standard of maintenance of equipment of doubtful value on the present basis of inspection at each 100-mile interval? Cars in subway service, which is certainly full of potential hazard, are economically and reliably maintained through inspection at intervals of 1,000 to 3,000 miles. The elimination of these intermediate terminals, with the resultant necessity of keeping the trains moving on the main line, would secure an enormous increase in miles per car with a corresponding saving in equipment.

Furthermore, with the dispatch obtained in handling trains, movement could be so marshaled and scheduled that the necessity of storing goods at terminals to protect exports and local consumption would be largely eliminated, and terminals would then become in fact, as in fiction, gateways open instead of closed.

Coming now to the comparative performance of steam and electric locomotives, it is important to bear in mind that one is a generator and the other a transformer of power. The generation of power in central stations is surrounded with many refinements, and in the consumption of coal there is every opportunity for skillful handling and supervision, so that the thermal efficiency of a modern central station is relatively high and is continuously maintained at a high value. With the steam locomotive, on the other hand, the thermal efficiency is dependent not alone upon the design of the locomotive but the manner in which it is worked, its condition, which differs widely from the best, and finally by the skill in firing. The electric locomotive, on the other hand, consumes power only when in service and works at any load at its designed efficiency. The average performance, in the case of the electric, approximates the maximum in efficiency, while the steam, on average performance, will differ widely therefrom. There is further economy due to the lesser work performed, because the electric locomotive does not have to trail supplies of fuel and water, nor is there need for the hauling of coal to points of local supply, which will always be greater than hauling to electric central stations.

There are a considerable number of different designs of electric locomotives all in successful operation, and each possessing certain advantageous features. The great latitude with which electric locomotives can be designed, while fundamentally most desirable, is in itself at the present time somewhat of a handicap. This is now the subject of intensive analysis and this study is undoubtedly developing as well a better knowledge of the running characteristics of the steam locomotive.

To state the case briefly, we are all interested in the transportation problem. Electrification is bound to be the most potent factor for its relief. We should, therefore, secure the closest possible co-operation with the engineering and mechanical skill which has been so productive in the steam locomotive field.

The Electric Locomotive in Heavy Traction*

The Several Factors in Its Application Are Stated and Illustrated by References to Data from Operating and Test Records

BY A. H. ARMSTRONG
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A COMPARISON of the modern steam and electric locomotive leads immediately to a discussion of the relative fitness of the two types of motive power to meet service conditions. At present railway practice has closely followed steam engine development, but are we not justified in looking at the transportation problem from the broader standpoint of a more powerful and adaptable type of motive power?

A locomotive is primarily a hauling machine. Its design is defined by recognized limits such as maximum degree of track curvature, coefficient of adhesion between driving wheels and rail, gross weight and dead weight per axle, tracking qualities at high speed, etc. Furthermore, the locomotive should be simple in construction, reliable and adaptable in operation and capable of being maintained in condition for a reasonable percentage of its cost.

Accepting the Mikado and Mallet as the highest developments of steam-road and helper engines for freight service, the general comparison of Table II, shown on page 872, is drawn with an entirely practicable electric locomotive that can be built without in any respect going beyond the experience embodied in locomotives now operating successfully.

The above analysis brings out the fact that to equal the hourly ton-mile performance of one electric locomotive it would require three and four engine crews respectively for the Mallet and Mikado types.

The electric locomotive has demonstrated its very great advantages in relieving congestion on single-track mountain-grade divisions. Due to the increase in number of meeting points through its higher speed,

TABLE I—COMMONLY ACCEPTED CONSTANTS IN HEAVY TRACTION

Limiting gross weight per axle, lb	60,000
Limiting dead weight per axle, lb	18,000
Limiting coefficient adhesion running, per cent	18
Limiting coefficient adhesion starting, per cent	25
Ruling gradient, per cent	2
Maximum curvature, deg	10
Maximum rigid wheelbase, ft	18
Maximum speed on level, passenger, m.p.h	65-70
Maximum speed on level, freight, m.p.h	25-30
Maximum drawbar pull, lb	150,000

and on account of the independence of climatic conditions of the electric locomotive and other time-saving factors, it is safe to say that the daily tonnage capacity of single-track mountain-grade divisions will be increased fully 50 per cent over possible steam-engine performance by the adoption of the electric locomotive.

