ments. Figure 1 shows the distribution by age category of 17 911 locomotives built by General Motors Corporation and in service as of January 1976. Twenty-two percent of this fleet has been in service for 20 to 24 years and 10.4 percent for more than 25 years. The average age is 13.7 years.

With the current rate of technological development in the electric locomotive field, it seems likely that new electric motive power introduced into the field will exhibit a life expectancy similar to that of current diesel-electric locomotives.

In summary, the maintenance costs of electric and diesel-electric locomotives will vary widely with the type of service. The maintenance costs of electric locomotives in heavy-duty freight service are expected to be in the neighborhood of 60 percent of the maintenance costs of equivalent-weight diesel-electric locomotives with the same number of axles. The maintenance-cost ratio can be reduced to 30 percent or less in lighter freight operations.

The life expectancy of diesel-electric and electric locomotives is expected to be similar—about 25 years. Both types of motive power are subject to technological obsolescence.

The price of electric locomotives is considerably higher than that of diesel-electric locomotives of similar weight and tractive-effort ratings. It is expected that electric locomotives for passenger service or for special high-speed freight service in which tractive effort is not a limiting factor will have prices closer to those of diesel electrics of comparable power.

Maintenance of Diesel and Electric Motive Power

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Numerous investigations of the capital and maintenance costs of railway electrification have been carried out since electrification became a practical traction system almost a century ago. Any further studies are unlikely to reveal new factors, but there is a wealth of information available on which to base judgments.

Consideration of the statistics derived from international experience in the field of maintenance can only be meaningful if the costs can be compared with those from an alternative form of motive power that performs similar duties. Since my experience has been principally in Britain, I propose to compare the costs, results, and problems of electric locomotives operating in the United Kingdom with diesel-electric locomotives operating under similar conditions.

Competition from air and road has intensified the demand for the shortest possible journey times by rail that are compatible with the increased cost of maintaining the track at a level suitable for the higher speeds involved, the cost and social acceptability of the increased energy consumption, and the more expensive motive power and passenger cars.

Premier passenger services in many of the developed countries of the world operate at maximum speeds of at least 160 km/h (100 mph) and in many cases at 200 km/h (125 mph). With these high speeds, impact forces must be kept low if rail failures and heavy track maintenance are to be avoided. This is usually achieved by restricting the unsprung mass of the vehicle trucks, and the resulting total maximum axle loading for high-speed operation is normally 16 to 17 Mg. Such traction units are not ideal for freight-hauling purposes so far as adhesive weight and gearing are concerned. Head-end power facilities for train heating, braking characteristics, and aerodynamic shape are just some of the features that make high-speed power units unsuitable for freight locomotive applications. Relatively few cases can be found in which mixed-traffic locomotives can now be efficiently employed; it is therefore proposed to separate passenger and freight statistics in comparing diesel-electric and electric alternatives.

COMPARISON OF ELECTRIFICATION AND DIESEL-ELECTRIC TRACTION

The examination of many cases in which electrification was one of the alternative forms of traction being considered has led to the clear conclusion that, if financial return is the main criterion for decision making, only exceptionally intense operating conditions justify the high capital costs of electrification. There are a number of benefits to be obtained from the use of electric traction, some of which can be quantified in financial terms; they include

1. Smaller fleet of locomotives to achieve comparable service,
2. Lower capital cost of each locomotive,
3. High reliability,
4. Greater availability,
5. Lower maintenance costs,
6. Lower operating costs,
7. Lower levels of atmospheric pollution in built-up areas, and
8. Ability to use energy from sources that do not deplete the valuable and finite natural oil reserves.

Among the key factors that must be recognized on the opposite side of the account are (a) higher overall capital cost of electrification and (b) reduction in operating flexibility.

Although all the above factors are relevant and there are many others, it is interesting to note the areas in which change is taking place.

1. Ten years ago there was a significant difference between the capital cost of electric and diesel-electric locomotives; in approximate terms a diesel-electric locomotive designed to carry out duties similar to those of an electric locomotive was then 50 percent more costly. Developments to improve performance and reliability and at the same time to reduce maintenance and track damage have increased the cost of those elements that are common to all types of power units. The resulting sophistication has narrowed the difference in initial

cost, and the equivalent diesel-electric locomotive would today cost approximately 15 percent more than an electric locomotive, if the same quantity were being manufactured.

2. The world-wide increase in electrification at the currently accepted standard of 25 kV 50 to 60 Hz and an approach toward common specification requirements through such internationally recognized organizations as the Association of American Railroads and the International Railroad Union should result in a greater volume of common equipment design and should therefore reduce the cost of unit manufacture.

