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 provide an integrated system.

## Catenary

Power delivery through a third-rail system is essentially limited to approximately 1000 V because of insulation and clearance limitations. This system is quite suitable for commuter lines, but heavy railroad operations require considerably more power than can be delivered at this voltage level. For this reason, overhead power-delivery systems are used for heavy freight and high-speed passenger operations. The system consists of a contact wire, usually of copper alloy, that is suspended by vertical droppers from a steel-reinforced aluminum messenger. Figure 1 illustrates several typical catenary configurations.

The simple catenary has been developed to a high degree and is the most popular configuration in use today. Where speeds in excess of 175 km/h (108 mph) are desired, a more uniform suspension system is necessary, and stitch wires or compound catenaries are used. In most cases, tension is maintained by counterweights, an approach that gives superior high-speed performance in the presence of varying temperature conditions. For yard wiring, low-speed branch lines, and sidings, the French have developed a simplified catenary that uses a single contact wire and stitch wire at each support point (see Figure 1). Savings in the range of 30 percent of the total cost are claimed for this system compared with the simple catenary.

The earlier European systems were designed to use 16.67 Hz as the operating frequency. Commutator traction motors will not commutate satisfactorily at commercial frequencies, and this compromise was necessary. With the advent of solid-state rectifiers and thyristors, it became possible to supply the locomotives with commercial-frequency power and deliver suitably smoothed direct current to the traction motors. For this reason there is a strong trend toward the application of 50 to 60 Hz directly to the catenary. While some British catenary is operating at 6.25 kV because of clearance limitations, 25 kV is becoming the most popular voltage level. The Black Mesa and Lake Powell Railroad in the United States is successfully operating at 50 kV. Frequency and voltage selection are key elements in the design of any electrification system, and they are dictated by clearance limitations, required catenary power, and interfaces with existing systems.

Engineering charges for catenary construction range from 5 to 14 percent of the installed catenary cost. The costs of 25-kV catenary construction shown below include engineering, materials, labor, and other costs incurred by the contractor but not the direct and indirect costs to the railroad. The heavy freight operations are expected to use speeds up to 130 km/h (80 mph) and the high-speed passenger service up to 240 km/h (150 mph); note that 1 km = 0.6 mile.

| Item | Cost ($/track km) Single Track | Double Track |
|---|---|---|
| Catenary | | |
| Heavy freight operations | 40 000 to 76 000 | 32 000 to 74 000 |
| High-speed passenger service | 79 000 | 76 000 |
| Flagman | 600 | 1 100 |

If 25 percent of the construction must be done on track, railroad crew and work-train costs add an average of $8700 to $12 500/track km ($14 000 to $20 250/track mile) for single track and $8000 to $12 000/track km ($13 000 to $19 250/track mile) for double track to total catenary installation (the lower figure is for freight operations and the higher figure is for passenger service). A sharply curved route through rocky terrain increases the costs by 30 to 35 percent. Installation of 50-kV catenary would increase costs by as much as 7 percent.

## Traction Substations

Traction substations are usually of somewhat simpler design than those used by electric utilities to supply distribution feeders. Usually, they are single phase. Because alternate sources of catenary energy are available through the normally open phase breaks, it is possible to conduct maintenance on these substations by removing them from service during periods of low traffic. To date, traction substations recently constructed in the United States have been built up from basic components on site. Oil circuit breakers (OCBs) are used on the secondary sides. On the primary side, some utilities supply the primary circuit breaker and others require that they be supplied by the railroad. In each case these are OCBs. Recent British substation designs use vacuum circuit breakers on the secondary side and are prepackaged for convenient field assembly. The primary is usually supplied by underground cables and the high-voltage circuit breaker is located at some distance from the substation.

It is necessary to have good central monitoring and control of the individual substations to implement optimum electric and motive-power load dispatching and to identify and correct electrical fault conditions. The cost of this capability has been included as an increment of substation cost.

Single-track, single-transformer, 20-MV·A and double-track, double-transformer, 40-MV·A continuous-load substations were selected to serve as the basic designs. The costs of these substations, including engineering costs of 10 percent, are shown below.

| Category | Voltage (kV) | Cost ($) |
|---|---|---|
| Single track | 25 | 560 000 |
| | 50 | 601 300 |
| Double track | 25 | 972 000 |
| | 50 | 1 061 200 |

The above costs assume that the utility furnishes the high-side breaker. Typical one-line diagrams of these substations are shown in Figures 2 and 3.