REGENERATIVE BRAKING IS A UNIQUE ELEMENT

The hazard of mountain operation is greatest on down grades, although the perfection of automatic air

*Abstract of paper read at joint meeting of A. S. M. E. and A. I. E. E. sections, New York City, Oct. 22, 1920.

TABLE II—COMPARISON OF STEAM AND ELECTRIC LOCOMOTIVES

	Mikado	Mallet	Electric
Type	2-8-2	2-8-8-2	6-8-8-6
Weight per driving axle, lb.	60,000	60,000	60,000
Number of driving axles	4	8	12
Total weight on drivers, lb.	240,000	480,000	720,000
Total weight locomotive and tender, lb.	480,000	800,000	780,000
Traction effort at 18 per cent coefficient	43,200	86,400	129,600
Gross tons, 2 per cent grade	940	1,880	2,820
Trailing tons, 2 per cent grade	693	1,495	2,430
Speed on 2 per cent grade, m.p.h.	14	9	16
Horsepower at driver rims	1,620	2,080	5,570
Indicated horsepower at 80 per cent efficiency	2,030	2,600	......
Trailing ton-miles per hour on 2 per cent gradient	9,700	13,500	38,800

TABLE III—ELECTRIC LOCOMOTIVE MAINTENANCE DATA FOR 1919

	N. Y. C.	C., M. & St. P.	B., A. & P.
Number of locomotives owned	73	45	28
Locomotive weight, tons	118	290	84
Annual mileage	1,946,879	2,321,148	566,977
Cost of repairs per mile, cents	6.39	14.65	6.48

brakes has done much to modify its dangers. It is left to electricity, however, to add the completing touch to the safe control of descending trains by supplying regenerative electric braking. Aside from the power returned from this source (14 per cent of the total on the Chicago, Milwaukee & St. Paul Railway) the chief advantage of electric braking lies in its assurance of greater safety and higher speeds permitted on down grades.

The electric locomotive shows great advantage over the steam engine in cost of maintenance. Special importance attaches to this item of expense in these days of high labor and material costs. In order to draw a fair comparison, however, there should be included in steam-engine repairs all expenses of roundhouses, turntables, ashpits, coal and water stations, in fact the many items contributing to rendering necessary steam-engine service, as most of these charges are eliminated by the adoption of the electric locomotive. Spare parts can be substituted so quickly that, excepting wrecks, there is no need of the back shop for electric locomotives, unless turning tires and painting can be considered heavy repairs. Electric locomotives are now being operated 3,000 miles between inspections on at least two electrified railways and the data that are given in Table III show recent costs.

On the basis of pre-war prices, maintenance costs were approximately 60 per cent of the figures given in Table II. In contrast, it can be stated that the present cost of maintaining a type 2-8-8-2 Mallet may be taken at 60 cents per engine-mile, without including many miscellaneous charges not shared by the electric locomotive. Possibly more direct comparison may be better drawn by expressing maintenance in terms of driver weight, as in Table IV.

TABLE IV—STEAM AND ELECTRIC REPAIRS ON WEIGHT BASIS

	Steam Mallet	C., M. & St. P. Elec.
Cost of repairs per mile, cents	60	14.65
Weight on drivers, tons	240	225
Cost of repairs per 100 tons locomotive weight on drivers, cents	25	6.52

