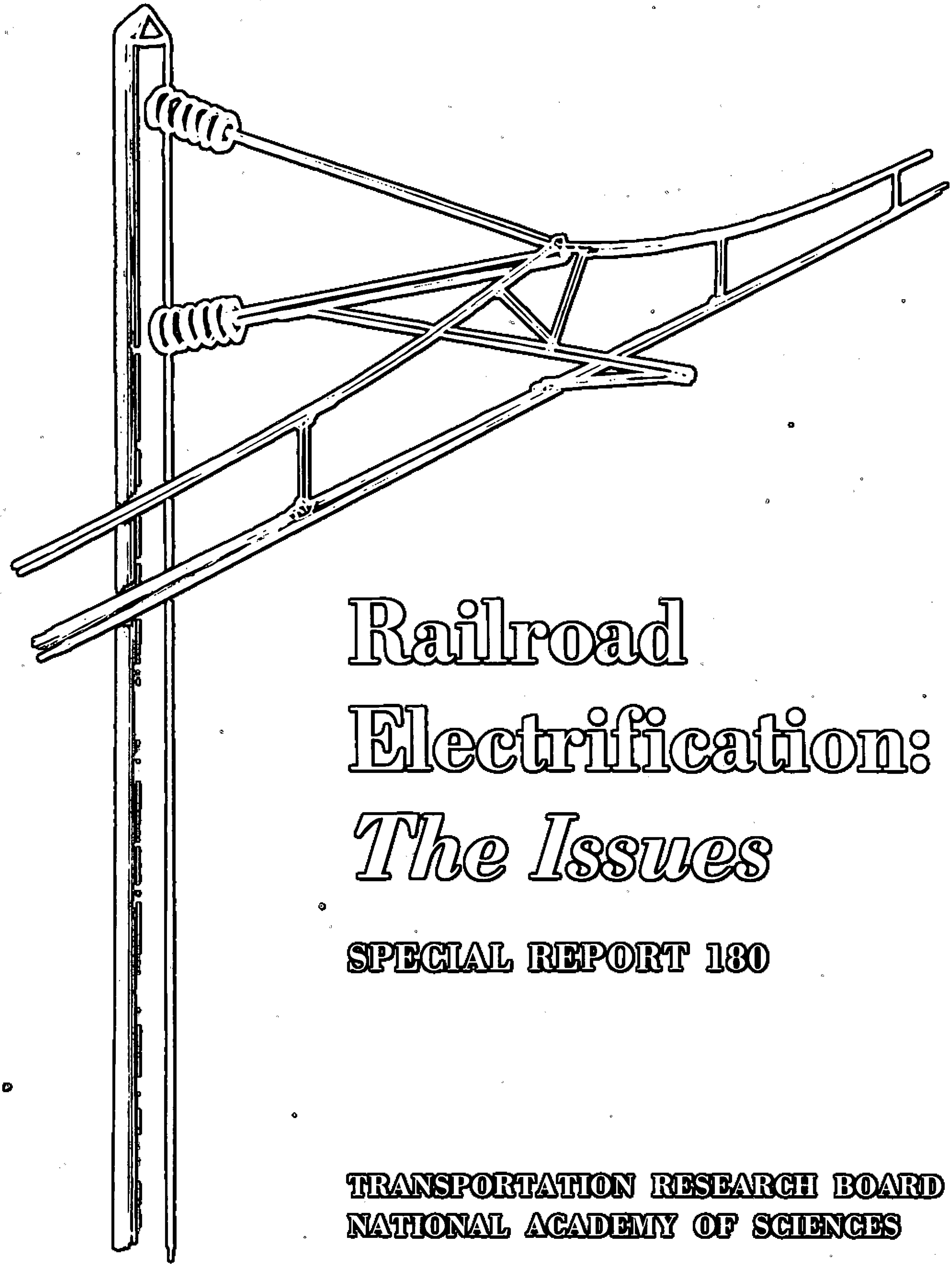

Railroad Electrification: *The Issues*

SPECIAL REPORT 180

TRANSPORTATION RESEARCH BOARD
NATIONAL ACADEMY OF SCIENCES

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Railroad Electrification: *The Issues*

SPECIAL REPORT 180

Transportation Research Board
Commission on Sociotechnical Systems
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1977

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The views expressed in this report are those of the authors and do not necessarily reflect the view of the committee, the Transportation Research Board, the National Academy of Sciences, or the sponsors of the project.

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Introduction

On almost every continent except North America, railroads are turning to electrified operation as a means of improving service, lowering costs, reducing adverse environmental impacts, and reducing dependence on petroleum fuels, which in many cases must be imported. Technological developments—including high-voltage, commercial-frequency electrification and thyristor control systems—have reduced the costs and improved the effectiveness of electric railroads. Although the North American railroads have electrified no major routes since the 1930s and in fact have deelectrified several routes since that time, there is now a renewed interest in electrification in North America. Several major railroads have seriously studied electrified operation of certain key routes, and the Northeast Corridor project plans to extend electrified operation from New Haven to Boston.

In view of the developments around the world and the renewed interest in electrification in North America, the Transportation Research Board Committee on Electrification Systems suggested that a major conference on railroad electrification in North America would be appropriate and timely. The purpose of the conference was to examine the institutional, economic, and technological issues of railroad electrification in North America.

The Federal Railroad Administration provided financial support and the Transportation Research Board appointed a study committee to plan and conduct the conference. The conference was held June 13 to 15, 1977, in Washington, D.C.

Part 1
Conference Papers

Summary

Liviu L. Alston, International Bank for Reconstruction and Development, Washington, D.C., and Chairman of the Committee on Electrification Systems

This conference dealt comprehensively with a wide range of issues. It has shown that a great deal of data is now available to serve as a basis for assessing the feasibility of individual electrification projects in North America, and the discussions have demonstrated that there is significant interest in railroad electrification.

Some questions remain controversial. For example, some speakers expressed much more optimism than others about the possible impact of railroad electrification on national consumption of fuel oil. We have heard different views on the extent of savings in locomotive maintenance costs and the impact of railroad electrification on the utilities' generation and transmission plants. Some of these questions were highlighted in the written discussions (the only portions of the discussions to be published). Many of these questions are best addressed in the context of feasibility studies for specific projects, and several such studies have already been made.

These differences of opinion notwithstanding, the following broad conclusions emerged from the papers and the general discussion that followed them.

1. Electrification involves a one-time investment of unparalleled magnitude, apart from the original construction of the railroad.
2. Because of the size of this investment, its contribution to profitability can be very much greater than that of individual investments and can produce a greater rate of return, but it must compete with an aggregate of such investments, some of which may be mandatory.
3. The financially successful railroads could raise the funds needed for electrification if top management decided to proceed.
4. Because of the large amounts involved, borrowing for an electrification project would tend to make future borrowings more difficult.
5. While there are no technological obstacles to an electrification project in the United States, further research and development in this area should result in some cost decreases. A subject that merits particular attention is interference with signaling and telecommunications. However, the probable impact of research and development does not justify a postponement of electrification.
6. In assessing the benefits of electrification, the main uncertainties concern (a) the energy policy and its impact on the cost of diesel fuel and electric power and (b) the effect on rail traffic of developments in other modes, notably pipelines, inland waterways, and intercity motor freight.
7. The most important next step is to kindle the interest of the top levels of railroad management so that electrification receives the attention needed to bring about a decision. Several railroads have carried out feasibility studies that could form the basis of a decision. Any investment involves a measure of risk, and some incentive is desirable to encourage management to make this large investment. The possibility of some risk sharing or other government involvement should be considered. The impact on future borrowings is particularly worrisome, and ways of minimizing this worry should be studied. For example, a project company might be set up to construct and own the fixed installations for electrification and sell power to the railroad at the pantograph. This company could be owned jointly by the railroad, utilities, and other organizations, including government agencies, or even by a government agency alone.

General Issues

The Advantages of Electrifying the Nation's Railroads

Milton J. Shapp, Governor of Pennsylvania, Harrisburg

Throughout history, it has been axiomatic that the nations that developed and used the most desirable forms of transportation for carrying the goods and materials then in demand flourished, while those nations that did not develop such transportation systems lagged. Camels carried goods during biblical times to the various centers of the Middle East, and villages and cities along the camel trails flourished to a greater extent than did those not on these trails. The Phoenicians were powerful when their ships plied the seas; afterward, Phoenicia fell into oblivion. Spain was a wealthy, powerful nation for as long as it controlled the sea lanes. Then England eclipsed Spain as a naval and industrial power.

Perhaps one of the most vivid modern examples of economic development's absolute reliance on transportation is shown in South Africa. This is the only African nation below the equator in which interior areas have developed economically. This is because, many decades ago, a railroad was built inland from the coast area to haul the gold, other ores, and diamonds from the interior. And so communities developed inland in South Africa, and commerce and agriculture have flourished in its noncoastal communities. Without the railroad, this would not have happened.

America's economy originally developed along the Atlantic coastal area. Ships hauled goods to and from Europe and between communities along the coast. Then canals were constructed, and roads were built inland. Then came the railroads, and America grew from coast to coast and became the world's most powerful industrial nation.

We are now slipping. Although there are many reasons for this, one of the most important and apparently least recognized is that many of the older industrial communities of our nation in the Midwest, Appalachia, and the northeastern states lack efficient transportation to move raw materials, fuels, and manufactured products economically to compete in the marketplace with those in other parts of the nation—and, for that matter, with those in other parts of the world. In the United States, we have developed highways, air transport, and in some areas barges. But the railroads, which should be the backbone of our transportation system, have been allowed to wither in the heavily populated industrial regions.

Let us be under no illusions. Modern industry desperately needs efficient railroads. Trucks can handle certain types of freight economically, particularly for door-to-door service, for short hauls, and in some cases for medium-distance hauls. Airplanes are superior for transporting some goods—particularly small packages and perishables for long distances—but railroads, properly constructed and maintained and using modern efficient rolling stock, switching yards, and signaling equipment, are absolutely essential if this nation is to continue to exist as a world power. This is particularly true in this era of energy shortages.

Unfortunately, the railroad industry in the United States has since its inception been manipulated to a large extent by entrepreneurs and bankers more interested in controlling the railroad for their own short-range financial schemes than in developing the railroads for long-range profitable growth. This pattern was observed in the early days of Vanderbilt, Fiske, and Gould and has existed for many years—right up to the debacles of the New Haven and Penn Central railroads. Fortunately, there are many railroads today that are well managed by transportation experts who supply good customer service and are investing substantial portions of their revenues in programs for modernization and maintenance.

But in our major eastern and midwestern industrial areas, there are only a few such rail companies in operation. And until and unless these vital regions have modern high-speed rail transportation, the United States will continue to flounder economically. We even risk the danger of slipping into a second-rate position as a world power.

It is therefore time to look at rail operations as a vital part of national policy. The United States can no longer afford to let rail operations be determined in a vacuum by piecemeal Interstate Commerce Commission (ICC) or court decisions that are based on yesterday's practices. Nor can these vital decisions that have such serious impact on the economy be made strictly on the basis of granting short-term advantages to a handful of financiers. Most importantly, particularly in view of the energy crisis, it is essential for the future well-being of our nation that our major railroads should be electrified. If we fail to do this, we are courting national disaster in the very near future.