It is necessary to install insulated phase breaks at the approximate midpoint between substations, since adjacent catenary segments are operated from different phases to provide system phase balance. Switching stations are located between substations at the phase breaks. The costs of these stations are as follows:

| Category | Type of Station | Cost ($) |
|---|---|---|
| Single track | OCB | 118 400 |
| | Air-brake switch | 72 200 |
| Double track | OCB | 188 500 |
| | Air-brake switch | 94 000 |

Typical one-line diagrams of switching stations are illustrated in Figure 4.

It has been convenient to express the cost of substations as an average cost per track kilometer. Given that a reasonable spacing for substations is 32 km (20 miles) for 25-kV and 64 km (40 miles) for 50-kV catenary, the basic substation design, including associated OCB switching stations, would involve the following costs on the basis of a continuous-load power-supply capability of 0.6 MV·A/track km (1 MV·A/track mile).

| Voltage (kV) | Unbalance Limit (MV·A) | Cost ($/track km) | |
|---|---|---|---|
| | | Single Track | Double Track |
| 25 | 20 | 21 000 | 18 000 |
| 50 | 20 | 16 600 | 16 200 |
| | 40 | 13 500 | 13 000 |

**Figure 1. Typical modern catenary configurations.**

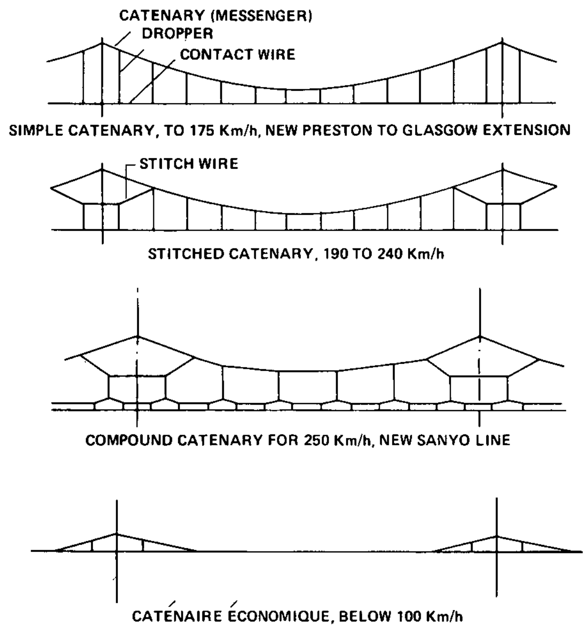
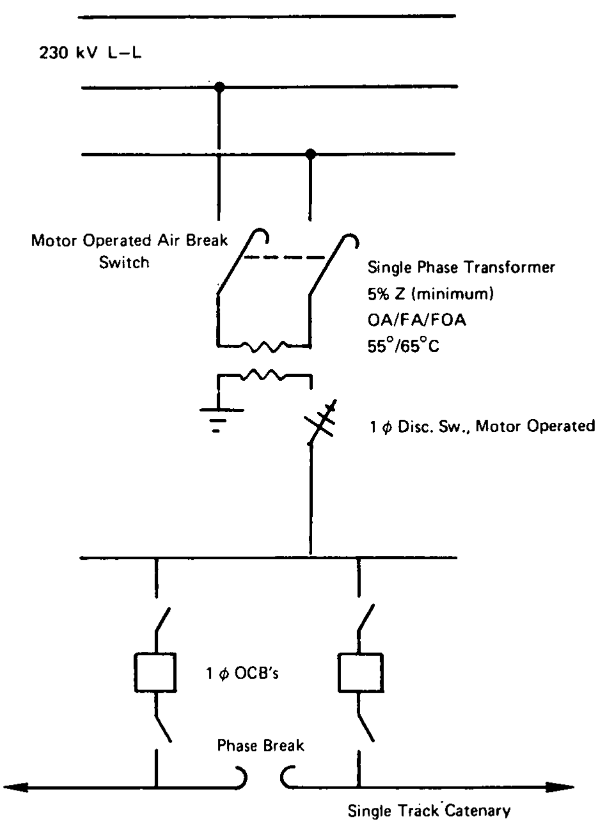