TABLE V—FUEL COMPARISON, SHOWING STANDBY LOSSES

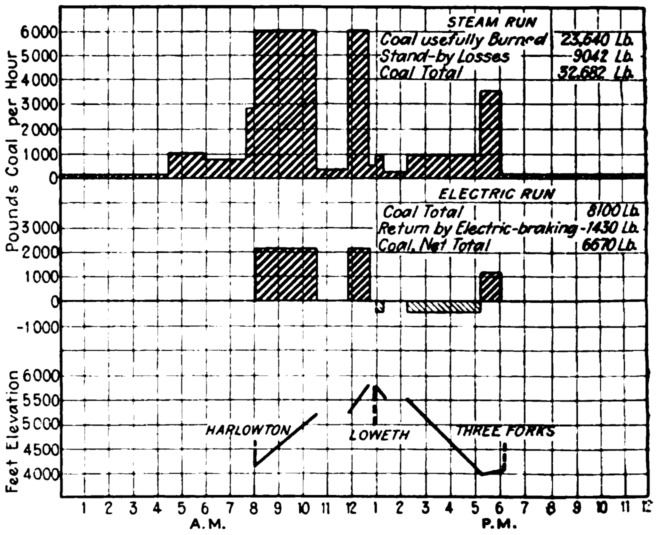
		Steam	Electric
Doing useful work, lb.		23,640	8,100
Making up fire, lb.	1,535		
Delay at Harlowton, lb.	2,270		
Held up at Lennep, lb.	394		
Held up at Loweth, lb.	128		
Held up at Dorsay, lb.	230		
Fire, banked 9 hr., lb.	1,425		
Coasting down grade, lb.	3,060		
Total standby losses, lb.		9,042	
Regenerative braking, lb.		....	1,430
Total net coal, lb.		32,682	6,670

Including all engine service charges, the facts available give foundation for the claim that electric locomotives of the largest type can be maintained for 25 per cent to 30 per cent of the upkeep cost of steam engines operating in similar service.

Fuel Saving as Promised by Electrification

As to fuel saving effected by steam railway electrification, estimates of electric engineers have been called extravagant by steam engine advocates. Fuel economy figured prominently among the reasons leading up to the replacement of the steam engine on the Chicago, Milwaukee & St. Paul Railway as brought out by a careful analysis of the performance of the steam engines then in service.

The following runs are chosen for illustration as bringing out most strikingly the inherent disadvantages of operating a steam engine over a single-track mountain-grade division and handicapped by the usual delays attending freight train service under such conditions: The run of 111.1 miles from Harlowton, elevation 4,162 ft., to Three Forks, elevation 4,066 ft.,



COAL CONSUMPTION COMPARISON ON IDENTICAL RUNS

over the Belt Mountain divide at Loweth, elevation 5,789 ft., was made by steam with 871 tons trailing load in twenty-six cars and by electric locomotive hauling sixty-four cars weighing 2,762 tons. The accompanying diagram shows the results reduced to a common basis of 1,000 gross tons moved, including the locomotive and tender weight. The running speed of the electric train was but slightly higher than the steam and the additional correction in the power demand rate of the former is made proportional to the lower speed. Both runs are therefore shown as made in identical time on the basis of 1,000 total gross tons moved in each instance. The fuel furnishing power to the steam train was 11,793-B.t.u. coal. Electric power was furnished by water and hence no direct coal equivalent is provided by the test result. To afford a common basis of comparison, however, a rate of 2½ lb. of coal per kilowatt-hour is taken as representative of fair electric power station practice. Coal burned under the steam engine boiler was determined by weighing at the end of the run and by detailed record of scoops en route. Power input to the electric locomotive was obtained by means of carefully calibrated recording watt-hour meters as well as curve-drawing volt and ampere meters. These values of locomotive input were raised to the value of three-phase power purchased, in the ratio given by R. Beeuwkes in his A. I. E. E. paper of July 15, 1920,* and the kilowatt-hours so obtained were reduced to coal equivalent in the ratio of 2½ lb. of coal per kilowatt-hour.

While the electric locomotive demands power only when in motion, the steam engine requires coal during twenty-four hours, whether doing useful work, standing idle or coasting down grade. In fact, the standby losses were such a large percentage of the total coal consumed that a careful record was kept of their several amounts, as may be seen by referring to Table V.

