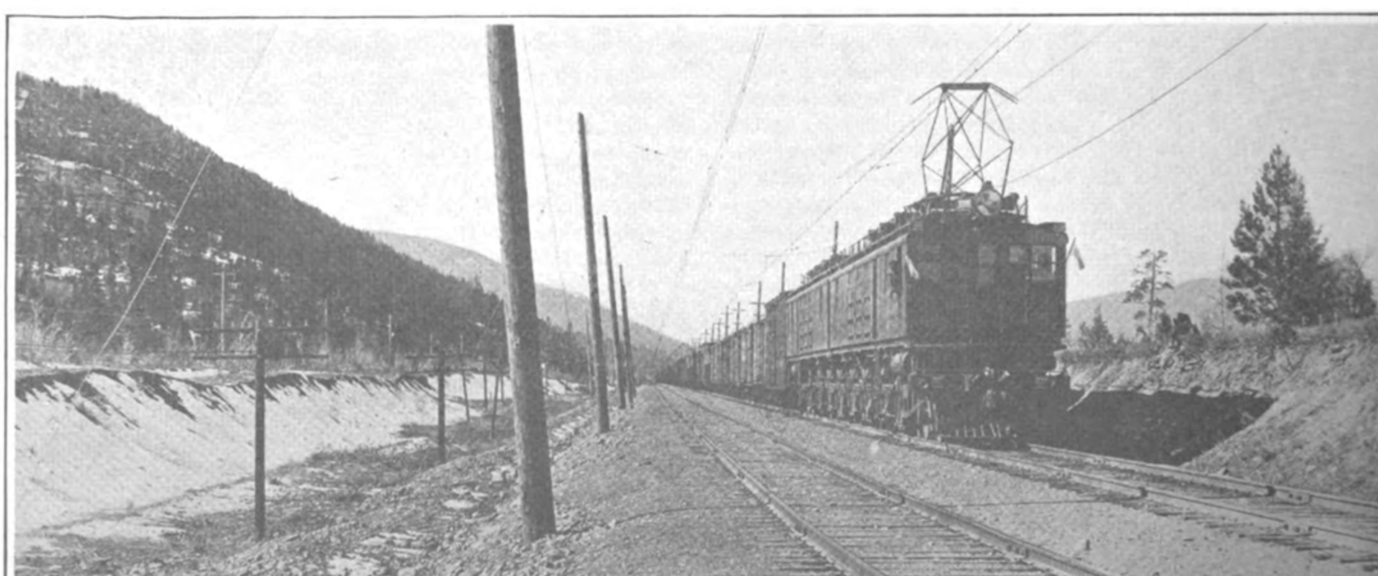
In both these instances the cost of repairs approaches closely to three cents per 100 tons of locomotive weight. Giving due credit to the excellent repair shop service rendered in each case, it is instructive to note that three cents per 100 tons maintenance cost of these direct-current locomotives is less than half the figures given for any of the alternating-current locomotives operating in the United States or in Europe.

Compared with the cost of repairs for equivalent steam engines, the above figures for electric locomotives are so very favorable as to justify the general statement that electric motive power can be maintained for approximately one-third the cost of that of steam engines for the same train tonnage handled. As locomotive maintenance is a measure of reliability in service and in a way expresses the number of engine failures, it is quite in keeping with the records available to state also that the electric locomotive has introduced a new standard of reliability that effects material savings in engine and train crew expense as well.

While the first cost of electrification is admittedly high, it may in certain instances be the cheapest way to increase the tonnage carrying capacity of a single track especially in mountain districts where construction is most expensive and steam engine operation is most severely handicapped. In this connection a comparison of steam and electric operation on the C., M. & St. P. Ry. may be summarized as follows:

For the same freight tonnage handled over the Rocky Mountain Division, electric operation has effected a reduction of 22½ per cent in the number of trains, 24.5 per cent in the average time per train, and has improved the operating conditions so that nearly 30 per cent more tonnage can be handled by electric operation in about 80 per cent of the time it formerly took to handle the lesser tonnage by steam engines. This means a material increase in capacity of this single-track line which may be conservatively estimated in the order of at least 50 per cent and probably more. In other words, on this particular road, electrification has effected economies which sufficiently justify the capital expenditure incurred and furthermore has postponed for an indefinite period any necessity of constructing a second track through this difficult mountainous country.

A careful study of the seriously congested tracks of the Baltimore and Ohio Railroad between Grafton and Cumberland disclosed vitally interesting facts. Company coal movement in coal cars and engine tenders constituted over 11 per cent of the total ton-miles passing over the tracks. In other words, owing to the very broken profile of this division, the equivalent of one train in every nine is required to haul the coal burned on the engines. Taking advantage of this fact and the higher speed and hauling capacity of the electric locomotive and its freedom from delays due to taking on water and fuel, it is estimated that the three tracks now badly congested with present steam engine tonnage could carry 80 per cent more freight with electric locomotive operation. The coal output of the Fairmont District is largely restricted by the congestion of this division of the B. & O. R. R. and it is probable that equal relief with continued steam engine



A 5,000-TON FREIGHT TRAIN (100 CARS) ON THE CHICAGO, MILWAUKEE AND ST. PAUL RAILWAY operation could not be secured without the expenditure of a much larger sum for additional track facilities than would be needed to put electric locomotives upon the present tracks.

Further instances could be cited where the benfits of electrification are badly needed and many of these are coal carrying roads among which the Virginian Railway stands out conspicuously as a good opportunity to make both a necessary improvement and a sound investment.