**Figure 2. Basic single-transformer single-track substation.**




## Utility Reinforcement

Until the past few years, electric utilities have been more than willing to absorb the costs of short transmission-line extensions, connections, and reinforcement of their transmission system to serve a consumer's load. Because of the difficult financial situation that electric utilities face at the present time, it is becoming common practice for the electric utilities to charge the customer for these various capital investments. These costs can be significant, and they must be included in any estimate of fixed-facility costs. Transmission-line extension costs vary widely, $30 000 to $150 000/km ($50 000 to

**Figure 3. Basic two-transformer double-track substation.**

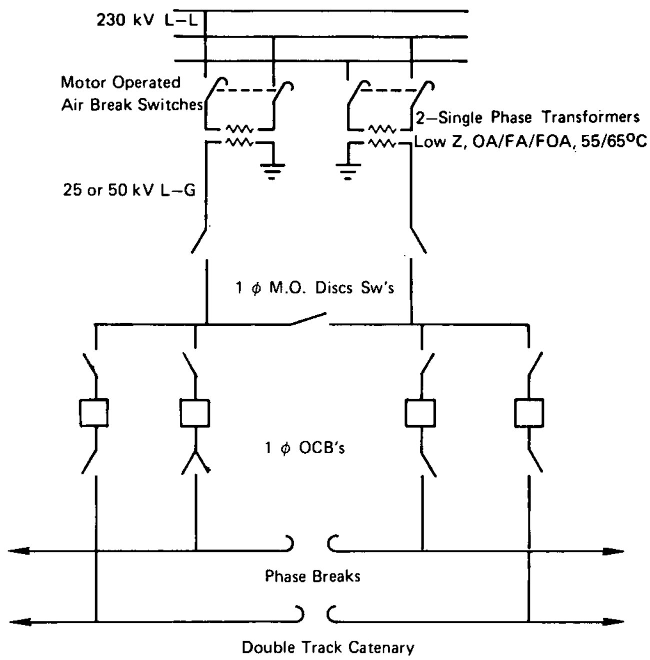
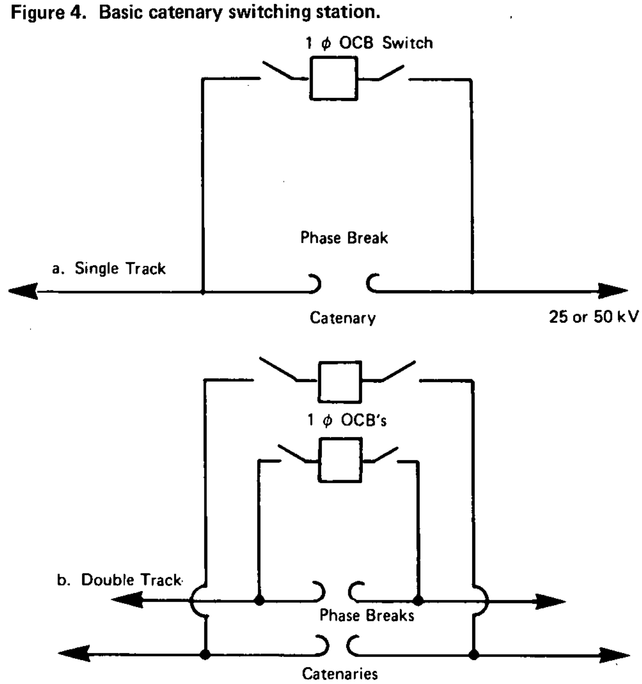



**Figure 4. Basic catenary switching station.**



$250 000/mile), exclusive of right-of-way. The charges for a line extension of this type can be handled as an initial one-time payment or a continuing service charge of 14 to 18 percent/year, or the charges can be amortized over a shorter period.

To place this in perspective, a recent study (5) indicated that, for the 66 000 km (41 000 miles) that Mitre has identified as justifying electrification, 6920 km (3670 miles) of transmission-line extensions would be required at an average cost of $3800/route km ($6100/route mile). This average can, of course, vary widely and must be analyzed on the basis of the individual line segments. If one were to allow a 1.6-km (1-mile) connection from each present transmission line to each new substation contemplated, the combined average cost could reach $4800/route km ($7700/route mile). When considered in their entirety, the new transmission line and connection costs represent about 4 to 6 percent of the cost of fixed facilities for rail electrification.