The Pennsylvania Energy Council has estimated that a 34 percent saving in energy could be achieved by using electric power. Electrification of just 10 percent of the present rail trackage (in the densely populated, heavy industrialized areas) could result in a 40 percent reduction of diesel fuel consumption. In addition to the benefits to freight traffic, electrification of rail lines in and around our big cities would greatly relieve present traffic jams by reducing the number of automobiles on the road. A few judiciously selected commuter lines near our major cities could readily replace 250 000 automobile passenger trips/d, saving almost 151 000 000 L (40 000 000 gal) of gasoline a year without government coercion or the imposition of heavy penalities. Thus, the potential for fuel saving is substantial. Safety is another factor. Statistics indicate that a rail passenger will travel 20 times farther than a motorist before a serious accident befalls him or her.

To illustrate the potential for savings, it is important to emphasize that rail passenger service today attracts only 1 percent of the nation's passenger trips. With electrification, this would rise dramatically. Electrification would make possible short, fast, and frequent train service near and in our cities. A one-car, 100-passenger electric train can earn \$3/km (\$5/mile) with 75 percent utilization. If track capacity is inadequate to operate enough one-car trains, it implies that a two-car train on an existing system can be added for \$3.7/km (\$6/mile), with a revenue of \$4.3/km (\$7/mile) at a 50 percent load factor. How often do two freight cars earn a \$0.60/km (\$1.00/mile) profit between them?

However, the main economic consideration is that the hauling of freight offers the greatest financial and energy- and time-saving advantages for rail electrification. Although diesel-powered locomotives have offered the advantage of lower initial capital commitment and lower engineering and initial construction costs, diesel locomotives do not handle as well at full speed. In fact, acceleration with diesels is rather poor. A generation or so ago, steam-powered trains operated at 160 km/h (100 mph). Speeds with diesel engines are now down to 110 km/h (70 mph) or even slower. It is not unusual for a highway truck to pass a so-called streamlined diesel-drawn passenger train where the roadways are parallel. But high speeds are essential if the railroads are to provide maximum benefits to both freight and passenger customers and, at the same time, resolve rail energy requirements. Therefore, the need to electrify our railroads is urgent. There is nothing new about this concept in the United States. Before 1937—more than 40 years ago—the New York, New Haven, and Hartford Railroad Company; New York Central System; Chicago, Milwaukee, and St. Paul Railway; Great Northern Railway; Virginian Railway Company; and Pennsylvania Railroad had electrified thousands of kilometers of track quite successfully.

In 1937, there was a switch to diesel-powered engines that generated their own electricity to drive individual axles. This system had the advantage at the time of lowering the requirements for the initial capital needs for rail engineering and construction, as well as achieving good performance at low and middle speeds. Now, however, with the tremendous increase in fuel costs, diesels have lost most of their former advantages. They are no longer cheap to operate; they consume too much precious fuel; their turnaround time is slow; and they are not as fast as is required to meet today's freight or passenger needs.

The decisions that may have been correct 40 years ago do not apply in today's world of high-speed truck and air competition and of fuel shortages. The pendulum has definitely swung in favor of high-speed electrified railroads for both passenger and freight service. Electrifying railroads offers the best chance to turn present money-losing operations into profitable operations, because electrification offers the greatest hope for our railroads to recapture the business of hauling the products that carry the higher rates. The bulk commodities that now move by rail generate revenue of about 1.7 cents/Mg·km (2.5 cents/ton-mile), and pay a rate of return on net investment of about 1¼ percent. It is obvious that there is no private-enterprise future for rails if the only effort made is to maintain the status quo.

Rail revenues have not kept pace with the economy. Future rail revenue must increase much more rapidly. Yet rates cannot be increased without the loss of more of the bulk traffic to waterways, which would in turn increase the pressure to increase rail rates again. Thus, new revenue cannot be derived by increasing the rates on the bulk loads now carried but only by offering improved services to attract the types of freight that pay 3.5 or 7.0 cents/Mg·km (5 or 10 cents/ton-mile) instead of 1.7 cents/Mg·km. The trucking industry is profiting and growing rapidly on rates that average 7.5 cents/Mg·km (11 cents/ton-mile). It is obvious that the railroads must develop new technologies to profitably sell service that will attract shipments in the higher revenue class. The present 100-car unit train so often cited as the epitome of rail efficiency grosses about \$95/km (\$150/mile) but, carrying bulk freight, it nets only a few dollars. However, if it were carrying high-rated manufactured products, a 50-car train of much lower weight, which would cause less track damage, could gross as much at a lower operating cost.

Also, operating expenses can be reduced through better maintenance. The rail carriers have cut the payroll from 1.2 million employees to about 0.5 million. Unfortunately though, many carriers have all but eliminated track maintenance. This is absolutely the wrong way to cut expenses since it raises the operating cost of the carriers, cuts the speed of service, and reduces the opportunity to compete effectively for the high-rated traffic. The record shows clearly that, as maintenance expenses of railroads are cut, revenues move downward and the chances for profitable operation are diminished. Railroads need to institute economies that increase revenues and profits rather than those that reduce them.

To make this progress, our railroads need capital to invest in new equipment, new track, and electrification. Under the existing circumstances, the carriers of the Northeast, Midwest, and Appalachian regions cannot possibly raise the required funds in the private financial markets. But it is a Catch-22 situation—unless they do modernize and become competitive in the handling of high-rated products to augment the carrying of heavy bulk products, railroad service will continue to deteriorate, and eventually the economy of the nation will suffer a major collapse. We must therefore find the financial way to modernize track and electrify our major railroads.

It is for this reason that I proposed 3 years ago a \$13 billion railroad construction trust fund to be used to modernize our railroads over a 6-year period. A good portion of this was for new track and electrification. It would take about \$18 billion to do the job today. At the time, the ICC had permitted a 10 percent freight rate increase earmarked for capital improvement. They too recognized the problem, but the solution they offered was really no solution because rate increases drive away customers. We have a highway trust fund, an aviation trust fund, and President Carter recently proposed a waterway trust fund. I do not know how the railroads can expect to survive without a similar type of federal fund that would provide the capital that the most hardpressed and most needy railroads cannot themselves raise in today's financial markets.

Under the rail trust proposal I suggested in 1974, funds would be made available to modernize all U.S. rail facilities. The improved track, centralized traffic control, and electrification would, after 6 years, save at least $1.5 billion/year in operating costs for the railroads—and perhaps much more. The return on investment was estimated in 1974 to be 15 to 18 percent, but this did not project increased earnings from the new high-profit traffic that electrification could attract. Thus, the actual rate of return should be much better.

The dilemma that impedes railroad electrification under normal financing, even if it could be arranged, is quite apparent. Most eastern and midwestern railroads are losing money at present. The national rail system earns only $1\frac{1}{2}$ percent on the old net investment. Though an electrification program would increase present rail net earnings tenfold, there are other investment projects that require less funding, that offer high rates of return for investors, and that are safer. Thus, important railroads, unable to raise equity funds, continue to slide down the drain. This slide must be halted. This major project of rail reconstruction must be financed. The need for implementing the rail trust fund concept is even greater today than it was in 1974. Improved track and electrification are the keys to future rail success and for profitable operation for the carriers. A few specific examples prove this point.

At present, the run from Harrisburg to Pittsburgh is a difficult one. Even an important expedited freight train needs nearly 11 h to make a one-way trip and 28 h to make the round trip, including fueling and servicing. Three such expedited trains per day require 15 diesel locomotive units, each train having 8.6 MW (11 500 hp). Contrast this diesel operation with one using electric power. A one-way trip could be cut to 10 h and the round trip to 24, since refueling is not necessary. Only two electric units would be needed to put 8.6 MW to the rail, so the locomotive fleet could be cut from 15 for each 3 trains/d to 6, a saving of 60 percent in motive power with better service provided.

If the railroads are to move more than bulk loads and be able to carry the high-profit loads efficiently, trains must do more than just start quickly, which is the main advantage of diesel power. They must be able to accelerate on the straightaway, decelerate around curves, and then get back up to moderate speed quickly. This can be done with electric powered trains.

There are those who would go the other way—cut the railroads' physical plant because it is currently said to be underutilized. I reject this bureaucratic suggestion to curtail service and shrink the plant. It is dangerous thinking for the future of the United States. The only way railroads will stay alive as a cost-effective business is to expand and improve service, to better use the plant, and thus to reduce the unit cost while increasing the net revenues.

Another example shows this can be done. There is now no overnight freight service by rail between Pittsburgh and Boston, which are only 1060 km (660 miles) apart. The rail could very well be electrified through Harrisburg, Philadelphia, and New York. The passenger tunnels do not permit large modern freight cars to pass through New York. With electrification, however, overnight freight trains, using captive freight cars within the clearance height, could be operated reliably. A freight train traveling at 80 km/h (50 mph), even allowing for reduced speed in strategic locations and counting 2 h delay for intermediate work, could make the run in 17 h; if it left Pittsburgh at 6:00 p.m., for example, it would arrive in Boston by 11:00 a.m. the next day.

The cost of operating such a train, with full overhead costs, could be roughly $25/km ($40/mile), or $9.08/$m^3$ ($0.257/$ft^3$), for a 30-car train over the full distance. At present, overnight freight by turnpike is a little faster but costs $11.34/$m^3$ ($0.321/$ft^3$). The energy difference however is striking—the equivalent of 20 000 L (5280 gal) of fuel saved by the electric train over that needed by trucks on the turnpike. This represents a 50 percent saving in energy requirements. Actually, all 40 000 L (10 560 gal) could be saved because the electricity for the rails could be generated by coal. The tremendous rate of use of these electric locomotive and freight cars is also worthy of note. Only six electric locomotive units are required—two operating each way each night and two in reserve. All six will average almost 16 000 km (10 000 miles) each month, assuming there is no weekend use. Most importantly, two trains operating between Pittsburgh and Boston could net a $1 700 000 annual profit.

As another example, a six-car multiple-unit freight train going east from Pittsburgh overnight with cars destined for Philadelphia, Baltimore, and New York would cost $4100/night each way. Assuming it carries 18 Mg (20 tons)/car and earns 7 cents/Mg·km (10 cents/ton-mile) for high-rated expedited shipments, revenue would be $4452/night, excluding local trucking costs. The favorable impact on industry and employment with this type of transportation service would be enormous and would stimulate new business operations and the expansion of existing companies.

I hope that I have made my point that innovative new sources of revenue and profit would accompany rail electrification and that this factor must not be omitted from consideration. Using long, slow, heavy trains has not proved to be the most profitable way to run railroads.

I would like to make one additional point. The decision for rail electrification cannot be left only to the electrical engineers or to the motive power chiefs or to the rail purchasing agents. The decision must be based on total system considerations, including finance, estimates of future inflation of petroleum costs, future availability of fuel supply, service quality, international balance of payments, new types of service, noise and air quality regulations, and other factors both within and outside the control of railroad management. Where electrification becomes necessary or desirable and capital is not forthcoming, the concept of the railroad trust fund must be reexamined. The United States must move in this direction to ensure its economic future.

It is time to rebuild and modernize the railroads of the United States. Electrification makes a great deal of engineering and economic sense. Rail electrification will save enormous quantities of fuel for other uses. Electrification will increase rail efficiency and lower the cost of transporting goods. Electrification of our railroads will increase U.S. employment by many hundreds of thousands in the plants that manufacture the equipment and, more importantly, by making rail service more competitive and thus creating thousands of permanent new jobs.