The run of a more modern steam engine would have effected a material reduction in the 23,640 lb. of coal burned in doing useful work, but the amount of coal wasted in standby losses (9,042 lb.) might have been duplicated or even possibly increased with larger grate area. As standby losses constitute so large a proportion of the total coal burned (27½ per cent in this instance) it is apparent that enormous economies over the simple engine tested must be realized in the modern superheater and other improvements since introduced to offset in part the high inherent efficiency of the electric locomotive.

The commonly used unit measurement of pounds of coal per 1,000 ton-miles is at best a very rough and unstable comparison of steam engine runs over different profiles, variable quality of fuel and operating conditions. For example, the data given in Table VI show that pounds of coal per gross 1,000 ton-miles may vary from 650 to 50.5, according to gradient, with no standby losses included. The boiler must always be kept hot, however, and fully 33 per cent can safely be added to the above figures to include the inevitable standby losses inherent to steam engine operation. Except over very long runs with terminals at the same elevation it seems hardly possible therefore accurately to compare engine performance over different profiles by such a variable unit as pounds of coal per 1,000 ton-miles.

A truer understanding of what takes place under the engine boiler may be shown by continuous records of coal burned, tons moved, profile, delays, etc., all reduced to pounds of coal burned per useful horsepower-hour of work done at the driver rims with segregation of the many standby losses, as in Table VII.

Under the same conditions a modern engine would undoubtedly have consumed much less than 9.02 lb. of 11,793-B.t.u. coal while doing work measured at the driver rims. The addition of superheaters gives greater output and economy, while mechanical stokers add output only and, it is claimed, at some expense in economy over good hand firing. However efficient the power plant on wheels may reasonably be developed without too seriously interfering with the sole purpose of the steam engine, the hauling of trains, it can never approach the fuel economies of modern turbine generating stations. Whatever transmission and conversion losses are interposed between power house and electric locomotive are more than compensated for by the improvement in the load factor resulting from averaging the very fluctuating demands of many individual locomotives.

*See issue of ELECTRIC RAILWAY JOURNAL for July 31, 1920, page 227.

TABLE VI—POUNDS OF COAL PER 1,000 TON-MILES

	2 per Cent Grade	Level Track
Horsepower-hours at driver rims	123	18.8
Indicated horsepower-hours at 80 per cent efficiency	154	23.5
Pounds water per indicated horsepower hour	20	16.0
Pounds water per pound of coal	6	8
Pounds coal per indicated horsepower-hour	3.33	2.0
Pounds coal per 1,000 ton-miles	513	47
Pounds coal per 1,000 ton-miles trailing	650	50.5

TABLE VII—ANALYSIS OF STEAM AND ELECTRIC RUNS HARLOWTON TO THREE FORKS, IN UNITS PER 1,000 TONS MOVED

	Steam	Electric
Kilowatt-hours at driver rims	2,038	2,038
Horsepower-hours at driver rims	2,625	2,625
Coal per horsepower-hour at driver rims, lb	9.02	*3.09
Credited regenerative braking, lb	.....	0.55
Standby losses, 27½ per cent, lb	2.47	.....
Total coal per rim horsepower-hour, lb	11.49	2.54

*Measured at power house; includes locomotive losses and 32 per cent transmission and conversion loss.

It would be a simple matter to carry through a series of runs over the electrified zones of the Milwaukee with a modern Mikado equipped with up-to-the-minute fuel-saving devices and thus provide the necessary data to draw direct comparisons with the electric locomotive. Such tests with modern steam equipment would undoubtedly discredit the above comparison based upon the economies of six years ago and might lead to something approximating the blend of fact and theory shown in table VIII.