## EFFECTS ON PUBLIC WORKS

The catenary often must be suspended from or run below structures that currently provide limited clearance over the railroad right-of-way. In August 1975 a committee of the American Railway Engineering Association reported to the Association of American Railroads that a maximum increase for existing clearances of approximately 120 cm (4 ft) should be sufficient to accommodate electrification under the worst circumstances. Most situations should not require clearances approaching this maximum. Recent construction involving railroad clearances provides a basic clearance requirement of 6.7 m (22 ft) vertically over the rails. However, earlier construction standards permitted clearances of as little as 4.88 m (16 ft). It is important to note that, although the additional clearance required for the catenary structure is correctly chargeable to an electrification project, any clearance that is added to this requirement to provide a modern loading-gauge minimum should be charged directly to the railroad as a capital improvement.

The costs of the actual reconstruction can vary due to local conditions, design and condition of the structure, and track accessibility during reconstruction. We have attempted, however, to develop average costs suitable for initial estimating purposes, to be augmented by field investigation. The costs given below cover the best estimate of public works costs that can be expected (1 cm = 0.4 in, 1 m = 3.3 ft). They represent typical costs for typical modifications. Prices are based on costs of labor and materials in Boston; allowances should be made for cost differences in other parts of the country.

| Item | Cost |
|---|---|
| Rail traffic under bridges | |
| Lower tracks, $/cm | |
| Single track | 1300 to 2200 |
| Double track | 2600 to 7900 |
| Raise highway bridge and approach roads, $/m | |
| Four-lane highway on embankment | 207 000 to 265 000 |
| Four-lane city street | 59 000 to 75 000 |
| Two-lane rural road, no embankment | 43 000 to 59 000 |
| Raise bridge by jacking up superstructure and modifying bridge, $/cm | |
| Four-lane multiple-girder bridge | 400 to 1200 |
| Two-lane two-truss or two-girder bridge | 260 to 730 |
| Rail traffic through tunnels | |
| Lower track (up to 8 cm), $/m | 575 |
| Lower tunnel invert, $/cm/m | 50 to 160 |
| Scarf tunnel roof (up to 10 cm), $/m | 400 |
| Raise tunnel roof, $/cm/m | 40 to 180 |
| Rail traffic over bridges, $/span m | |
| Replace girder bridge (15 to 45-m span) | |
| Single track | 2300 to 4900 |
| Double track | 4000 to 8500 |
| Replace truss bridge (45 to 60-m span) | |
| Single track | 3600 to 4900 |
| Double track | 6900 to 9900 |

## SIGNALING AND COMMUNICATION SYSTEM MODIFICATIONS

In electrifying a railroad, we must usually interface with existing signal and communication systems. The existing equipment of most railroad systems requires modifications to make it compatible with the electrified operation.

At the present time most railroads use direct-current track circuits for wayside signaling, and 60-Hz carrier systems are used for in-cab signaling. Data are transmitted between signal locations by overhead open-wire lines running along the right-of-way. Communication is handled either by microwave data link or by open-wire overhead lines. Communication between and from trains to wayside stations is accomplished by VHF radio. The electromagnetic and electrostatic fields developed by a catenary system can, and usually do, induce in the signaling and communication systems closely associated with railroad operations currents and voltages that are adverse to operations. One must consider the sources and effects and take appropriate action to keep these effects within tolerable limits. These adverse effects arise from:

1. Magnetic induction—current produced in the data communication lines by the effects of the varying catenary current as a result of the inductive couplings.
2. Electrostatic induction—voltage produced in the data transmission lines as a result of the capacitive coupling.
3. Ground current conduction—voltage produced in the communication lines as a result of common grounding of the communication and traction-power circuits.
4. Radio frequency interference—produced by pantograph arcing and higher frequency components of the thyristor-controlled locomotive-power circuits.

The major modifications required to make existing railroad systems compatible for electrification include 100-Hz alternating-current or other noncoherent-frequency track circuits, preferably coded; shielding and burying signal communication cables; additional grounding of all signaling and communication equipment; installation of impedance bonds at insulated joints; heavy bonding of rail joints; and modifications to highway track circuits.