We can help start a new industrial revolution in the United States if we use logical programs to conserve on fuel and improve transportation facilities. Electrification of our railroads is a major step needed to achieve this goal.

Amtrak's View of Railroad Electrification

Paul H. Reistrup, National Railroad Passenger Corporation (Amtrak)

Because not much has been done with electrification is this country, the original Northeast Corridor, completed in 1933, is the only real example of an operating electrified railroad in the United States. Early reasons for electrification were to cut down on the smoke produced by steam engines and, before the advent of diesel locomotives, to increase tractive effort. The GG-1 locomotive, which was built 40 years ago, is still being used in the Northeast Corridor. One reason for its long life is that some speeds that were expected in the Northeast Corridor were not attained.

Why did electrification stop here? There were many reasons, of course. The depression was one, and World War II followed on its heels. After that, the railroad industry saw most of its passengers take to the automobile, with first-class passengers going to aircraft. Also, the improvement in the nationwide highway network financed with government funds made it possible for the motor carriers, hauling freight by truck, to take over a lot of the freight business. The big changes from railroad to motor carriers took place in the northeastern United States, where distances were shorter and the railways were laid out in a rather primitive alignment. We have simply not been able to compete; trucks can travel anywhere.

I would like to tell briefly why I am so interested in electrification. At the Illinois Central Gulf Railroad Company I had my first real brush with this side of the business. The commuter line was electrified, and one of my tasks was to obtain federal funding, which had never been received in Chicago before, for a portion of the cost of the new commuter cars. We actually went through a study at that time, in the late 1960s, to determine whether we should keep the electrification. Of course, we had the alternative of a diesel-electric push-pull operation if we wanted to tear down the wires. It was determined that, in spite of the age of the electrified installation and some of the shortcomings of the 1500-V direct current system, we would retain the electrified system, and the bilevel electric-motorized unit car was designed, tested, and built. Not too long after that, I was asked to chair the in-house feasibility study on electrification for the freight lines, specifically on the line from Chicago to Memphis, which is a route with heavy traffic. The decision in this case was not to proceed with electrification.

WHERE WILL ELECTRIFICATION BEGIN?

There are about 13 000 km (8200 miles) of rail line in this country that could justify electrification, extending what now exists. Those are the lines that carry 36 Tg/year (40 million gross tons/year). There are those who believe we might even electrify as many as 32 000 km (20 000 miles), but I think we ought to walk a little before we try to sprint. The Federal Highway Administration has directed the states to build highway overpasses and railroad underpasses 0.61 m (2 ft) higher than standard to ensure that there is clearance for the pantograph collector above electric locomotives. That would be for lines that carry 27 Tg/year (30 million gross tons/year). There are some 27 000 km (17 000 miles) of track that fit into that category in this country. I think it is very gratifying to see that kind of advance planning and coordination between the highway people and the railroad people in the U.S. Department of Transportation, so that we do not build bridges that would interfere with progress in rail electrification on high-density lines.

The National Railroad Passenger Corporation (Amtrak) appears to be the leading edge of this move toward electrification because of the Northeast Corridor Improvement Project, which includes the electrified line we are now operating and the extension of that line that will go on from New Haven to Boston. We will be the operating test-bed for a lot of the experience that will be invaluable to others. Some mistakes will be made but, on the technical side, there can be a great deal of assistance to other interested parties as the project moves forward and we actually gain some operating experience.

There are some complexities. Our power is currently 11 kV, 25 Hz; the power in the New York Metropolitan Transportation Authority and Connecticut Transportation Authority sectors will be 12.5 kV, 60 Hz; the Northeast Corridor Improvement Project is pursuing a higher voltage—25 kV—in its own sector. I believe we ought to build everything we need toward that ultimate level. Depending on the market projections for demand in the future, we should install the proper equipment from the start.

The real question, however, is not technical but financial. The financial constraint on electrification, even with federal assistance, as in the case of Amtrak, is the overwhelming issue. I can only think of a couple of technical issues that trouble me at this time. One is the problem of phase breaks; we will have to have three separate phases as we go from section to section. And this really has not previously been done at high speeds, at least to my knowledge. Our trains now travel at 190 km/h (120 mph), and we are trying to build up to 240 km/h (150 mph). At those speeds, the phase-break problem has not been solved yet. The other issue is the costs of adapting the signal system to electrification. I do not think that is a very serious problem technically—it is largely a matter of dollars. And that is a big problem.

It appears that everybody is in the race to be second in the railroad industry, but where are the dollars coming from? I do not think any more track will actually be electrified for operation until we determine where the capital is coming from. Looking for a moment at what this does to the income statement and balance sheet, some of the risks involved show why we have not seen progress in the recent past.

Consider a project to electrify about 800 km (500 miles) on a railroad with heavy traffic that runs through relatively flat country. This railroad probably has about 9500 km (6000 miles) of total trackage, so we are dealing with less than 10 percent of the entire operation. Such a railroad is probably capitalized at about $1 billion to $1.2 billion, so this would represent a tremendous increase in the capitalization of that property—probably 20 to 25 percent, depending on what signal system is in use on that sector of line. This is not bad, considering the rate of return, particularly with appropriate financial maneuverings, such as leverage leasings. This is one way to see what actually happens both to the bottom line of the financial report and to the total capital invested in this business. The other needs for capital must be taken into account and, on a railroad this size, that could amount to another $100 000 000/year.

One of the risky issues in any analysis of electrification is what to do with the diesel fleet that is released. Generally, a railroad like the one we have been considering will have a fairly good locomotive fleet. A lot of assumptions about disposition are possible, even such extreme optimism as being able to lease out 100 locomotives at $300/d, but it really depends on how many companies electrify. And although such leasing opportunities may be available to the railroad that gets there first, in the railroad business, as I have seen it in my 20 years, everyone will try to move at once.

The issue of the diesel locomotives and how they might be used is tied in with traffic projections. How much business will there be? How many trains will be run 10 years from now, and how many of these could be diesels? There is a very high risk in making erroneous judgments. In the past few years everybody was projecting ever-increasing traffic. Then came the energy crunch in 1973, and with it came shortages of materials; the bottom dropped out so fast that we wound up trying to find out every day how far the traffic was going to drop.

EQUIPMENT USED WITH ELECTRIFICATION

I would also like to mention some of my feelings about the equipment that should be used under electrification, particularly as it applies to the passenger business. In the Northeast Corridor today we have a mixture of electrified multiple-unit (EMU) equipment and locomotive-hauled equipment. My prejudice is toward EMU equipment, as you might guess, because of my experience at Illinois Central Gulf and because of the success of the Metroliners. The 61 Metroliner cars, even with the difficulties we have keeping them maintained, are producing about 16 percent of Amtrak's revenue. They have never had a heavy overhaul yet, although they have had about 10 years of service running back and forth, many of them 1100 km/d (700 miles/d).

As a practical matter, we are going to see a mix of EMU equipment. It may begin with an overhauled Metroliner, since something has to be done about overhaul if we are going to continue to run them. Then we shall also need locomotive-hauled trains because of the tremendous fluctuations of volume that we have. At Thanksgiving, everybody in the United States goes somewhere; nobody wants to eat alone. The highways are bumper to bumper, and the airways are all filled up, so everybody comes running to the trains. I do not see any way, especially in the Northeast Corridor, to handle such a surge with only EMU equipment. There must be the flexibility that additional locomotive-hauled trains provide of lengthening trains and at least getting people where they want to go. That is what we are in business for.

The next step will occur when we achieve speeds above 190 km/h (120 mph). Then, EMU equipment will have the edge because of the power-to-weight ratio and the reliability required. It is possible to lose a car (or even two, in the case of a Metroliner) and still get there, but if a locomotive is without power or the pantograph drops for any reason, that is the end of the game.

I would like to address another issue. In the Northeast Corridor we have both passenger and freight trains, and some of the freight operations between Washington and New Jersey involve very heavy loads. A short time ago one of those freight trains broke what I call the first commandment of railroading—"Thou shalt not run into each other." One freight train ran into the rear of another at a point where there are four tracks. Just think what would have happened if there had been passenger trains on either side of them at that time. Amtrak assumes a considerable degree of risk, particularly when striving to maintain speeds above 190 km/h (120 mph), in trying to operate a reliable, high-speed, intercity passenger operation in coexistence with the freight operations, especially in view of the heavy axle loads associated with freight cars in this country. The British, French, and Japanese have expressed considerable concern in this regard since the axle loads in this country run approximately 9 Mg (10 tons) higher than they do on railroads in other countries. It is very difficult to maintain the necessary track tolerances with such high axle loading.

I would like to conclude by making a few predictions that may come back to haunt me.

1. I think electrification will take place, and I mean electrification beyond what is going on at Amtrak between New Haven and Boston.
2. I think electrification is a nice, graceful way toward rationalization of the railroads, something we need because we do have excess railway plant and inefficiencies. I hope that electrification will tend to draw the freight to the more efficient lines and that rationalization will foster the joint use of track. Many of the things intended under the provisions of the Railroad Revitalization and Regulatory Reform Act actually support such endeavors.
3. Except for the relatively minor technical problems that I mentioned earlier, electrification does not present major technical problems.
4. The major issue is the financing of this effort. I do not believe the private railroads can do it by themselves.

An Examination of Some Economic Obstacles to Electrification

Thomas J. Lamphier, Transportation Division, Burlington Northern, Inc., St. Paul, Minnesota

It has been said at this conference that a great new era in railroad electrification is coming. I recognize that there is a tremendous weight of evidence in favor of that. We cannot go on spending $32 billion/year for imported oil. Production in the United States is down from 556 000 000 m^3 (3.5 billion bbl) in 1970 to 477 000 000 m^3 (3 billion bbl) in 1975, even though the wellhead price for crude oil has quadrupled and the United States accounts for three-quarters of all the drilling activity in the free world. Even the oil from Alaska—318 000 000 m^3/d (2 million bbl/d) are expected to be flowing by 1977—will only stop the decline temporarily.

However, it may be a little early to write off oil as our industry's primary fuel. It is true that petroleum resources are finite; it is also true that intensified drilling activities in the 4 years since the Arab oil embargo have not yielded enough to ease our concern about worsening shortages and escalating prices.

But I am reminded that in the early 1920s experts were also predicting the imminent exhaustion of domestic oil supplies, and by the end of the decade their predictions had been proved overwhelmingly wrong. I am also reminded that it took 8 years of fruitless drilling before the Standard Oil Company of California first discovered oil in Saudi Arabia. It took 9 years of similar frustration before Atlantic Richfield Company first struck oil on Alaska's North Slope. I think that, as we strive to conserve energy and push forward with the development of our enormous coal reserves, we should not totally disregard the consideration that 5 or 10 years from now a technical innovation or a major new strike could change our energy outlook significantly.

Personally, I doubt that we will ever again be able to consume our oil resources as recklessly as we did before 1973. I think the minor belt tightening we are doing now in energy consumption is just the prelude to even stricter conservation practices, which will be with us for decades until our technology enables the family of man to use solar energy universally or some other new energy source is found. And I believe that electrification of heavily used railroad main lines is inevitable. However, I am also sure that electrification is some distance down the road and that our progress toward electrification should continue to be at a very deliberate pace.

