Economics of Electric Traction to Transport Coal on Richards Bay Line

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In 1975, South African Railways completed a new railway line between coal fields in the Eastern Transvaal and Richards Bay Harbour for the export of coal. In 1978, this line was electrified by using a 25-kV 50-Hz alternating-current system. Between Ermelo and Richards Bay the line drops about 1700 m, which considerably reduces the energy demand of loaded coal trains. However, empty return trains of about 30 percent of loaded train mass must climb the same height and in fact require slightly more energy. The use of the momentum of the long heavy trains on this line leads to considerable savings of energy. The effect of the three-part electricity tariff applied by the supply authority results in a reduction of the cost of electricity per kilowatt-hour as the traffic increases and also as the load factor (ratio of average load to maximum demand) improves. The manner in which the maximum demand is metered at substations along the line is of critical importance to economical electrical operation. Cost of electrical energy, which comes to $0.60/net ton (U.S. dollars), is the most important factor in the electrical economics of this line; it is far higher than are interest and redemption on capital and maintenance costs. For comparative purposes, fuel cost for diesel electric operation is about three times higher on an equivalent basis. Electrical costs in service now fully justify the decision to electrify this line, and capacity will shortly be increased to meet expected future demand. An extra 2700 km of other main routes in South Africa is also now being electrified, and the 25-kV alternating-current system will in future be the standard. The target now is to be able to handle 85 percent of all railway traffic on a ton-kilometer basis by means of electric traction.

In 1975, South African Railways completed a new railway line between coal fields in the Witbank area and Richards Bay in order to transport coal in bulk for export from Richards Bay Harbour. Figure 1 shows the location of this line as well as certain other major routes in South Africa, including the Sishen-Saldanha Bay iron-ore line. The Richards Bay coal line traverses some of the most difficult topography in the country; it requires many tunnels, viaducts, and curves and is a remarkable civil engineering undertaking.

Initially, the operation of the line was by means of diesel electric locomotives. However, in 1973, as a direct result of the energy crisis and increased costs of imported fuel, it was decided that the line should be electrified, and 25-kV 50-Hz alternating-current (AC) traction has now been introduced over the 400-km route between Ermelo and Richards Bay, whereas existing 3-kV direct-current (DC) traction in the Witbank area has been extended from the coal fields to Ermelo.

At first, 10 million tons of coal was the annual export target through Richards Bay, but this figure has already been surpassed. In 1980, 27 million tons were exported, and by 1985 a further increase to 40 million tons is expected.

The prices of both imported fuel and locally produced electric power have increased still further and, since shortages of both could occur, conservation of energy is now of primary importance. This paper considers the economics of electric traction, specifically on the Ermelo-Richards Bay 25-kV AC electrification.

In the transport of the 27 million tons of coal now being sent from Ermelo to Richards Bay, the gross traffic handled on the coal line in this direction is 37 million tons annually. Returning trains consist of empty cars and gross an additional 11 million tons. This amounts to 19 000 million gross ton-km of traffic annually, and the quantity of electrical energy used for this traffic is approximately 365 million kW•h. This comes to about 13.5 kW•h/ton of coal transported over the 400-km line.

EFFECT OF GRADIENT, SPEED, AND TRAIN LOAD ON POWER REQUIREMENTS

Figure 2 is a profile of the coal line between Ermelo and Richards Bay, which falls approximately 1700 m in height. This considerably reduces the energy demand of the loaded trains, which now are each made up of 84 cars and a trailing mass of 6720 tons. Empty trains have a trailing mass of 1760 tons, but since these trains must climb the same height at higher speeds, they in fact consume 6 percent more energy than the loaded trains do.

The 400 route-km of this line can be roughly divided into the three following categories with respect to the gradient that affects the loaded trains:

1. A down gradient of 67 percent for which negligible power is required and of which 38 percent is between 12 and 15 km/1000, in which speed is restricted to 40 km/h for safety in braking the heavy coal trains;
2. Level and easy gradients of 15 percent that are less than 10 km/1000, in which the power requirement of the trains is moderate; and
3. Up gradients of 18 percent that are more severe than 10 km/1000, which includes 4 percent of the ruling 15-km/1000 gradients (only on this 18 percent is full power of the hauling locomotives required).