The costs of modifying existing systems to include these features will establish the basic costs that should be charged to electrification. This requires a buildup of components and modules within a given system that vary in cost due to differences in track circuits, means of communication between signal locations, differences in signal hardware and aspects employed, specific railroad standards, and many other variables. The following ranges of cost estimates are indicative of the costs that may be encountered.

| Item | Cost |
|---|---|
| Undergrounding of data and communication circuits, $/km | |
| Communication cable | 680 to 2000 |
| Signal cable | 2400 to 8000 |
| Cable installation by plowing | 1800 to 2700 |
| Total | 4800 to 12 400 |
| Track circuits, including installation | |
| Individual 100-Hz circuit, $ | 4300 to 8400 |

| Item | Cost |
|---|---|
| Cut section (required for long blocks), $ | 9600 to 11 200 |
| Major interlocking, $ | 24 000 to 110 000 |
| Communication cable repeaters, $/km | 300 to 400 |

As has been mentioned previously, the costs of signaling-system modifications vary widely according to the complexity of the existing signal system, terrain conditions, and adaptability to electrification requirements:

| Item | Cost ($/track km) |
|---|---|
| Most adaptable single-track system | 15 000 |
| Most complex double-track system (Northeast Corridor) | 27 000 |
| New Haven to Boston | 61 000 |
| Expected average range | |
| Single-track | 16 000 to 22 000 |
| Double-track | 28 000 to 37 000 |

To these costs must be added those of modifying the communication system. Assuming that cable will be installed concurrently with the signal cable, the cost will range from $1600 to $3100/route km ($2500 to $5000/ route mile), including repeaters, grounding, and so on. A new microwave system will cost in the range of $3600 to $4300/route km ($5800 to $7000/route mile), including removal of existing overhead lines.

## ENGINEERING

The expected engineering costs for design of the fixed facilities have been included in each of the basic cost elements. Those costs range from 5 to 14 percent of the installed cost for the catenary design; 10 to 20 percent, with the lower range expected, for the substation design; and 5 to 20 percent for public works. Widely varying amounts must be allowed for signaling and communications; system engineering costs are usually absorbed or included by manufacturers, while supplemental engineering costs must be added.

## MAINTENANCE

The two major fixed-facilities maintenance factors introduced by electrification are catenary and substation maintenance and changes to signal and communication system maintenance. Quantifying the difference in cost of maintaining a signal and communication system that is compatible with electrified rather than diesel power has been difficult. Generalized experience with similar underground telephone circuits indicates that costs will be lower. This is primarily because underground cables are markedly less vulnerable to physical and climatic damage, even though repairs themselves may be more difficult. Since the alternating-current track circuits present no significant maintenance problem, the total maintenance cost can be no higher. To be on the safe side, it is not usually included in economic evaluation.

Experience with catenary and substation maintenance in the United States is quite limited, in fact available only from the records of the former Penn Central Transportation Company. Since their substations are quite old, these figures are not typical. For catenary only, costs are in the range of $600/km/year ($1000/mile/year), and this is probably low because of deferred maintenance credits.

To provide an up-to-date approach to catenary maintenance using modern highway-railway tower cars instead of work trains, a prototype catenary and substation maintenance program for a theoretical 3200-km (2000-mile) system would have equipment costs of $360 000 for 9 percent highway-railway tower cars and $75 000 for a catenary-checking car. This total of $435 000, spread over a 5-year life with 10 percent interest added, amounts to $130 500/year. Materials and miscellaneous tools would cost an additional $250 000/ year. The labor costs (four 4-person crews, five two-person crews, 10 reserve crew members, and 30 support personnel) amount to $2 380 000/year, giving a total annual cost, including substations, of $2 760 500 or (for 3200 km) $870/km/year ($1400/mile/year). A maintenance organization of this type would be quite flexible, and relatively wide variations in size would not significantly affect the annual cost per kilometer.

## ECONOMIC METHODOLOGY

A brief discussion of the economic approach must be given for completeness. Essentially, how do we handle the cost figures? The initial elements of concern are the operational and technical analyses. Basically, the system must work well. After ascertaining that this will be true, economic viability must be demonstrated.