The above table is based upon actual electric locomotive performance, Harlowton to Three Forks, coal taken at 2½ lb. per kilowatt-hour at assumed steam power station. Steam engine values are based upon the known working efficiency of a Mikado equipped with superheaters but penalized with the same standby losses actually determined with a simple engine tested Harlowton to Three Forks. A test run from Harlowton to Three Forks with a modern Mikado engine hauling 1,420 tons may possibly show a lower average fuel rate than 3 lb. per indicated horsepower-hour at drivers less standby waste than 9,042 lb. of coal, but the average annual performance of many such engines would be most excellent if it reached the net figure arrived at of 5.9 lb. of coal per actual horsepower-hour of work performed at drivers. The electric run, however, is being duplicated daily, as to relation between kilowatt-hours and ton-miles, and it is just this reliability of electric operation that may at times give rise to misunderstanding in the comparison of steam and electric data.

In view of all the facts a broad statement may be made that the general adoption of the electric locomotive would probably result in saving fully two-thirds the fuel now burned on present steam engines and possibly one-half the amount of fuel necessary to steam engines of the most modern construction.

TABLE VIII—THEORETICAL COMPARISON OF MODERN STEAM AND ELECTRIC LOCOMOTIVES, HARLOWTON TO THREE FORKS

	Mikado	Electric
Type	2-8-2	4-4-4-4-4-4
Weight on drivers, lb	240,000	450,000
Weight engine and tender, lb	480,000	568,000
Tractive effort, 18 per cent coefficient, lb	43,200	81,000
Trailing tons, 1 per cent grade	1,420	2,836
Horsepower-hours at driver rims	4,360	8,200
Coal per indicated horsepower-hour, lb	3	....
Coal per driver, horsepower-hour, lb	3.75	....
Standby loss, test result, lb	9,042	....
Standby loss, per horsepower-hour, lb	2.15	.....
Total coal per driver, horsepower-hour, lb	5.90	....
Coal at power house, per kilowatt-hour, lb	....	2.5
Coal at power house, per horsepower-hour, lb	....	1.86
Coal at locomotive driver, per horsepower-hour, lb	....	3.09
Coal credit due regeneration, lb	....	0.55
Net coal at driver per horsepower-hour, lb	5.90	2.54
Total net coal, lb	24,800	20,900
1,000 trailing ton-miles	157,500	314,000
Coal per 1,000 ton-miles, lb	158	66.7
Ratio coal burned	2.37	1

The superior operating advantages of the electric locomotive are admitted by many who believe the first cost to be prohibitive, largely due to the necessary trolley construction, copper feeders, substations, transmission lines, etc. Such auxiliaries do add an amount that may equal the electric locomotive expense and the task of proving the electric case is not made easier by the fact that steam engine facilities are already installed and may have little or no salvage value to offset new capital charge for electrification.

Comparing the cost of equivalent steam and electric motive power, it is apparent that on the basis of the same unit prices for labor and material the first cost is approximately the same. While electric locomotives cost possibly 50 per cent more than steam for equal driver weight, the smaller number required to haul equal tonnage may quite offset this handicap, especially with quantity production of electric locomotives of standard design.

The steam engine also demands a formidable array of facilities peculiar to itself, as shown by expenditures made on fourteen railways included in the Northwestern group from 1907 to 1919. This expense covers fuel and water stations, shops and engine houses, shop machinery, turntables, ashpits, etc., and amounted to $42,200,000 as compared with expenditures of $68,000,000 for engines. Proper facilities for rendering adequate steam engine service apparently add some 62 per cent to the cost of the latter.

One of the advantages of electric locomotives rests in the longer engine divisions which they make possible. Considered as a problem of construction only, electrification of a new road may, in some instances, compare quite favorably with the complete first cost of steam engines and all facilities incident thereto. The general problem, however, is one of replacing steam engines now running so that the economic advantages of electrification are rather individual to the particular railway under consideration. The operating economies effected under favorable conditions have been found sufficient to show an attractive return upon the additional capital charge incurred besides providing the improved service which was the main objective in view in replacing the steam engine.