At Burlington Northern, we are continuing to study the subject thoroughly. We anticipate that diesel fuel, which now costs about 9 cents/L (34 cents/gal), will rise to between 36 and 44 cents/L ($1.35 and $1.65/gal) by the year 2000. That is significant to Burlington Northern, which uses an average of nearly 4 million L (about 1 000 000 gal) daily. We are even more concerned about the future availability of diesel fuel than we are about the price.

The same study shows that, while electric rates will also continue to rise, the increases will not be as rapid, and all-electric train operations will be more economical than diesel-electric operations. But several things must happen before Burlington Northern can embark on electrification.

First, there is the important question of the source of the large amounts of capital that will be required. A few years ago, the matter of electrification was being evaluated very seriously by Burlington Northern and a number of other carriers. We thought then that we could finance it from revenues and our usual capital sources. Today such optimism no longer appears to be justified. Cost estimates have gone up dramatically. Government studies tell us that it would cost $8 to $10 billion to electrify just 32 000 km (20 000 miles) of high-density railroad lines, and our own studies verify this. Although railroad industry revenues and payloads are rising, they are not rising enough or fast enough.

Although capital formation continues to be the principal roadblock to electrification, there are other issues that must be addressed. For example, once a railroad makes the decision to electrify, it will immediately face the need to develop an environmental impact statement covering the construction and operation of the transmission system and catenary. Some environmentalists are going to view those transmission lines and catenaries as blights on the landscape. In addition, other environmentalists will raise questions about radiation and interference with telephone communications, radio broadcasting, and human life.

I would not suggest that environmental protection problems are unsolvable, but a lot of time and effort—and a good deal of frustration—will be involved. I was recently reading about a 5.8-km (3.6-mile) relocation of a two-lane road on US-202 around a small town in New Hampshire that has been delayed 10 years in order to resolve the environmental objections and complete a suitable environmental impact statement, which was 211 pages long.

I think there are several technical problems associated with electrification that have not been addressed adequately thus far. One is the potential for personal injuries that is offered by a 50-kV system in densely populated areas, where catenaries will be heavily exposed. And there are still some problems with phase breaks where commercial three-phase power is being used and electric locomotives are loaded and unloaded at the breaks. Considering all the factors involved, including the additional capital required, I wonder whether consideration should not be given to conversion of the commercial power to single-phase alternating current or high-voltage direct current for traction purposes.

Furthermore, I have not been convinced that our industry's suppliers have developed electric locomotives that are suitable for operation on high-density rail lines. I have great difficulty believing that the demonstration locomotives being tested by American and European manufacturers are the best locomotives, for example, for Burlington Northern to use on 11.8-Gg (13 000-ton) unit coal trains.

Stanley Crane originally raised the issue of the economic life of electric locomotives, questioning the anticipated 30-year life of an electric compared with the 15-year life of a diesel (1). We all see the GG-1 as the epitome of the long-lived locomotive. Some of the classes of electric locomotives used on the Pennsylvania Railroad had very short lives because of poor design, poor construction, and changing requirements. The Great

Northern Railway's W-1s lasted only 9 years. It could be argued that those engines could have run for another 21 years, but in fact the system was obsolete. And electrification lasted only 5 years on the Detroit, Toledo and Ironton Railroad Company during the period when the Ford Motor Company was in control of that road. So we should look very carefully at the economic life of electric locomotive systems—not just the locomotives.

To return to the costs for a moment, we must remember that we not only will have the cost of actually installing the catenary system, but we will also be investing in new locomotives, improved roadbeds and plant to handle higher speed electric locomotives, new plant and machinery to maintain the electric fleet, and new training programs to teach people how to operate the new systems. There will be a loss of flexibility. A diesel is much easier to shift from one location to another, and it will be impossible to shift units to meet seasonal traffic demands in areas that are not electrified. In the event of accidents in which both track and catenary are damaged, we also foresee much longer downtime to repair both track and catenary than if only the track were damaged. Addition of sidings and double track would significantly increase the cost of electrification.

I raise these points only to pose some of the questions that must be answered before we can proceed with electrification. We know the advantages that would accrue once electrification became a reality. The fuel cost factor is, of course, a major consideration. But electric locomotives would also require less servicing between runs and fewer major overhauls, which would reduce overall maintenance between 30 and 50 percent. Also, the greater power of electric locomotives would permit faster over-the-road transit time because they are capable of higher speeds.

It is a very encouraging sign that this conference has been called to deal with some of the really difficult problems of electrification. I am here to raise questions, but I would not presume to answer them. I do want to impress you with the seriousness with which the railroads view our role in the new era we have entered.

The energy shortages that gave rise to this conference are changing every facet of our lives. Some of the changes we do not like very much, and perhaps we never will. But one change that I as a railroad man do like is the growing dependence on the railroads in our new scheme of things. The continuing shortage of energy and the increased cost of fuels are going to make railroads more necessary than ever, and that is good.

No matter how you look at it, railroads are more efficient users of fuel than any other transportation mode, and they will be even more so in the future. They are also the most efficient and least expensive haulers of coal, on which our energy programs are becoming increasingly dependent.

Burlington Northern, which is currently the fifth largest coal-hauling railroad in the country, has seen a tremendous increase in the amount of this commodity hauled over the past several years. In 1970, we hauled 19 Tg (21 million tons) of coal. By 1980, we expect to be carrying 113 to 136 Tg (125 to 150 million tons).

This will happen because we are the principal carrier serving areas of the West that are the heart of the expanding low-sulfur coal industry, which will be a vital factor in serving electric generating plants, including those that will be involved in rail electrification service.

Our railroads and others involved in the growing coal transportation service are benefiting greatly from the increased profitability and stability this business offers. Not very long ago, many people were predicting that the railroads were about to go the way of the barge canals of the nineteenth century. But people have since rediscovered that railroads are, in fact, absolutely necessary to carry the bulk of the goods on which we all depend.

As a result, there is a new optimism in railroading today. There is renewed hope that the challenges can be met and the problems that have impeded growth can be solved. Indeed, there is a feeling that our industry is entering a new era of greatness that will surpass anything yet seen.

This is not to say that the future of the railroad industry as part of our private enterprise system is assured. There are still many challenges ahead. But I believe that we are in the best position we have been in for years to pull ourselves together and solve these problems. The new importance of the railroads and the new and increasing sources of revenue will, I think, enable us to pull ourselves up and do those things that need doing to keep us in the private sector.

What are these things? One is the need for the industry to trim down and consolidate into fewer, more efficient systems. Our current national system is a fractured, balkanized structure that hinders our ability to work together and deliver reliable, assemblylike transportation service to our customers. Consolidation would, I believe, make a larger percentage of each railroad's traffic local to that railroad by reducing the number of interline moves. This would in turn produce more efficient on-time service.

Second, we must install an industrywide computer-based scheduling system that provides a complete itinerary for every freight car, from origin to destination. And we will have to invest even larger sums on improvements in plant and equipment, including electrification.

As we accomplish these goals and become even more competitive with petroleum-dependent motor carriers, barges, and airlines, we will have taken a large step toward the financial stability necessary to keep the industry healthy and functioning.

It is not going to be easy, but I firmly believe that, if our country is to meet its energy conservation goals and continue to prosper, the railroads must prosper also. There remains the question of how and when electrification can be accomplished.

I see one threat to the railroads that could also put electrification beyond our reach for decades to come—the threat posed by coal slurry pipelines. Hearings have been held in the House of Representatives on a measure that would grant the right of eminent domain to proponents of slurry pipelines, so that they could compete with the railroads and barge lines that now move coal through the Rocky Mountain and midwestern states. In order to move coal by pipeline, it has to be crushed and mixed half-and-half with water to form a slurry. Many people in the West oppose these pipelines because each one of the 15 now planned or under discussion would waste enormous amounts of water from areas of our country that are haunted by the specter of drought.

I am opposed to that; I am also opposed to slurry lines because they would use 20-year and 30-year contracts to exclude the railroads from hauling most of the coal that will need to be moved in the years ahead. Obviously there would still be some coal business left for us, but the best of the business would be skimmed off, leaving the railroads with the least profitable part of the traffic.

I will not go into all the ramifications this situation could hold for our industry, but I think it is appropriate to point out that railroad electrification is dead in our time—stone-cold dead—if these monopolistic coal slurry pipelines are allowed to be built.

After all, if a minimum of 27 Tg/year (30 million gross tons/year) would be required on a segment of main line before electrification could be justified, then the railroads would need a traffic level of 875 Pg·km (600 billion gross ton-miles) over the 32 000 km (20 000 miles) of main line in the United States that are being considered for electrification.

Last year the class 1 railroads of the United States had a traffic level of slightly less than 3000 Pg·km (2000 billion gross ton-miles). That was an increase of only about 300 Pg·km (200 billion ton-miles) since 1966. Since coal last year accounted for 29 percent of the loads the railroads hauled, where will the traffic to justify electrification come from if slurry pipelines are allowed to monopolize the best of our future growth in the coal-hauling business?

Coal is both the largest and the fastest growing part of the rail industry's traffic mix today. Last year we hauled more than 360 Tg (400 million tons) of that fuel. William Dempsey of the Association of American Railroads has estimated that increased coal production would raise our industry's coal traffic to 660 Tg (725 million tons) by 1985 (2). That figure never will be realized if coal slurry pipelines are allowed to be built, and our hopes for electrification of our industry's busiest main lines will be frustrated.

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Institutional and Economic Issues

Electrification and Railroad Organization and Operations

E. R. Craven, Burlington Northern, Inc., St. Paul, Minnesota

The managements of several railroads today are asking themselves whether they should consider electrifying parts of their systems. There is a lot of activity in the East designed to upgrade existing systems and possibly to add some new line segments. There are two new projects under very serious consideration. One of these is a part of the Northeast Corridor Improvement Project, which will include electrifying the line from New Haven to Boston as well as modernizing the existing electrification between New Haven and Washington, D.C. The second project under consideration is installation of modern commercial-frequency electrification of Consolidated Rail Corporation's main line from Harrisburg to Pittsburgh. We now have two separate and distinct systems, the first a high-speed passenger operation and the second one of the highest density freight routes in the United States.

What about railroads in the Midwest and West? There is nothing new except for the electrification of individual, isolated sections for moving coal. The utilities have led the way in the West in implementing cost-effective electric railroad operations. In 1968, American Electric Power Company started their Muskingum operation in southeastern Ohio. Although it is only 24 km (15 miles) long, it has been very successful operating in a fully automated mode. Next to follow was the Black Mesa and Lake Powell Railroad, a 125-km (78-mile) operation in northern Arizona. The latest electric railroads in the United States are two in eastern Texas operated by Texas Utilities Services, Inc. All of these are coal operations.

Let us consider for a moment what has caused our present situation. At the turn of the century, the United States led the world in railroad electrification. As late as the early 1930s, it contained 20 percent of the world's total electrified lines. This is certainly not so today. Less than 1 percent of the railroad trackage in this country is now electrified. A look at the rest of the world shows that, outside the North American continent, electrification has become the standard way to expand high-volume main-line railroads. The United Kingdom, Germany, France, the Soviet Union, Taiwan, South Africa, Japan, Iran, and Brazil are proceeding rapidly in many locations.