The maximum speed for heavy trains on this line is 60 km/h, and only moderate locomotive power is required for a loaded train for 82 percent of its run.

The coal line was designed for operation by trains of 76 cars (18.5 tons/axle) that have a gross trailing mass of 5600 tons and are hauled by three class 7E electric locomotives that each have a 3000-kW output. These trains have a balancing speed of 35 km/h on the ruling 15-km/1000 grades and operate at about 27 percent adhesion due to the locomotive axle load limit of 21 tons. Later, in order to increase the tonnage that could be hauled on the line, trains were increased to 84 cars (20 tons/axle) and 6720 tons trailing mass; this is the maximum length of train that crossing places would permit. This step now requires four locomotives to be used per train. Locomotives are therefore loaded slightly less but achieve a higher speed on gradients; adhesion has been reduced to 24 percent.

The same four locomotives required for the loaded train are capable of hauling the empty train up the severe return gradients at speeds well above the speed limit now allowed. Speed reduction results in lower efficiency, and the solution adopted is to use three locomotives for return haulage only and to shut down the fourth one. Three locomotives haul the empty cars at a speed of nearly 75 km/h, and this represents a 25 percent decrease in the maximum power required although there is a very slight increase in running time for the empty train.

Actual saving in energy required for the empty train, including power loss in auxiliaries that use one less locomotive, have been assessed as better

Figure 1. Diagram of electrified lines, South African Railways.

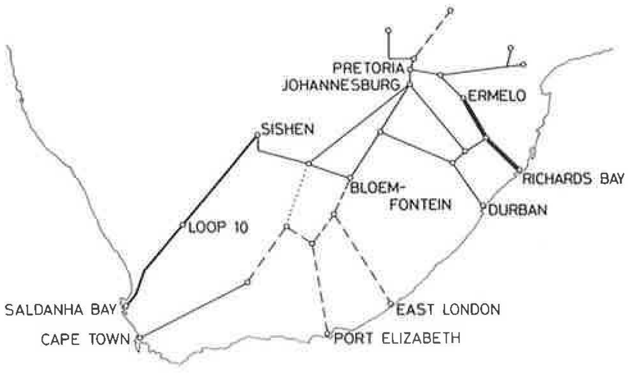
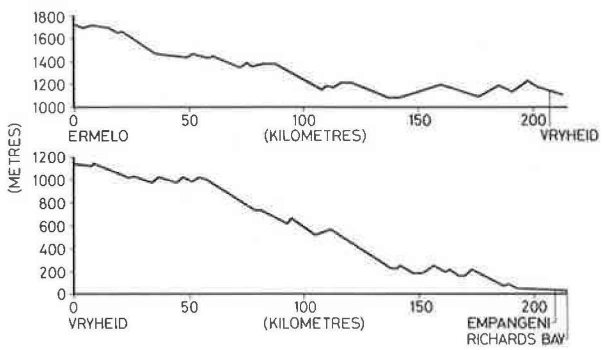


Figure 2. Line profile: Ermelo-Richards Bay.



than 3 percent. Further, maximum demand from the power supply system is more affected by the empty trains, which draw power steadily for long periods on the up gradients, than by the heavy trains, which draw power intermittently. Reduction of maximum-demand payments is therefore also achieved.

USE OF MOMENTUM

In the design of the electrical system for this line, an original computer simulation was devised that was able to predict all electrical and physical conditions for any train and combination of trains at any point on the line. This simulation proved to be remarkably accurate when it was eventually checked against test results.

From these simulations it was also known that optimum use of momentum by locomotive drivers in progression from steep downgrades to the many relatively short up gradients would result in about a 10 percent saving in electrical energy. In practice it has been found that experienced drivers achieve considerable savings in this respect, and when loaded test trains are used, the gross specific energy consumption achieved is 10.7 W•h/ton-km. (These figures exclude locomotive mass and are measured at the pantograph.)

The same economy cannot be achieved by using an empty train, which hauls more consistently on steady up gradients and has a specific energy consumption of 38.8 W•h/ton-km. The average is therefore 16.8 W•h/ton-km based on gross tonnage hauled.