An accepted and effective approach is to compute the internal return on investment that will result from savings on operating cost accruing from electrified operation by using the discounted cash-flow method. The principal line items are

1. Investments—power delivery system (including catenary), signal and communication systems modifications, reconstruction of public works, purchases of electric locomotives, and diesel locomotive credits;
2. Costs of electrified operation—electrical energy, catenary maintenance, and electric locomotive maintenance; and
3. Savings on the cost of diesel operation—diesel fuel and lube oil and diesel locomotive maintenance.

There are several other factors that should be included in any full study of economic feasibility. Sensitivity analysis is also a useful tool in developing an understanding of the risk and impact of uncertainties.

It is, of course, useful for preliminary estimates to present the costs for all fixed facilities on the basis of unit length. Approximate general ranges for costs, including catenary, substations, controls, and signal and communication system modifications, are $73 000 to $150 000/route km ($118 000 to $250 000/route mile) for single track, including 10 percent sidings, and $120 000 to $290 000/route km ($194 000 to $467 000/ route mile) for double track, including 5 percent sidings. These figures do not include reconstruction of public works, which has varied from $4000 to $80 000/route km ($6500 to $130 000/route mile), or utility connection costs, which can vary from virtually nothing to millions of dollars to supply a single remote substation.

## ACKNOWLEDGMENTS

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# Interference of Electrification With Signaling and Communication Systems

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Signal and communication systems are an integral part of railroad operations and are essential to provide safe and expeditious train movements. The major functions performed by these systems are

1. To maintain safe separation between trains and to detect unsafe conditions in the track ahead of a train, e.g., a broken rail, misaligned switch, open bridge, rock slide, or high water;
2. To detect unsafe conditions on cars and locomotives, e.g., overheated journal bearings (hotboxes), dragging equipment, broken flanges, loose wheels, or high, wide, or shifted loads; and
3. To increase the traffic capacity of a railroad through centralized traffic control and automated terminal control systems.

Signal and communication systems must function with utmost reliability under a wide range of environmental conditions and must also withstand the interference effects produced by commercial power systems along the right-of-way and, in the case of electrification, the additional interference effects produced by the propulsion power supply and the locomotives. It is reassuring to note that there have been signal and communication systems designed and currently in service both in this country and abroad that are fully capable of reliable operation under any or all of the above conditions. These systems are in general more complex and costly to install and maintain than those currently employed in nonelectrified territory. Deciding whether to electrify a railroad does not therefore depend on the availability or lack of signal or communications technology but depends rather on its economic justification.

Those railroads that carry more than half of the freight traffic in this country, and therefore are logical candidates for electrification, have signal and communication systems that are for the most part complete, quite modern, well maintained and long lived. Without a very substantial increase in rail traffic, these facilities would not require alterations or additions. Unfortunately, the changes required to render these systems compatible with electrification represent a substantial expense that has very little economic justification in terms of increased safety or ease of railroad operations. In reality, it is an expense that a railroad must make solely because of electrification. The signal engineer is therefore in a difficult situation and is sometimes considered a roadblock to electrification. In the past, the signal engineer has only been able to make capital expenditures on the basis of sound economic justification. Electrification will require large sums of money just to recover the use of facilities that are already in service under diesel operations.

Open-wire lines along the right-of-way are generally used in nonelectrified territory for interconnecting various elements of the signal system, for transmitting power for battery-charging purposes, for transmitting commands and indications for centralized traffic control, and for the maintainer's and dispatcher's telephones and other communication purposes. Over the years, the signal-to-noise ratio in these circuits has been gradually degraded by the interference effects produced by high-voltage power lines that have been erected along the right-of-way. In some instances, it has been necessary to place these circuits in shielded cable to effect satisfactory coordination.

In electrifying a railroad, the interference effects are greatly compounded. The proximity of the catenary to the open-wire lines creates intolerable signal-to-noise ratios in these circuits and also increases the danger of shock to personnel. On this basis, these lines must be either eliminated or placed in suitably shielded cable.

Double-rail direct-current track circuits are generally used in nonelectrified territory to detect trains and broken rails. Insulated joints in the rails are required to isolate one track circuit from the next. In electrifying a railroad, the propulsion current flows through the rails on its return path to the substation. A means must therefore be provided for this current to bypass the insulated joints. The commonly accepted means for accomplishing this creates a low-resistance path between the rails at each end of the track circuit, just as the wheels of a train do. Double-rail direct-current track circuits