If electrified rail operation has so many advantages, why has there not been more of it in North America? Three significant factors were involved.

1. At the end of World War II, Europe had to practically rebuild its rail system. The decision was made to start electrifying.
2. In the United States at this time, there were many demands for capital to be used to catch up with the maintenance and acquisition of equipment that had been deferred because of the war. This precluded the investment that electrification required. Also, at this time, the diesel electric era was getting a good start. This permitted a conversion from steam to a modern motive power system that required only the purchase of locomotives with small support systems. It was possible to buy one and try it; then if the purchaser did not like the change from steam to diesel (and there were many who were sure it would not work), large sums of capital had not been committed to trying the new system.
3. The electric supply systems and motive power in use on early operations were not advanced enough to be competitive with the highly developed diesel electric locomotive. The dieselization program extended over several years, and U.S. railroads could not see the reason for shifting to electrification. Fuel oil was abundant and cheap, and labor costs were not prohibitive. That brings us up to the present.

During the past few years, feasibility studies have been conducted by several major U.S. railroads that are considering electrification—Union Pacific Railroad, Southern Pacific Transportation Company, Southern Railway Company, Atchison, Topeka and Santa Fe Railway Company, Illinois Central Gulf Railroad Company, Canadian Pacific Ltd., and Burlington Northern, to name a few. In my opinion, there are three major items that have caused this interest to become more active—the increased cost of petroleum fuels, the prospect of a continual shortage of crude oil for years to come, and the question of how long the supply will last. Railroads were not too concerned when diesel fuel was 2.5 cents/L (9 cents/gal). Today that cost can run between 8.5 and 9 cents/L (32 and 34 cents/gal), and there is a shortage of fuel.

There is also concern over the fact that our transportation function is basically tied to one type of fuel. We cannot convert our power plants (the diesel-electric locomotive) from oil to coal, as some utilities are currently being required to do. To my knowledge, there is no way to convert a diesel to natural gas either. For the electric locomotive, although we would like to use coal as the basic fuel, there is the full range of nuclear power, hydroelectric power, oil, and gas available to generate the energy required. It should be plain that our national policy must be reshaped to take into consideration our increasingly urgent need to develop substitute sources of energy in this country, which requires the analysis of some alternative type of basic fuel. This in turn presents an opportunity for Burlington Northern and other western railroads to give serious consideration to the conversion of part of our operation to fossil-fueled electrical energy as a prime source of power.

Some studies have indicated that diesel-electric locomotives use about 1.6 percent of the fuel consumed in the United States. In the operation of Burlington Northern, we burn in the range of 3 800 000 L (1 000 000 gal) of diesel fuel a day. How long will this be available, at any price? There are methods of converting coal to oil and gas. Pilot plants are under construction and commercial plants are on the drawing boards. When and in what amounts will they be available? What will be the cost of these fuels?

ELECTRIC LOCOMOTIVES TODAY

Let us look at what is available today in electric locomotives. Modern technology and the development of the alternating-current rectifier locomotive have made possible the use of high-voltage commercial-frequency power. This allows for a much lower cost power system because the need for special conversion equipment is eliminated. We also have a thyristor propulsion control system that features easily maintained solid-state equipment that provides smoother acceleration over the entire speed range. Another modern development is individual-axle wheel-slip control. The conventional wheel-slip control system on diesels corrects the slip by reducing the torque on all axles even though only one of them has lost adhesion. To improve adhesion or the total pulling capability of the electric locomotive, a system has been designed that corrects wheel slip on the slipping axle only, allowing the other axles to continue at full tractive effort. A final example of recent locomotive development is the use of a vacuum circuit breaker. For primary protection on the electric locomotive, a virtually maintenance-free vacuum breaker is used.

The straight electric locomotive can attain two to three times the tractive power that a diesel-electric locomotive can within the same space configuration. It requires significantly less time for servicing between runs, since it does not need fuel, water, or lubricating oil, and major overhauls are less frequent and of shorter duration. The overall maintenance cost of an electric locomotive is 30 percent of that required for a diesel. There are some 3000 wearing parts in a diesel that are not found in a straight electric locomotive, which is considered to have twice the economic life and, because of the lower maintenance requirements, has a substantially higher availability for service. The electric is not power limited. Burlington Northern is looking for a locomotive for our coal operations with power in the range of 6 MW (8000 hp). It is possible to acquire 7 to 9 MW (10 000 to 12 000 hp) if the situation requires it. The diesels are limited today to 2.7 MW (3600 hp).

What effect does this have on our organization and operations? If these figures are correct, we should be able to operate through a given territory with half the present number of locomotives. We would need fewer locomotive maintenance facilities. The number of people needed would be fewer. Operation would be improved by at least 25 percent. Both British Rail and French National Railways confirm the lower cost of electrified operation, but it is impossible at this point to convert their costs to dollars.

Burlington Northern is considering a 25 and 50-kV system. Practically all new electrification construction in the United States will be either 25 or 50 kV. Depending on the clearance restrictions a railroad is confronted with, 50 kV may have the advantage. Incidentally, it was the development of the vacuum circuit breaker that allowed the quantum jump from 25 kV and the development of a 50-kV electric locomotive. Operating at the higher voltage reduces the current required by half for the same output. Thus the catenary current rating can be significantly reduced, compared with a 25-kV system. This means that substations can be spaced further apart—65 km (40 miles)—and, therefore, that there can be fewer substations. The implied savings are obvious.

Possible side effects of electrification should also be discussed. One effect that is receiving a lot of attention today is interference to signaling and communications. The conductivity of the soil, whether it is a single- or double-track railroad, the distance between the catenary and parallel wire circuits, the length of the circuits, mutual inductance, the current and frequency of the power in the track circuit, and the design of the catenary all play controlling roles in interference. On a single-phase system, the traction current travels from the substation through the catenary system to the locomotive. The current returns from the locomotive to the substation through the running rail as well as through the ground. Magnetic and electric fields created by the single-line transmission circuit can now induce various interferences. The amount of interference created is dependent on the voltage, frequency, and current flows through the catenary system. It is important that the signal and communications engineers work hand in hand with the electric design engineers. This, of course, results in a very expensive control system and adds to the cost of electrifying. The large single-phase load that railroads will require could present some difficulties for the utility if this represents a large percentage of the load. Although preliminary studies indicate that this is not insurmountable, it nevertheless is a problem that must be looked into.

What are maintenance costs of the new support systems—the catenary, substations, signals, and communications? There is no way to make a simple comparison with the cost of maintaining an old existing plant. How many people are involved? What about replacement parts? The best guess now is that it would cost $950/km ($1500/mile) for catenary and $3000/substation/year. Until figures based on actual experience are available, these numbers should be suspect.

VOLUME OF TRAFFIC

One of the key factors to be considered in electrifying a railroad is traffic volume. Many studies and assumptions have indicated that an annual movement of 27 Tg (30 000 000 tons) would be adequate to economically justify the conversion. Naturally, there are different types of traffic. The Northeast Corridor is basically a passenger operation that requires high speeds—190 km/h (120 mph). In our section of the country, we have a lot of manifest trains traveling 95 to 110 km/h (60 to 70 mph) and, in our particular situation, heavy coal trains traveling 80 km/h (50 mph). The electric locomotive is capable of handling any of these. The Burlington Northern's initial candidate for electrification is the line from Lincoln, Nebraska, to Alliance, Nebraska. In this area, about 34 Tg (38 000 000 tons) are currently being moved annually and this could increase to more than 90 Tg (100 000 000 tons) by 1980. The number of trains could increase from 15 to 50/24-h period. This potential increase in such a short period of time is related entirely to the movement of coal out of Wyoming and Montana.

We at Burlington Northern are taking a long view and making major investments to provide an expanded efficient transportation system for western coal. This is essential to the electric utility companies because assurance of a continuing fuel supply at relatively stable prices is a critical factor in the planning of new generation stations. We have seen that the availability of low-sulfur coal can stimulate major investments in coal-fired generating plants. I do not think it is possible to weigh the outlook for the movement of coal without considering the impact that major railroad electrification programs would have on utilities.

Electrification could require substantial amounts of coal, and railroads would then indirectly become major customers of the coal industry as well as of the utilities. This would not solve all our country's fuel problems, but it would be a beginning to the railroads' answer to the energy situation. The long-term strategy is aimed at a shift away from dependence on petroleum fuels. Railroad electrification may well serve the new national energy policy in a more direct way since, at today's level of technology, electrification offers the only available opportunity to convert a significant share of transportation requirements from petroleum to coal, nuclear power, or hydroelectric energy sources. It has been estimated that conversion could be justified for 32 000 km (20 000 miles) of the country's rail system. This length of track handles approximately 50 percent of the total traffic and would require a fleet of approximately 3500 to 4000 electric locomotives. To put this in perspective, the total U.S. railroad fleet of diesel locomotives numbers about 30 000. What is the cost of this conversion? Some estimates say $10 billion.

From an energy standpoint, this produces a potential market of 72 to 90 PJ (20 to 25 billion kW·h) of electricity annually and is the equivalent of 13 to 16 Mm^3 (85 to 100 million bbl) of oil. This seems like a large number, but it represents only about 3 percent of the electric energy used in the United States and, because of the relatively high load factor of electric railroad use, only 1.5 to 2 percent of the power demand.

The cost of an electrified operation, depending on the geographical location, can vary from $55 000 to $80 000/km ($90 000 to $125 000/mile). This involves catenary, substations, and signal and communications modifications. The main solution to the inductive interference indicated above is to bury signal power cables and use microwaves for communications. Electric locomotives cost from $700 000 to $1 000 000 each. We are thus talking about a lot of money.

The benefits of railroad electrification are

1. Reduced locomotive maintenance costs,
2. Longer locomotive life (electric = 30 years; diesel = 15 years),
3. Increased reliability of service,
4. Some increase in line capacity,
5. Overload capability for acceleration,
6. More tractive effort, and
7. More stable long-term energy costs.

The drawbacks of conversion to electrification are

1. The all-or-nothing aspect of the decision entailed in the financial commitment required, particularly in the face of inflationary capital interest rates, which demands very critical and detailed examination of the operational cost factors of the overall program;
2. The high initial capital investment in facilities and locomotives required to convert a portion of the existing plant;
3. Restricted service application, since electric locomotives require catenary and support systems; and
4. The dependence of economies on a high volume of traffic.

PROGRESS TO DATE

The first electric locomotive in the United States was conceived by Thomas Edison about 100 years ago and first put on a track in 1880. The pioneering main-line project was the electrification in 1895 of a 6-km (4-mile) tunnel through the city of Baltimore on the Baltimore and Ohio Railroad Company. The locomotive used was built by General Electric in Schenectady and operated on a 600-V direct-current trolley. It had four direct-current motors and had maximum power of 805 kW (1080 hp). Within the next 20 years, more than a dozen other railroads followed suit, electrifying the tough portions of their runs to solve specific problems, such as smoke in tunnels and terminals, or to supply high tractive effort to cross steep mountain grades. The New York Central System put the S-class locomotives in service on their 600-V system in 1906. Some of them are still operating in Grand Central Terminal. The Chicago, Milwaukee and St. Paul Railway Company put 3-kV direct-current locomotives into service in 1915 to get over mountains. Then in the 1930s the Pennsylvania Railroad completed its 11-kV 25-Hz alternating-current system and introduced the famous GG-1 locomotive, of which 139 were built and approximately 100 are still operating 40 years later.