In tests that use still heavier loads of up to 12 000 tons hauled by six electric locomotives, a still greater saving in energy has been measured and 9.3 W•h/ton-km (which is a 12.7 percent saving) has been achieved. This is due to greater momentum and the 2.0-km length of the train, which is much the same as the length of shorter gradients. In actual service over a 12-month period, an overall consumption of 18.2 W•h/ton-km measured at the high-voltage supply substation input has been achieved. This figure includes all losses in the system and the effect of practical train operations.

EFFECT OF ELECTRICITY TARIFF

The railway in South Africa obtains its electricity from the national grid of the Electricity Supply Commission (Escom), and the tariff for electric traction is no different than it is to any other bulk consumer. A three-part tariff is applied as follows:

1. Fixed charge: This is related to the supply authority's cost of extending the distribution from the national grid to the individual consumer and is based on interest and redemption on the capital cost of this extension;
2. An annual kilovolt maximum-demand charge: This is based on the maximum 30-min loading at any time during each month and is derived from the capital cost of the generating plant (and national grid system), which must be held on load to meet a consumer's peak load requirement; and
3. Energy consumption or kilowatt-hour charge: This is based on the actual cost of producing the energy used by the consumer.

In effect, therefore, the three-part tariff means that cost per kilowatt-hour varies widely depending on how the power is used. The fixed charge results in a reduction in cost per kilowatt-hour as the amount of energy consumed increases, and the maximum-demand charge results in a reduction in cost per kilowatt-hour as the load factor (ratio of average load to maximum demand) improves. Figure 3 illustrates how, in a typical case, cost per kilowatt-hour varies with these factors. Load factor is also influenced considerably by the annual kilovolt demand of individual heavy trains and in particular by the spacing of these trains. This effect is illustrated in Figure 4.

Of critical importance is the number of substations or supply points that the supplier agrees to meter together for maximum-demand charges. This is due to the fact that maximum demand usually occurs at different times at different supply substations and is usually caused by abnormal local train operations. Over the line as a whole, these abnormal operations even out and a more-uniform demand is drawn from the whole system. It is usual in a main-line traction operation for the load factor on individual substations to be as low as 30 percent, whereas over all the substations of a long section it may be as high as 70 percent.

ELECTRICAL BRAKING

For an operation of this nature in which heavy trains descend steep gradients, electrical braking is a requirement that hardly needs justification. However, whether regenerative braking, which feeds power back into the supply system, is economical needs careful consideration. Plain rheostatic braking in which resistors are mounted on the locomotive is extremely reliable and inexpensive and has been proved in service on both diesel and electric locomotives. Regenerative braking requires the provision of inverters and as a result is more complicated and expensive.

On this line it has been calculated that, even if a 25 percent reduction of energy consumption could be achieved, this would not affect the fixed and

Figure 3. Cost variations per kilowatt-hour.

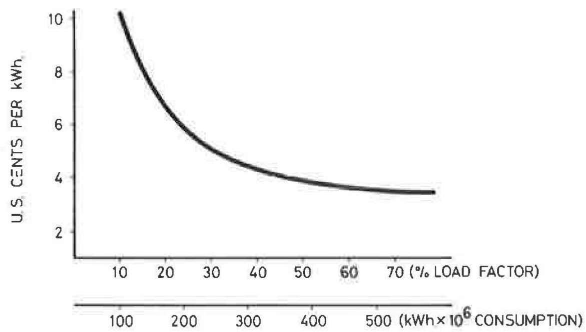
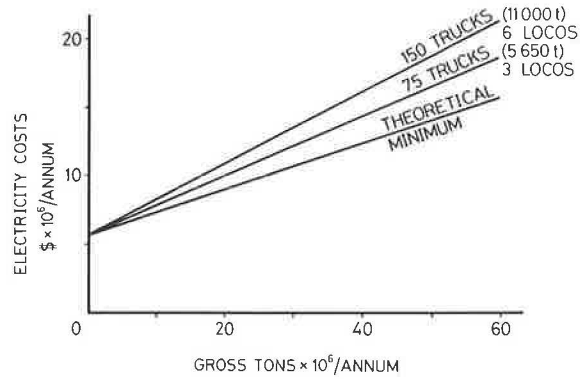


Figure 4. Effect of train mass on electricity costs.



maximum-demand charges and would result in only a 5 percent saving in electricity costs. Also, this saving could be offset about 2 percent by extra locomotive equipment costs.