3. Although experience has shown that the electric locomotive has a higher reliability rating than any locomotive that contains its own prime mover, the potential for improvement is evident. Reduction in dependence in electromechanical equipment and the consequential increase in the use of solid-state electronics will increase reliability in service if care is taken in design and manufacture. The tendency to even greater sophistication has to be resisted and every additional requirement thoroughly examined to ensure that the benefits more than outweigh the cost and vulnerability to failure. Manufacturing standards of solid-state equipment have improved significantly during the last 10 years, and this has resulted in higher reliability at lower cost. Potential failures can be avoided not only by employing higher quality components but also by duplication of circuitry where vulnerability justifies the additional cost.

4. Fewer failures in service and longer periods between inspections, together with the lower volume of maintenance and repairs, lead to a lower downtime for maintenance and ensure that electric locomotives and multiple-unit trains not only have lower maintenance costs but also have a higher overall availability for operation in service than their diesel-electric counterparts.

5. In most of the countries in which electric traction has been widely used and statistics on costs produced, it has been clearly demonstrated that maintenance costs of straight electric-power units are significantly lower than those for the diesel-electric equivalent. The savings on capital cost of the maintenance depots and the savings on labor and materials are usually the largest contribution to any case for electrification. The factors that make these savings possible will be analyzed below.

6. Operating costs for locomotives and traction units are normally divided into a number of clearly definable elements: (a) locomotive crews, (b) fuel, and (c) cleaning.

Locomotive Crews

The form of traction does not itself have any impact on crew costs but the following factors frequently do.

1. The higher average speed normally obtainable from electric traction allows a train to travel farther per shift, if the conditions of service negotiated for the necessary staff permit the savings to be exploited.

2. There are even fewer duties for the assistant driver or engineer to carry out on an electric locomotive than on a diesel locomotive, and therefore a stronger case exists to negotiate for single manning.

3. Electric locomotives do not have to visit fueling points nor do they return to maintenance depots at anything like the same frequency as diesels. In fact, the maximum period between maintenance can extend to 14 days for electric locomotives, while diesel locomotives with similar duties would require a maximum period of 2 to 3 days. The saving in locomotive crews to ferry them back to depots is significant.

Fuel Costs

The relative costs of electric power and diesel fuel vary considerably from country to country and over time. In Britain, the cost of fuel oil has risen sharply during the last 5 years. Although 5 years ago the ratio of costs of electricity to diesel fuel was 1.4:1 to achieve the same operating results in terms of speed and load, it is now 1.1:1. In terms of national economics, the ratio is probably well in favor of electrification in Britain because of the high cost of oil imports. Practically no indigenous oil was being exploited 5 years ago; by the end of 1977 it is anticipated that 50 percent of the nation's needs will be met by oil from the rapidly expanding North Sea fields, and in 5 years' time all U.K. requirements should be satisfied by indigenous oil supplies. This bonanza does not, however, alter the long-term economic importance of energy conservation and oil conservation in particular. Despite all the newly identified oil resources, the demand for energy is still increasing and the North Sea oil fields will be effectively worked out in 30 to 40 years' time.

It is interesting to note that, on average, each citizen of the United States uses twice as much energy in a year as does an inhabitant of the United Kingdom. In the United States transport uses 25 percent of all the energy consumed, while in the United Kingdom the comparative figure is only 12 percent. Transport energy used per person per year in the United States is 100 GJ (95 million Btu), while in the United Kingdom and in much of Western Europe the figure is only approximately 20 GJ (19 million Btu). These figures indicate the greater use of public transport in Europe and the consequently fewer automobiles, each of which is also smaller and has much lower overall fuel consumption than in the United States.

The cost of fuel for diesel-electric locomotives includes transport, handling, and train fueling facilities, as well as tax. Although it is alarming that in the last 5 years fuel costs have risen almost fivefold, it is still a fact that they represent only approximately 22 percent of the total controllable working expenses; the remainder consists of labor and material costs.

Cleaning

Electric traction equipment contains few elements that cause pollution, whereas the diesel engine through its fuel system, lubrication, and products of combustion pollutes not only the atmosphere but also the locomotive and its equipment. Despite mechanization, much of the cleaning has to be carried out by hand and the labor cost is high. The number of person-hours involved in this task for diesels is almost exactly double that for electric locomotives but, because the total labor costs are so much lower for electric traction, the proportion spent on cleaning for electrics is relatively high—approximately 30 percent, i.e., 150 person-hours out of a total of 500, compared with 24 percent for diesel locomotives, i.e., 300 person-hours out of a total of 1240.

MAINTENANCE COSTS

British Railways uses a maintenance depot control system that monitors the cost of labor and materials in the course of carrying out standard inspections and the repair work arising therefrom. These statistics are available for some 2350 main-line diesel-electric locomotives and 230 main-line electric locomotives that operate on 25 kV 50 Hz alternating current.