Reviewing the progress made in a short twenty-year period, we have seen the steam turbine and electric generator drive the reciprocating engine from the stationary power field. The same replacement is now taking place on our ships, big and small, notwithstanding the fact that the marine reciprocating engine is a very good engine indeed and operates under the ideal conditions of steady load and constant speed. And now the steam locomotive must in turn give way to the electric motor for the same good reason that the reciprocating steam locomotive has become obsolete and fails to respond to our advancing needs. Electrification affords a cheaper and better means of securing increased track capacity and improved service than by laying more rails and continuing the operation of still more steam engines in the same old wasteful way.

To conclude the startling picture of our present railway inefficiency, we are today wasting enough fuel on our steam engines to pay interest charges on the cost of completely electrifying all the railways in the United States, fuel that Europe stands in sad need of and which England and Germany, the pre-war coal exporting countries, cannot now supply. With operating expenses mounting to 82 per cent of revenue, inadequate equipment and congestion of tracks, what we need in addition to constructive legislation and real cooperation on the part of the Government in the matter of rates and safeguarding invested capital, is wise direction in the expenditure of the large sums that must speedily be found and used to bring our railways abreast of the times. Accord full honor to the reciprocating steam engine for the great part it has played in the development of our railways and industries, but complete the work by replacing it with the electric motor and enter upon a new era of real railroading, not restricted steam engine railroading.

Measuring Thermal Expansions*

Accuracy of the Stretched Wire Dilatometer

By Arthur W. Gray

DETERMINATIONS of linear thermal expansivity involve:

(1) Production of temperature uniformity.
(2) Determination of temperature.
(3) Measurement of small length changes.

Of these, the last is by far the most difficult.

DIFFICULTIES IN MAKING RELIABLE MEASUREMENTS.

The difficulties that arise in connection with the measurement of length changes are of two kinds:

First, the displacements are generally so small that in order to attain even moderate percentage accuracy, high absolute accuracy is necessary. It is comparatively easy to arrange devices of sensitivity sufficient to indicate displacements smaller than one-tenth of a micron; but it is not quite so easy to attain such precision upon repeated attempts to measure the same length. It is not at all easy to make sure that such precision, when attained, represents real accuracy, that is to say, correctness.

In the second place, measurements of thermal expansions are far more difficult than ordinary length measurements requiring the same degree of accuracy. The very nature of the case demands that the body under investigation be measured at several different temperatures; and changes of temperature are always accompanied by displacements in various parts of the measuring apparatus. Unless special precautions are taken, these displacements give rise to errors which are always difficult, and often quite impossible, to determine with certainty. So-called compensating devices are generally unreliable. Rather than trust them when accuracy is of importance, it is better to design apparatus which will render the errors negligible, or at least will make them determinable with certainty.

It was for the reasons just given that the writer introduced the use of stretched wires in 1911 when designing for the Bureau of Standards the equipment still used in determining the thermal expansivity of materials in the form of bars.

STRETCHED WIRE METHOD FOR MEASURING LINEAR DISPLACEMENTS.

With the aid of such a simple device as a tightly stretched fine wire it is fairly easy to measure with great accuracy a displacement which occurs within a region otherwise difficult of access.[1]

Apparatus on this principle has been employed for the past eight years in the determination of thermal expansions. Two such arrangements of stretched wires are represented diagrammatically by Figs. 1 and 2. In each the expanding bar is indicated by *AB*. In Fig. 1, wires are freely suspended in contact with the ends of the bar and are stretched vertically by the weight of vanes immersed in oil, the viscosity of which is adjusted to damp any swinging of the wires so that their motions will be almost, but not quite, aperiodic. In Fig. 2, suitable for cases in which the bar is immersed in a liquid, wires are stretched upward to another bar *CD* rigidly connected with the central portion of *AB*. In both arrangements the transverse motions of the wires are observed through micrometer microscopes focused at convenient points *E* and *F*. Disturbances from changes in level are avoided by grinding ends of *AB* to form portions of a horizontal cylinder, the axis of which passes through the center of the bar.

ACCURACY AND RANGE OF THE METHOD.

Unless one has had actual experience with this method of rendering displacements accessible to measurement, it is difficult to believe the accuracy attainable when proper precautions are taken. Thousands of observations have convinced me that the method is the most reliable yet devised for the measurement of thermal expansions. I have used the arrangement of Fig. 2 in an oil bath maintained at any desired temperature from near —150 deg. C. up to +350 deg. C., and I have used the arrangement of Fig. 1 in an electric furnace at various temperatures up to about 650 deg. C. I have not personally tested the method at temperatures much above 650 deg. C. Sufficiently fine wires of nichrome or other non-oxidizable material strong enough at higher temperatures to sustain the weights of the damping vanes were not obtainable while I was at the Bureau of Standards. Nor were my ar-

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[1]Expansion measurements by this method were reported to the American Physical Society at the Washington meeting in December, 1911, and at various times since then. (A. W. Gray: "A New Type of Apparatus for Measuring Linear Expansion," *Phys. Rev.*, Vol. 34, p. 139, 1912.) The principle of the method was also described in a communication to the Washington Academy of Sciences. ("New Methods for Displacement Measurements and Temperature Uniformity Applied to the Determination of Linear Expansivity," *Journ.*, Wash. Acad. Sc., Vol. 2, p. 248, 1912.) See also "Production of Temperature Uniformity in an Electric Furnace," Bull. Bureau of Standards, Vol. 10, p. 451, 1914; Scientific Paper No. 219.