In the mid 1950s, ignitron rectifier locomotives were put in service on the New York, New Haven and Hartford Railroad Company. The significant contribution of these locomotives is that the rectifier direct-current traction motor propulsion system made practical the use of high-voltage commercial-frequency power on the catenary. Then in the early 1960s the Pennsylvania Railroad purchased 66 new 3.3-MW (4400-hp) freight locomotives that ushered in the solid-state era with the introduction of the silicon rectifier.

The utilities then led the way in applying this new technology to implementing cost-effective electric railroad operations. In 1968, the American Electric Power Company began operation of a 24-km (15-mile) coal-hauling railroad in southeastern Ohio. This was the first commercial-frequency electric railroad operation in the United States; it operates at 25 kV and 60 Hz. It is a fully automated, two-train operation in which coal is loaded into one train as the other train runs the 24 km, dumps its coal, and returns for more. No one rides the locomotives; speed and braking commands are supplied in a fail-safe manner to the locomotives by passive transponders that are mounted between the track at specific intervals along the track. The locomotives were also the first in the United States to be built with thyristor propulsion control. This system has been operating successfully now for nearly 10 years, and the trains have made thousands of automated round trips.

Another pioneering electric railroad operation was the Black Mesa and Lake Powell Railroad, a 125-km (78-mile) railroad in the desert of northern Arizona that runs from a large open-pit mine at Kayenta on the Black Mesa—altitude = 2 km (6700 ft)—to the huge new Navajo

Power Station at Page, Arizona, on Lake Powell—altitude = 1.3 km (4300 ft). The purpose of this railroad is to haul coal from the Black Mesa Mine to the power plant. The Black Mesa and Lake Powell is the first 50-kV installation in the world. The advantages of using 50 kV were overwhelming, since the number of substations required for this railroad could be reduced from three to one.

The latest electric railroads in the United States are two in eastern Texas operated by Texas Utilities Services, Inc., to haul lignite from lignite mines to power plants.

A final illustration of the significantly higher level of power possible with an electric unit and the greater overload capability of an electric locomotive compared with a diesel is found in the high-speed passenger locomotives that operate in the Northeast Corridor. These have a continuous power rating of 4.5 MW (6000 hp), with 7.5 MW (10 000 hp) available on a short-time basis for acceleration of the train. They have demonstrated a capability of accelerating a seven-car train from a standstill to 160 km/h (100 mph) in 2 min.

This may be seen as a golden opportunity but, when we realize that electrification of railroads has been in existence since 1895, our progress would have to be classified as not too great.

I would like to close with my opinion of what will happen. We will see electrification of the main trunk lines on western railroads. The economic considerations are favorable, and few will dispute the arithmetic. When will this occur? That is hard to predict. One of the key issues may well be the federal energy policy that is being put together now. We do not know what it will contain. Today we are in a wait-and-see position. When you consider what alternatives there are, it seems that railroad electrification presents one suitable means for the transportation industry to do its share in conserving energy.

Financial Considerations of Railroad Electrification

Richard Fishbein, Kuhn Loeb and Company, Inc., New York

Several years ago, the Federal Railroad Administration organized a task force to study railroad electrification in the United States. The task force was composed of representatives of railroads, equipment manufacturers, electric utilities, and trade associations and government officials. The report of the task force (1) included the conclusion that, notwithstanding the technical feasibility and operating benefits of electrification, the principal obstacles to electrification in the United States were financial considerations. In particular, the following issues were named as having influenced decisions by railroads not to electrify:

1. Investment in electrification creates a long-term obligation for a railroad and thus affects its credit standing and ability to obtain capital for other necessary improvements.
2. The long-term earnings prospects for the railroad industry in general have not appeared to be strong in recent years. This has limited the interest in long-term railroad capital investments and precluded the opportunity to take full advantage of tax incentives when making large capital investments.
3. The economic benefits of electrification occur gradually over a long period of time, but the large investments necessary to initiate the flow of benefits must occur first and over a short period of time.
4. The investment of fixed electrification facilities may become subordinate to previous railroad mortgage commitments.

For a railroad, the issue of electrification is ultimately an investment decision that must compete with other investment opportunities for available funds. The amount of the investment is formidable. Current estimates by Arthur D. Little, Inc., indicate that the cost of a typical electrification system, including catenary, substations, communications, and signaling, would approximate \$95 000/km (\$150 000/track-mile). Double track would cost about \$155 000/km (\$250 000/mile). Assuming an average cost of \$125 000/km (\$200 000/route-mile), the total cost of electrifying the approximately 16 000 km (10 000 route-miles) in the United States that have traffic densities of at least 36 Tg/year (40 million tons/year), which is considered necessary by some experts under current economic and technological assumptions to realize a satisfactory return from electrification, would approximate \$2 billion.

In addition to the electrification system, there would be the cost of the electric locomotives, although in some cases this would not require substantial additional investment but rather would substitute in large part for diesel locomotives the railroad would otherwise have to purchase. There would, however, be the added cost of structural changes in track conditions, such as bridge and tunnel clearances, and new investment in electric power facilities. These costs could be very large in some instances.

In sum, the total cost of a national program of electrification would be at least several billion dollars initially, with potentially greater sums required if electrification becomes economical for route segments that have traffic densities of fewer than 36 Tg/year.

It is clear that the railroad industry cannot possibly, with its own resources, finance such sums. During the last 10 years, capital expenditures by class 1 railroads averaged approximately \$1.5 billion annually, most of which was expended on rolling stock. Only about \$400 million/year was expended on roadway and structures. Electrifying the railroads would be the largest investment in roadway and structures the railroads would make since the laying of the original track in the nineteenth century.

The declining fortunes of the railroads and the difficulties they face in meeting capital requirements, exclusive of railroad electrification, have been well documented. A recent study (2) by First National City Bank (Citibank) projected that from 1976 through 1985 class 1 railroads, outside the Consolidated Rail Corporation (Conrail) system, would incur cash outlays for capital expenditures, deferred maintenance, debt service, dividends, and taxes of $21.1 billion in excess of internal cash generation (net income before depreciation and other noncash charges but after dividends) and proceeds from rate increases, which will have to be met either from new capital or additional profits. Of this amount, Citibank estimated that $11.8 billion could be raised through traditional means of equipment financing, leaving a $10 billion financing problem.

Allowing for alternative assumptions and Citibank's hyperbole as a major lender to the railroad industry and creditor of the Penn Central Transportation Company, the railroads will undoubtedly have difficulty meeting their capital requirements in the years ahead. This makes it unrealistic to expect them to finance, from their own resources, the substantial sums required for a national program of electrification.

On the other hand, it is clearly possible for particular electrification projects to be financed by individual railroads. Although significant benefits of electrification may be realized on a route segment as short as 320 km (200 miles), it is more typical for railroads to consider electrification of route segments of 800 to 2400 km (500 to 1500 miles) or longer. A longer route segment, other things being equal, will tend to yield a higher return on investment. Using an average cost of $125 000/km, an 800 to 2400-km system would cost $100 million to $300 million, plus the cost of electric locomotives, structural modifications of rights-of-way, and additional power facilities.

There are railroads that are in a position to finance such sums. For such railroads, the problem is not the availability of funds but rather whether the railroad wishes to use its financial resources for an investment of this type. The answer will depend principally on the projected return on investment. In these cases, the financing problem is a conventional one of how best to finance a large capital project. There are four principal options.

FINANCING OPTIONS

Sale of Mortgage Bonds

First, a railroad can consider the sale of mortgage bonds. In recent years, the amount of railroad mortgage bonds sold has been limited. The costs have been significantly greater and the terms of maturity sometimes materially shorter than those of comparable industrial issues. In general, institutional investors have been wary of railroad obligations except for equipment trust certificates, which provide special security to the investor. The principal reasons for this are the generally poor earnings of most railroads, the low return on investment, the long-term deterioration of balance-sheet ratios, the bankruptcies of the northeastern railroads, and the unpromising outlook for many companies.

In addition, the treatment of creditors of the bankrupt northeastern railroads under the United States Railway Association's Final System Plan, whereby the railroad assets conveyed to Conrail were valued at net salvage value and consideration was proposed to be paid in Conrail securities, will tend to discourage private investment in railroad obligations. Insurance companies in particular, which have historically been the largest buyers of railroad mortgage bonds, have been reducing their investment in the industry over a long period of time.

There is an additional problem in railroad mortgages—the "after-acquired property" clause, which is a covenant in many existing railroad mortgages that typically states that all property hereafter acquired is subject to the lien of the mortgage. This means that a mortgage issued on a new electrification system may be subordinate to existing mortgages on the underlying track. In such circumstances, the railroad may have to add the electrification system to the lien of the underlying mortgage and issue additional bonds under that mortgage.

Notwithstanding the declining interest of investors in the railroad industry, there is a market for mortgage bonds of particular railroads. There are nine major railroads whose outstanding mortgage obligations are rated A or better by Moody's Investors Service, Inc. These railroads probably can sell mortgage bonds, although in more limited amounts and at higher costs than comparable industrial issues. In addition, some of these railroads are subsidiaries of holding companies that have substantial nonrailroad income from natural resources, real estate, and other activities. In these instances, long-term debt could be issued at the level of the holding company and invested in the railroad subsidiary as debt or equity.

Common Stock Equity

A second option for financing railroad electrification is new common stock equity. There have been no railroad common stock offerings in recent years, although the Burlington Northern did issue convertible subordinated debentures in 1972 and is in the process of issuing convertible preferred stock. The absence of railroad equity offerings is due partly to the low price/earnings ratios at which most railroad common stocks sell and also to the limited appeal that such issues are believed to have in the marketplace. Nevertheless, an argument can be made that certain railroads might consider common stock to finance, in part, a major investment in electrification.

Electrification is a long-term capital investment with an exceedingly attractive projected return that lends itself to permanent equity financing. Moreover, the shares of certain railroads currently sell at prices of 7 to 11 times their earnings, which makes the sale of common stock not unduly expensive. In addition, there is, in my judgment, a market for such issues, principally among institutional investors. It is based on good earnings records, substantial dividends, a very positive investor appraisal of management, and favorable prospects for both rail (especially where coal is an important element of traffic) and nonrail operations. For these reasons, rail stocks have performed better than the general stock market averages since early 1976.

Leasing

A third option for financing electrification is leasing. Leasing would have the advantage of permitting the electrification system to be financed by itself, unencumbered by existing railroad mortgages. This could be desirable in cases in which there are restrictions on additional indebtedness under existing mortgages or in which the collateral of existing mortgages has insufficient value to support the issuance of additional bonds.

Although there is some question as to whether, under the after-acquired property clause, title to property as closely connected to the underlying track as an electrification system can be secured to a lessor, it appears that there is a reasonable possibility that this can be done in particular instances.

The disadvantage of leasing is that it tends to be more expensive than debt financing because of the possibility of disaffirmance in the event of a bankruptcy. Moreover, the tax advantages of leasing may not be available for the leasing of most railroad electrification systems.