No discussion of electric railway economies would be complete without comment upon the increased value of real estate brought about by terminal electrification. Not only is neighboring real estate benefited thereby, but the "air rights" over the electrified tracks may become so valuable as to largely pay the cost of the change from steam. With the work but partly finished the Grand Central Terminal district is already a remarkable example of the indirect benefits derived from electrification.

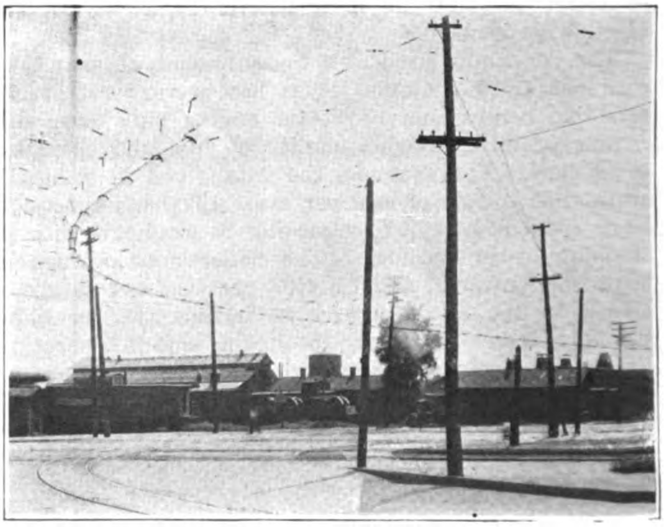
A Summary of the Whole Matter

Some of the principal advantages claimed for the electric as compared to the steam locomotive may be briefly stated as follows:

1. No structural limits restricting tractive effort and speed of electric locomotive that can be handled by one operator.
2. Practical elimination of ruling grades by reason of the enormously powerful electric locomotives available.
3. Reduction of down grade dangers by using regenerative electric braking.
4. Very large reduction in cost of locomotive maintenance.
5. Very large saving of fuel, estimated as two-thirds the total now burned on steam engines in operation.
6. Conservation of our natural resources by utilizing water power where available.
7. Material reduction in engine and train crew expense by reason of higher speeds and greater hauling capacity.
8. Increased valuation of terminal real estate following electrification.
9. Increased reliability of operation.
10. Material reduction in operating expense due to elimination of steam engine tenders and most of the company coal movement, the two together expressed in ton miles approximating nearly 20 per cent of present gross revenue ton-mileage.
11. Large reduction in effect of climatic conditions upon train operation.
12. Postponement of immediate necessity for constructing additional tracks on congested divisions.
13. Attractive return on cost of electrification by reason of direct and indirect operating savings effected.
14. Far-reaching improvements in operation that may revolutionize present methods of steam railroading.

Unusual Trolley Guard Installation

On one of the Council Bluffs, Iowa, lines of the Omaha (Neb.) & Council Bluffs Street Railway the track crosses at grade a group of thirteen steam railroad tracks, including main-line tracks of two railroads, and at the same time curves through an arc of about 75 deg. The difficulty of holding the trolley wheels on the wire while traversing this curved crossing may be readily appreciated, likewise the necessity to resort to every means available to keep the trolley wheel on the wire. If the car were to lose power at any point of the crossing it would be practically certain to be stranded and consequently would be in a dangerous predicament.



A 507-FT. TROLLEY GUARD INSTALLED ON A CONTINUOUS CURVE OVER THIRTEEN STEAM ROAD TRACKS

In coping with this situation, the Omaha company installed an unusually long stretch of Ohio brass overhead trolley guard. It is 507 ft. long and none of it is tangent. Its installation was a difficult piece of work. Not only was there very heavy traffic on the several steam lines to contend with but the linemen found it difficult to bend the trolley guard sideways and still retain the V-shape. This was done by using bending clamps, which were kept in place while the guard was worked sideways. A ⅜-in. backbone messenger cable was first installed and the trolley guard supported from this, with double pull-offs to hold messenger and trolley wire in proper position over the tracks.

W. O. Jacobi, superintendent of electric lines, reports that this installation is of great assistance.