The actual design adopted was to provide plain rheostatic braking on locomotives and to improve the power factor of these locomotives by use of forced commutation circuits, or switched capacitors, to 0.93 at full load. Improvement of the power factor reduces the maximum demand by 10 percent, but overall reduction of electricity costs is about 4 percent for little extra equipment cost on locomotives.

ELECTRICAL ENERGY AND OTHER ELECTRIFICATION COSTS

The following tabulation reflects costs in service during the financial year 1979-1980 on the coal line of electrical energy and of the capital and maintenance of electrification. Figures are tabulated on the basis of cost per 1000 gross ton-km hauled (includes the mass of coal cars but excludes the mass of locomotives). Approximate costs of the original diesel electric operation corrected to a 1979-1980 basis by using $0.45/L for diesel fuel are also given for comparison. (All figures have been converted to U.S. dollars, which at the 1980 exchange rate are equal to $0.76 in the Republic of South Africa.)

	Cost ($U.S.)	
Item	Electric	Diesel Electric
Energy and power supply		
Electricity or fuel	0.88	2.67
Lubrication	--	0.12
Interest on fixed equipment	0.36	--
Maintenance of fixed equipment	0.11	--
Subtotal	1.35	2.79
Locomotives		
Interest on capital	0.87	0.87
Maintenance	0.25	0.57
Subtotal	1.12	1.44
Grand total	2.47	4.23
Cost per ton of coal hauled	1.65	2.82

Maintenance costs of electric locomotives are not firm until their first major overhaul has been completed after seven years or about 1.4 million km. The tabulation above is based on the average in service by using 3-kV DC locomotives of $0.24/km and for diesel electrics of $0.34/km. Experience to date with 25-kV AC locomotives indicates that these will in future be more economical to maintain.

Fixed-installation cost is about $66 000 per single-track kilometer and is direct-electrification cost only. Maintenance of the fixed electrification installation costs about $1850 per single-track kilometer. All interest and redemption figures have been calculated at 12 percent per annum.

The tabulation includes only costs associated with the electric operation and excludes costs of drivers and train operations.

It will be noted in the figures above that the interest on capital costs is the same for both electric locomotives and diesel electric locomotives, since their cost per kilowatt-hour of output power is of the same order. For reasons given earlier, four electric locomotives of 3000-kW output are used for a train of 84 cars that is hauling 6720 tons. Six diesel electrics of 1500-kW output each at the rail were formerly used for the same load at lower speed on gradients.

The economical life of electric locomotives is still taken to be in excess of 30 years. Older locomotives were in service for more than 50 years but, with increasing costs of skilled labor, this is no longer an economical proposition. The economical life of diesel electric locomotives is not yet known, since experience with main-line locomotives of this type is still too limited.

Costs of providing a suitable signaling system for AC electrification on this line also cannot be given due to the difficulty in attributing a portion of the costs of a system that must be provided as a whole. Costs incurred in immunizing the public telecommunication system in the mainly rural area traversed by this line were almost negligible.

FUTURE EXPANSION

It has recently been decided that the coal line must be expanded to handle over 40 million tons of coal per annum, which, with other traffic and the empty return trains, amounts to more than 100 million gross tons per annum.

Usually such tonnage requires that a line be doubled, but the cost of this step in the difficult terrain is extremely high. Various alternatives, all of which use longer and heavier trains, were evaluated. Using more trains of the present tonnage is not practical due to the operational problems of crossing a large number of trains on a single line.

A practical limitation to heavier trains exists, however. The coupler strength of standard coal cars will be exceeded if more than four coupled electric locomotives haul from the front of a train. This problem can of course be overcome by placing helper locomotives further back on the train; however, this can then introduce difficulty in control.

It has now been decided that in the long run it will be more economical to ease the limited number of gradients in the direction opposite the loaded trains to 6.25/1000 uncompensated, so that four electric locomotives can haul a 200-car train from the front without exceeding allowable coupler strength. At the same time, investigations have proved that it will be practical to increase the axle loading of coal cars to 26 tons and that of electric locomotives to 28 tons. The trailing mass will then be 20 800 tons.