An attempt has been made to select electric and diesel

Table 1. Comparison of data on electric and diesel-electric locomotives in high-speed passenger serive.

Type of Locomotive	Class	Power Rating (MW)	Maximum Speed (km/h)	Average Speed (km/h)	Annual Distance Traveled (km)	Trailing Load (Gg)	Total Annual Maintenance Costs ($)	Maintenance Costs ($/km)
Electric	87	3.78	160	128	274 000	437	36 000	0.13
Diesel electric	55	2.46	160	120	226 000	406	135 500	0.59
	47	2.32	153	112	113 000	356	69 100	0.61

Note: 1 km = 0.6 mile, 1 Mg = 1.1 tons.

Table 2. Comparison of data on electric and diesel-electric locomotives in freight service.

Type of Locomotive	Class	Maximum Speed (km/h)	Average Speed (km/h)	Annual Distance Traveled (km)	Trailing Load (Gg)	Total Annual Maintenance Costs ($)	Maintenance Costs ($/km)
Electric	86/0	130	90 to 105	176 000	863	35 620	0.20
Diesel electric	37	130	65	81 000	813	35 570	0.44
	47	130	65 to 72	113 000	1219	69 090	0.61

Note: 1 km = 0.6 mile, 1 Mg = 1.1 tons.

Table 3. Comparison of hours of maintenance time spent annaully on eletric and diesel-electric locomotives.

Equipment Element	Class 87 Electric Locomotive		Class 47 Diesel-Electric Locomotive	
	Number	Percent	Number	Percent
Body	25	5	75	6
Bogies and traction motors	110	22	310	25
Engine	0	0	285	23
Main generator	0	0	25	2
Pantograph, circuit breaker, and transformer	55	11	0	0
Rectifier	20	4	0	0
Auxiliary motor/ generators	25	5	60	5
Control equipment	35	7	10	1
Batteries	10	2	50	4
Brakes	70	14	125	10
Cleaning	150	30	300	24
Total	500		1240	

locomotives that are predominantly assigned similar traffic duties but, because of geographical differences, even in a small country such as Britain it is very difficult to find exact comparisons. Table 1 presents typical statistics for high-speed passenger trains. The ratio of maintenance costs per kilometer shows an advantage to electric locomotives of approximately 4.5:1 over diesel-electric locomotives operating on similar high-speed services in the United Kingdom.

Similar statistics for typical freight locomotives are presented in Table 2. The ratio of maintenance costs per kilometer shows an advantage to electric locomotives of between 2.2:1 and 3:1 depending on the type of diesel-electric locomotives being compared.

Let us now examine some of the elements that make up these total maintenance costs. There are three main categories: standard inspections, repair work arising from these inspections, and main workshop costs.

Standard examinations are carried out on electric locomotives at intervals of 14, 42, 84, and 168 days and annually. These examinations are carried out on the basis of time rather than distance traveled since the traffic control system enables utilization to be well regulated. For diesel-electric locomotives, the timing for standard inspections is determined by the number of hours operating in traffic, i.e., engine hours. For example, for a class 47 locomotive, the inspections (besides minor ones at refueling) are carried out at 55, 275, 825, 2500, and 5000 h. An analysis of the work carried out on an annual average basis during inspections is shown in Table 3.

Taking into account the annual distances traveled, the ratio of maintenance time per kilometer between the electric and the diesel-electric locomotives shown in Table 3 is 1:6. The repair work arising and main workshop costs indicate the same general ratios. The maintenance work load for the various elements of equipment is similar for high-speed passenger services and heavy-duty freight service, even though the cost per kilometer shown in Tables 1 and 2 indicates a much more significant advantage to electric locomotives in high-speed passenger service. The apparent increased benefit mainly stems from the greater annual distances operated by electric locomotives in passenger service.

Apart from the very significant difference between electric and diesel-electric locomotives in the total number of hours spent on maintenance, there are differences in the maintenance of detailed equipment. In the case of an electric locomotive, maintenance of pantographs, circuit breakers, transformers, and rectifier equipment amounts to approximately 15 percent of the total labor cost and 75 h of labor/year. This has to be compared with maintenance on engine and main generator equipment on a diesel-electric locomotive, which makes up approximately 25 percent of the total labor cost and 310 h/year. Ratios that compare electric with diesel-electric locomotives on the basis of hours per year per kilometer can be derived. The ratio for high-speed passenger services is 1:10 and that for freight duties is 1:6.5.