On April 11, 1975, the Internal Revenue Service published Technical Information Release 1362, which set guidelines for advance rulings on certain types of lease transactions. The release reflects a continuing policy to discourage lease transactions as a means of passing tax benefits on to passive investors. In particular, the release and subsequent rulings of the Treasury Department indicate that it will be difficult to obtain advance rulings with respect to special-purpose property that is expected not to be usable by the lessor at the end of the lease term except for purposes of continued leasing or transfer to the lessee. This would probably apply to most railroad electrification systems. Without an advance ruling, lessors would be reluctant to enter into a lease arrangement in which the tax benefits would be important to the lessor's total return.

One type of electrification project that may possibly be leased in a manner that passes the tax benefits to the lessor is an electrification system that is leased as part of the lease of a new rail line. It may be argued that at the end of the lease term the rail line, including the electrification system, would have value for a number of parties and consequently would be usable by the lessor for purposes other than continued leasing to the lessee. In such a case, the tax benefits of accelerated depreciation and the investment tax credit, which the railroad may not be able to use fully, may be passed to the lessor with benefits accruing to the railroad through lower lease payments.

In November 1976, the Financial Accounting Standards Board published Statement of Financial Accounting Standards 13, which requires that capital leases, which would typically include leases of railroad electrification systems, must be recorded at their inception as an asset and an obligation of the lessee and amortized in a manner that is consistent with the lessee's normal depreciation policy. Interest expense must be recognized in proportion to the remaining balance of the obligation. Such assets and obligations recorded under capital leases must be separately identified in the lessee's balance sheet, and additional information must be disclosed in the footnotes.

The statement of accounting standards for leases applies to all leases entered into on or after January 1, 1977. Although the new accounting practice will not change the economics of lease financing and the additional disclosures should not prove burdensome for most railroads, the inclusion of the lease obligation as a long-term liability may create problems for current indentures, which sometimes define indebtedness restrictions in terms of debt and other long-term liabilities under generally accepted accounting principles.

Project Financing

Fourth, there is the possibility of financing a railroad electrification system through project financing in which the system would be jointly owned or financed by the railroad, the utilities that provide the power, and institutional investors and would be leased to the railroad and possibly, in part, to the utilities as well. Railroad electrification lends itself to project financing because of the limited financial resources of certain railroads and their inability to fully use the tax advantages of ownership. There are many variations of project financing, but the basic idea is to spread the capital requirements and risks of ownership among several parties. The railroad, of course, would have to forgo part of the return to obtain these advantages.

Project financing can be structured in different ways and is subject to various technical considerations under indenture restrictions, accounting requirements, and tax regulations. A principal advantage is that it can be tailored to the needs of a particular project. One factor that suggests that project financing may play an important role in financing railroad electrification is that the major insurance companies, which until now have not been active in this type of financing, are becoming more interested.

For each of the above means of financing a particular railroad electrification project, there are various factors to be considered, including the financial condition of the railroad, its projected internal cash flow, future capital requirements, the marketability of its debt and equity securities, its tax position, relevant IRS regulations, accounting considerations, and indenture restrictions. There is also the possibility that an electrification project would be eligible in part for tax-exempt financing on the basis of its contribution to pollution control. Circumstances vary, and each railroad must select the financing package that best meets its particular needs.

NEED FOR GOVERNMENT ASSISTANCE

Financing a national program of electrification in the United States at a cost of at least several billion dollars is, as stated previously, simply beyond the means of the railroad industry. If it is to be done, it will require government assistance.

Although the federal government participates directly in the economy through fiscal and monetary policy, regulation of certain industries, public ownership, promotion and subsidization of various economic activities, and other ways, it does not, for the most part, unlike some other industrial countries, participate in the process by which investment capital is allocated among various sectors of the economy. The amount of capital invested in specific sectors of the economy, such as electric power, transportation, or natural resources, is determined privately, for the most part, through financial intermediaries and the capital markets.

There are exceptions. First, in areas in which the federal government owns economic enterprises, such as federal power projects, atomic energy plants, military manufacturing facilities, the Government Printing Office, and the Postal Service, the federal government does as a matter of course use its own financial resources to channel funds to particular areas of investment.

Second, there are areas of economic activity in which the risk to the investor is such that they do not attract the amount of capital from the private sector, at reasonable cost, that is deemed desirable. In such cases the federal government may undertake to use its own financial resources to lend directly or to reduce the risk of investing in those sectors through federal loan-guarantee or insurance programs.

There are a number of federal agencies that make loans or guarantee loans for private economic activity. Among the more important activities that benefit from these programs are housing, agriculture, and foreign trade. The federal government has also made direct loans to corporations. For 20 years, the Reconstruction Finance Corporation was the largest lender in the United States. In more recent years, the federal government has made loans to or guaranteed loans for the National Railroad Passenger Corporation, Lockheed Aircraft Corporation, and Conrail. The Carter Administration has also proposed an urban reconstruction bank to make borrowing easier for large cities.

In addition to direct loans and guaranteed loans, there are numerous federal agencies that insure investor risks. Perhaps the most important are the Federal Deposit Insurance Corporation and the Federal Savings and Loan Corporation. Other important federal insurance programs that directly affect the allocation of capital are undertaken for housing, shipping, agriculture, and foreign investment.

A third exception to the general rule of private allocation of capital is the case in which the federal government, through tax subsidies, undertakes to make certain types of investment more attractive by improving the after-tax return to investors. The most important instance is found in state and local obligations that are not subject to federal income taxes. In the natural resource industries, depletion allowances and capital-gains treatment of certain types of investments serve a similar purpose.

In addition to the above, any governmental promotion or subsidization of economic activity has an indirect effect on the allocation of capital insofar as it improves the capacity of a particular economic activity to pay a satisfactory return on new investment. Thus, the Interstate highway system, by lowering the costs of highway transportation, helps the trucking industry to attract capital, just as public improvement of the inland waterways helps the inland shipping industry to attract capital.

The question of whether the federal government should intervene in the allocation of capital for the benefit of a particular economic activity is an important one that has not been adequately studied or discussed. Historically, the federal government's participation stems from political circumstances rather than economic theory. Many of these programs originated in the 1930s when there was an obvious need to stimulate investment, especially in certain sectors of the economy. In more recent years, the issue has been considered in terms of how the economic and social benefits of investment compare with the costs of promotion or subsidization.

There are two new factors that prompt a more careful look at the costs and benefits of government intervention in the process of capital allocation. First, there is the enormous size of certain capital investments, particularly in the energy field, that may be desirable as a matter of national policy and beyond the means of the private sector. Second, there are risks attendent on certain of these investments (stemming from the unpredictability of the price of energy in the long run and other factors) that make such investments inappropriate for the private sector. In the case of railroad electrification, the size of the investment in relation to the financial resources of the railroads has already been discussed. Equally important is the uncertainty of the investment return to the railroads, since no one can predict the relative costs of diesel fuel and electric power over the next 30 years, though this will in a large part determine the rate of return of an electrification project.

As a matter of national policy, the benefits of electrification would seem to lie in the areas of energy conservation (or at least the conversion of a major use of energy from petroleum to coal and nuclear sources), ecological considerations, and more efficient railroad operations.

As an investment banker, I can point out that, if federal government assistance is to be effective, it must provide an incentive for the railroads to make the investment in electrification projects and also provide an inducement for investors to advance capital to the railroads for this purpose. At the same time, the assistance should not be in such a form that electrification projects with relatively low rates of return are undertaken.

Given these objectives, the best means of government assistance would appear to be federal guarantees of loans or leases made for the purpose of railroad electrification. A program similar to that administered under title 11 of the Merchant Marine Act of 1936 would seem workable. A federal guarantee would provide a strong inducement for investors to advance funds for electrification purposes, since the obligations would be backed by the full faith and credit of the federal government. At the same time, a federal guarantee would provide an incentive for railroads to make investments in electrification projects, since it would assure funds at a substantially lower cost than other long-term funds and consequently would improve the relative attractiveness of investment in electrification. On the other hand, federally guaranteed obligations would still have to be repaid, which would tend to discourage railroad investment in electrification projects that would have relatively low rates of return.

From the federal government's point of view, a program of federally guaranteed loans or leases would have the advantage of not requiring the direct advancement of funds. Moreover, it may prove not to be expensive. The federal government's experience with such guaranteed loan programs has been favorable.

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Implementing an Electrification Program: The Northeast Corridor Improvement Project

Richard P. Howell, De Leuw, Cather and Company, Washington, D.C.

The Northeast Corridor Improvement Project is providing an opportunity, unparalleled in almost two generations, for the implementation of a railroad electrification system in North America.

As we all are acutely aware, there has been limited effort toward electrification in this country; the Black Mesa and Lake Powell Railroad and one or two other single-track, short-haul unit train lines have been constructed within the last few years. Other contemporary activities have encompassed only modifications to existing systems, such as the conversion to 60-Hz frequency between New Haven and New Rochelle (now under construction through the efforts of the Transportation Authority of the states of New York and Connecticut in conjunction with their suburban passenger-train improvement program) and a large freight-yard revision now under construction at the Potomac Yard in Alexandria, Virginia.

The Northeast Corridor Improvement Project, in fact, deals with two major and distinct electrification program objectives. The first is the planning, design, and construction of an entirely new system between New Haven and Boston, and the second involves conversion and rehabilitation of the existing system between Washington and New Haven. In order to set the scene for further explanation of this project and for those who may not be totally familiar with the Northeast Corridor situation, I shall briefly describe the existing layout.

The Northeast Corridor is 734 km (456 miles) long. The route from Washington to New York City covers 364 km (226 miles) of essentially multiple track. It then traverses more than 30 km (20 miles) of the double-track Hellgate Line to New Rochelle, New York. The system is electrified over this total distance, using 11.5-kV 25-Hz propulsion through fixed-anchorage compound catenary. High-voltage transmission lines are also an essential part of this system. In the 87 km (54 miles) of four-track line between New Rochelle and New Haven, a power-supply conversion project to 12.5 kV 60 Hz is now under construction. The catenary throughout this territory is of the oldest vintage; it dates back to the early 1900s. The balance of the 251 km (156 miles) of double track between New Haven and Boston is not electrified.

As a result of extensive engineering and cost-effectiveness studies, it has been recommended to the Secretary of Transportation that this entire system be designed and constructed to facilitate 25-kV 60-Hz operation. This includes the conversion of the existing 11.5-kV 25-Hz propulsion between New Rochelle and Washington and the 12.5-kV 60-Hz operation now being implemented from New Rochelle to New Haven.

Before further discussing the project implementation plans, I would like to examine the basic technological and economic issues that led to their selection.

UNDERLYING TECHNOLOGICAL AND ECONOMIC ISSUES

Previous studies have largely shown that, beyond question, dense high-speed intercity passenger service is most economically operated with electric propulsion. Given this premise, it was then necessary to decide whether to reconstruct the existing system and extend it to Boston or to modify and rehabilitate it for a different voltage or frequency. Throughout the analyses it had to be remembered that the Northeast Corridor was established as a system and should not have different electric subsystems unless economic reasons become overpowering. The primary factors considered in the analyses were the

1. Normal and peak power requirements for each train, as well as all passenger-service and freight trains;
2. Speed requirements and number of pantographs;
3. Current transfer limits between wire and pantographs;
4. Voltage-drop limitations;
5. Climatic conditions;
6. Impact on vehicles, signals, communications, and so on; and
7. Operating and maintenance costs.