Tests have already been carried out that approximate the performance of a 200-car train on a regraded line, and measurements indicate that a specific energy consumption of about 7 W•h/ton-km for the loaded train and 34 W•h/ton for the empty one can be expected. These reductions are due not only to better use of momentum with a heavy train 2.5 km long, but also to a better ratio of trailing mass to locomotive mass, in which a 130 percent improvement over the present ratio by using 84-car trains is effected.

CONCLUSION

After the first year of full electric operation and two major fuel price increases, the first of which in 1973 led to the decision to electrify this line, the figures given fully justify this decision and confirm the economical use of electric traction in a heavy main-line operation of this nature. An annual saving of 120 million L of diesel fuel is now being effected on this line alone.

In the future in South Africa, it is foreseen that most diesel and other fuel oils will be obtained by conversion from the abundant coal resources. However, to convert coal to electricity and use this for an electrified railway is a 100 percent more-efficient use of this natural resource. This fact and the economic advantages illustrated in this paper have led to a decision to proceed with a further 2700 km of electrification on four major routes by 1985. This will result in a total of 16 000 km of electrified track in the republic.

Already 70 percent of all traffic on a ton-kilometer basis is hauled electrically on the South African Railways, and with these extensions and other traffic increases the target is to increase this figure by 85 percent.

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Railroad Electrification: An Alternative for Petroleum Savings

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Evaluation of various scenarios of construction rates, freight growth, and fuel-price escalation shows that electrification of the nation's high-density railroad routes is a cost-effective alternative when compared with the cost and output of synthetic-fuel plants. If 15 000 miles of the existing rail routes, which handle more than 30 percent of the nation's freight, were electrified today, the cost of the diesel fuel saved would be equivalent to $1.00/gal or less. After a 30-year period of construction and with a reasonable freight growth, the resulting 25 600 miles of electrified rail network would save more than 300 000 bbl of oil per day over the amount that would have been used by not electrifying. The investment per fuel equivalent produced or saved is approximately the same for the two alternatives. However, the fuel plant has a specific and limited output, whereas the growth in freight traffic that can accrue on electrified rail will generate increasing substantial returns on the investment, an investment that has the potential to last 50 years. The principal barrier to electrification is the large investment required relative to the railroad's financial condition. Preliminary analyses of costs and returns, however, indicate that rail electrification is a feasible energy-conservation opportunity. A mature technology, as shown by more than 60 000 route miles worldwide, it would provide substantial returns on investment and improve productivity. Given the escalation of fuel prices and a national desire for energy independence, electrification should be of high priority on the list of energy policies.

The use of electricity in railroads offers an option to diversify fuel sources by replacing a system now dependent on petroleum with energy generated from other basic resources such as coal, hydroelectric power, or nuclear reactors. Nurtured on inexpensive fuels such as wood and coal, railroads currently derive more than 97 percent of their energy from petroleum products. In the 1940s and 1950s, the switchover from steam to diesel-electric locomotives brought considerable improvement in energy productivity because of the low cost of oil then and the increase in propulsive efficiency. Now soaring diesel fuel costs indicate that it may be time for another switchover, this time to the electrification of the high-density portions of the U.S. railroad network. In addition to fuel conservation, electrification offers other advantages to the railroad, namely, an increased return on investment [generally well above 15 percent (1,2)] and improved productivity, mainly through reduced consist weight and lower maintenance costs.

This paper combines cost and planning data from several existing electrification and synthetic-fuel studies in order to compare investment in railroad electrification as a fuel-conserving option with an alternative investment in liquid-coal plants to produce an equivalent amount of fuel oil. Resulting cost analyses reveal that railroad electrification is both competitive as an energy-saving investment and efficient in the use of coal. This study treats total national costs, borne either by the railroad or by the electric utility, according to a systems perspective. Ultimately, of course, decisions about investments in electrification must be made on the basis of individual route segments, although differences among individual segments should not be significant enough to invalidate the general results.

INVESTMENT SCENARIOS

The Railroad Revitalization and Regulatory Reform Act of 1976 (4R Act) required that the Federal Railroad Administration (FRA) perform a study of the potential costs and benefits to be derived from electrification of the high-density lines. Forty