Most of the locomotives that operate on British Railways have been in service for many years and do not therefore incorporate the latest available improvements in the design of equipment. The direct-current generator has been the accepted method of converting power from the diesel engine into electrical energy for traction. Increasing engine outputs, higher rotational speeds, and the cost of maintenance of direct-current machines has led to the adoption of the salient-pole alternator as a successor to the direct-current generator on main-line locomotives. The only real inconvenience caused by using an alternator is that separate diesel-engine starter motors have to be provided, since the direct-current generator previously acted as a very large and reliable starter motor. The elimination of the commutator and brush gear reduces maintenance on the main energy converter to an insignificant amount. The other principal advantage of the alternator is that its output, using present designs and the frequencies that have been adopted, is approximately double that of a direct-current generator of the same weight and size.

There are a number of improvements in equipment design that are available today and are likely both to give higher reliability and to reduce maintenance costs, for example, the thyristor and chopper controls that have been developed in the last 10 years. Compared with the previous design, which used silicone-diode rectifiers and tap changers, the thyristor electric locomotive not only has approximately 15 percent greater hauling capacity but also has lower maintenance costs. The main circuit breaker on an alternating-current electric locomotive has traditionally been of the air-blast type, but vacuum circuit breakers have recently begun to be used more frequently in the United Kingdom. These require a minimum of maintenance, since the circuit breaker itself is totally enclosed in a sealed envelope and the only equipment that requires any maintenance is the actuator.

On control equipment the increasing use of solid-state electronics has already improved reliability and reduced the level of maintenance, although there has not been any appreciable reduction in either capital cost or overall maintenance costs since replacement spares are so costly. As reliability increases and the need to replace failed equipment is reduced, the effect should be to show an increasing advantage of the use of electronics to replace electromechanical equipment.

FUTURE DEVELOPMENTS

One of the most attractive developments currently being tested is the application of asynchronous motor drives for locomotives. This system is applicable to any direct- or alternating-current traction-power supply and in addition can be used in a self-powered locomotive equipped with a diesel engine or gas turbine driving a synchronous alternator.

More than 12 years ago, Brush Electrical Engineering Company, with the support of British Railways, designed and manufactured a prototype locomotive named Hawk that incorporated a diesel engine, alternator, inverter, and three-phase induction motors. Unfortunately, the concept was ahead of the supporting technology that was needed to design and sustain the inverter to produce the three-phase, variable-voltage and variable-frequency power supply. Rapid developments in power semiconductor technology during the last decade have enabled inverters that consist of an arrangement of diodes, thyristors, capacitors, and choke coils to become a reliable and economic practical proposition for such a traction-drive system.

The most important benefit to be derived from this new development is the use of robust, economic, and practically maintenance-free asynchronous motors for locomotive traction. These machines are much smaller and lighter than the equivalent direct-current motor required for the same task and thus contribute to reducing track maintenance. The variable-frequency and variable-voltage power supply has a further attractive feature in that the system possesses inherent regenerative capability and can thus make possible very effective electrical braking. Although such a traction system will not be completely maintenance free, it does make a significant impact on the overall maintenance costs and is likely to have a wide application within the next 5 to 10 years.

The world is finally becoming much more conscious of the serious energy problem that will manifest itself before the year 2000. We simply have to start to move away from the present predominantly oil-powered transport economy to one that uses other basic forms of energy. Electric power systems can use any of the fossil fuels but can also use all the other energy sources that are either available now or could be made available in the future, e.g., nuclear, wave, tidal, hydroelectric, wind, or solar power.

Railways should be able to come back into a strong competitive position for freight traffic and for medium-distance—650 km (400 miles)—high-speed passenger traffic. Electrification will help this process where the traffic density justifies such a solution. There will be many cases in which even the reduced maintenance costs would not provide sufficient reason for departing from the well-proven diesel-electric locomotive.

Capital and Maintenance Costs for Fixed Railroad Electrification Facilities

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A successful railroad electrification project must perform satisfactorily from operational, technical, and economic points of view. This paper is directed principally toward the fixed-facility costs.

To electrify an existing diesel railroad system, a power delivery system—including catenary, substations, interconnections to electric utility power sources, and an adequate source of electrical energy—must be provided. In addition, since most existing dieselized railroads have signaling systems that are not compatible with the electrical interference produced by the traction and power-delivery systems, extensive modifications are required.

After ensuring that the proposed electrified system will meet operational and technical performance requirements, an economic analysis is required to ensure that an adequate return on investment will be produced. To provide accurate inputs for an economic analysis of this type, it is necessary to develop costs for the basic investments and for maintenance.

Arthur D. Little, Inc., has recently conducted feasibility studies for railroad electrification of segments of the Union Pacific Railroad, Burlington Northern, and Consolidated Rail Corporation (1). The cost data developed for these studies were further refined and updated (2), and it is from this work that the following information has been developed. Reports on previous work (3) have also been very helpful.

POWER-DELIVERY SYSTEM

The various elements of the power-delivery system are treated separately in this paper, but they must, of course, be combined technically and economically to