The most basic requirement was that sufficient power should be available to provide reliable service at speeds that would meet the travel-time goals set forth by the Railroad Revitalization and Regulatory Reform Act without setting unmanageable constraints on the size or frequency of trains. The electrification system was also expected to last at least 30 years after the completion of the project. Analysis of patronage demand showed a potential need for trains of as many as 14 cars at 15-min headways on some segments of the system. These trains would need a tractive effort (using up to three locomotives) capable of sustaining a cruising speed of 190 km/h (120 mph), with the maximum power demand occurring during acceleration at between 55 and 130 km/h (35 and 80 mph). Under these conditions the existing minimal propulsion supply (at any frequency) would require about 3.2 kA at 12.5 kV. This is nearly double the safe wire-annealing limit of the existing catenary. To enable trains to draw power of this magnitude, therefore, the voltage must be raised or the diameter of the wire must be significantly increased.

The other basic consideration was the power-capacity requirement for each substation projected for a typical schedule of trains (commuter, long-haul, high-speed intercity, and freight trains). Projections of patronage demand for 1981 and 1990 were derived through the use of a train consist and schedule simulation program adapted to provide data on power requirements. As might be surmised, the demand far exceeded the existing installed capacity of the existing individual substations and converter stations. Adding the requirement of a 30-year future life for the existing substations to the power-demand projections strengthened the argument for complete replacement on all existing substations.

The problem of capacity, as it applied to the costs of catenary and the power supply and as it is affected by a change in voltage and frequency, was then considered in one economic equation. Increasing the voltage to 25 or 50 kV would permit using the existing catenary with no change to the wires, but it would require greater overhead clearances. The option for 50 kV was discarded when it was determined that it could not be installed within the clearances of the New York tunnels or a majority of the 515 overhead bridges that exist along the route.

It was also found that new 50-kV catenary was no more economical than 25-kV catenary because the diameter of wire needed to satisfy mechanical loading problems of wind and ice, together with the high tension required to satisfy speed criteria, exceeded the requirements for the electrical capacity.

Since the existing system was constructed with double insulation (to compensate for steam engine exhaust), the voltage could be doubled to 25 kV with only minor modifications in some places where the clearance was tight. On the other hand, any voltage increase would require modifying to some extent most vehicles that use the Northeast Corridor, and these costs would have to be added. It also should be recognized at this point that, under any alternative, replacement vehicles would be required for the GG-1s and old commuter cars, which are considered uneconomical to convert.

Thus, since vehicles would have to be modified for a voltage change, the potential for conversion to a commercial frequency was further evaluated. The use of 25-kV 60-Hz power would eliminate the need to build and install new frequency converters, step-up transformers, and new high-voltage transmission lines over the railroad from New Haven to Boston and would eliminate the requirement to install additional frequency converters, step-up transformers, associated switching gear, and protection devices, as well as to replace the old existing units, transmission lines, and impedance bonds between Washington and New Rochelle. Considering all these factors, including the number of substations and the flexibility of using commercial power, the results favored a frequency change and higher voltage.

Finally, the existing fixed-anchorage catenary system from New Haven to Washington was analyzed for sustained high-speed performance. Temperature-induced tension variations were established as the prime factor in the ability of this existing system to perform, particularly under reaction to high temperatures. It was determined that, if the voltage were increased to 25 kV, the resulting current-induced temperature increase would be at acceptable levels for continuous speeds of 190 km/h (120 mph). In addition, the hangers adjacent to the supports would have to be modified, in conjunction with wire retensioning and selected reprofiling at "hard spots" (places at which the catenary has less flexibility and greater resistance to upward movement). The reliability needed to sustain higher speed ranges in the future would require conversion to a system using constant tension.

DESIGN AND CONSTRUCTION COSTS

For the new system between New Haven and Boston it was determined that the difference in design and construction cost between a new 240-km/h (150-mph) catenary system and a new 190-km/h (120-mph) design was negligible. It was therefore decided to make the new catenary system from New Haven to Boston capable of sustaining operations at 240 km/h (150 mph) by three power units. The new catenary will be of a compound style with constant tension, telescopic hangers, and a typical span length of about 64 m (210 ft) in territory without curves. A simple-catenary version of this design will be used in heavily curved segments, where speed cannot exceed 160 km/h (100 mph) without track realignment. Yards and complex terminal trackage will be equipped with a simple catenary or possibly only trolley wire with fixed anchorage, since speed is of no concern.

To turn to the economics of these analyses, the 25-kV 60-Hz electrification program that has just been delineated would involve the following estimated costs on the basis of a schedule projected to 1990:

Subsystem Component	Cost ($000 000s)
Catenary	113
Substations	69
Conversion equipment	–
Transmission	31
Other required modifications	
Bridges	32
Tunnels	5
Signals	70
Rolling stock	79
Subtotal	399
Replacement vehicles	173
Grand total	572

The $399 million projected cost can then be compared with the costs for two of the alternative systems evaluated.

System	Project Cost Without Replacement Vehicles ($000 000s)	Annual Maintenance Cost ($000 000s)
12.5 kV 60 Hz	541	8
12.5 kV 25 and 60 Hz	532	11
25 kV 60 Hz	399	5

The comparison shows an approximate first-cost advantage to the 25-kV 60-Hz system of 20 to 25 percent. Since the projected maintenance costs are also significantly lower, there is a good basis for recommending this system.

With the system engineering part of the project fairly well along at this time, the implementation of the program is proceeding on several other fronts in preparation for making the final design subcontracts.

Work is now in progress on such typical project elements as the development of a commercial power-supply service and the establishment of a service agreement, the location of substations and identification of equipment requirements, location of the switching stations and their equipment, finalizing the power-demand analysis, completion of bridge and tunnel clearance surveys, rehabilitation survey of the existing catenary system and the tensioning requirements, establishing design standards and specifications for catenary, establishing the pantograph type, developing a high-speed phase-break assembly, providing an outline design of poles and headspan assemblies, determining the outline requirements of the supervisory control system, providing the interface with the signals and communications facilities, performing an interference survey and determining the requirements for its mitigation, establishing a preliminary layout for track configuration, and making preliminary studies for the power-factor conversion equipment and mitigation of harmonics.

The most complex of these basic elements is the establishment of the commercial power-supply system. The decision to use a 25-kV 60-Hz power supply entails many additional problems in arranging commercial delivery to each of the approximately 36 substation locations from 10 different power companies between Washington and Boston. Engineering studies are now in progress to determine the best locations for the substations and the power supply points by using cost-effective trade-offs between the power-supply requirements and geographic location, e.g., the possibility of locating a substation at an existing high-voltage right-of-way crossing location or providing more right-of-way transmission rather than constructing a new high-voltage branch across country to the substation location. There are 20 substations between New York and Washington. It is hoped that these supply points can be established at existing substation locations in order to minimize the potential for new environmental intrusions.

Between New York and New Haven there are 6 substation locations, while between New Haven and Boston there are 10 or 11 new substations to be constructed. The substations are standardized to provide a continuous power rating of 15 to 30 MV·A. Each will occupy an area approximately 20 m by 14 m (65 ft by 45 ft), and they will be approximately 16 to 19 km (10 to 12 miles) apart. The supply system to the catenary will use a center feed. Thirty-five switching stations will be located midway between the substations.

ENVIRONMENTAL IMPACT

The most important institutional requirement for the current phase of the electrification program is also in progress. An environmental impact statement for the Northeast Corridor Improvement Project will be published shortly, followed by public hearings within a few weeks. This document addresses the environmental issues involved in the proposed electrification along with its accompanying subsystems.

Potential impacts are being identified and evaluated as the various program requirements are identified. As conflicts are recognized through this procedure, engineering designs are evaluated for mitigating solutions, which are then applied. It is through this process that we hope to achieve maximum sensitivity of design and construction to the environment and, thereby, acceptance from the public sector.

There are obvious potential conflicts, particularly from New Haven to Boston along the coastline, where the catenary structures will cause aesthetic intrusions into the natural background. However, it is hoped that, since they are documented in the environmental impact statement, the advantages that will result from implementation of the electrification, such as providing a source of power that is independent of the availability of one type of fuel and reducing the air, noise, and vibration pollution, will be sufficient, on balance, to carry this project forward.

The basic electrification program is also contingent on other designated subsystem improvements. Curve realignments are necessary to achieve the maximum speeds, which in turn are dictated by the travel-time goals. Increased superelevation, spiral-length increase, and curvature-reduction requirements will cause shifts from a few centimeters to a meter or more to be made on selected curves.

Between New York and Washington, problems in the implementation of this program are particularly acute because of the proximity of the existing catenary poles to the track. Staged construction for this type of structure relocation is of prime importance in the current design and scheduling process. The information above on cost factors noted the significance of the impact of electrification on the signal systems. This is not of major design concern between New Haven and Boston because the age and condition of the existing signal system make it only sensible to replace the entire subsystem with new centralized traffic control facilities. The new track circuits will be designed to be compatible with the electrification system and can be independently installed while the existing system continues to function. Between New York and Washington, however, almost all track circuits will require modifications of the necessary hardware for compatibility with 25-kV 60-Hz propulsion. This represents a major cost and, more importantly, a very complex installation process.

Forty-nine overhead bridges, most of them between New Haven and Boston, require increased overhead clearance. Several of these, for example, those near South Station in downtown Boston, cannot be raised and may therefore cause a stretch of track to be lowered by as much as 0.6 m (2 ft). Several others may be adjusted in conjunction with the track undercutting program. The New York tunnels will require approximately 50 mm (2 in) of additional air-gap clearance for the installation of 25-kV lines. At this point in the engineering investigation, it appears that this may be achieved through lowering the track while implementing the necessary track rehabilitation program in the tunnels.

The electrification program also creates additional requirements for support facilities. The equipment-servicing facilities must be designed to have electrified storage and running tracks that will be sufficient to accommodate the split of equipment now planned to handle 1981 service (75 percent locomotive-hauled trains and 25 percent self-propelled multiple units). Plans for the facilities and equipment to service and maintain such a fleet at Boston and Washington will soon be placed for final design.

Maintenance-of-way base track layouts and buildings are also being designed to accommodate the equipment and crews for substation and catenary inspections and repair. Performance specifications are now being developed for new, specially designed catenary maintenance and inspection vehicles. An important part of these efforts in the design process is the analyses of constructibility and the ordering of the phases of construction, especially in regard to the track use requirements. Although there is no doubt that both passenger and freight service will be severely degraded by the construction program from now through 1981, there must be practical limits on the location, frequency, and duration of the interruptions of service.

Attaining the project objectives is dependent on the efficient planning of the various stages of construction. All subsystem construction needs must be identified and then combined to the maximum extent possible. The installation of the new system between New Haven and Boston will be the least complex portion of the program, both because it is being built from scratch and because the freight and commuter service schedules are minimal, which allows the tracks to be taken out of service for longer intervals.

The portion from New York to Washington, with its dense commuter and freight operations, presents more of a problem for hardware rehabilitation, retensioning, and reprofiling of the catenary, since these operations require that the track be occupied by the service trains. In addition, it will be necessary to interrupt the power to provide for construction around power-supply areas, and this will require careful coordination. With these factors uppermost in mind, the construction phasing and scheduling group has examined each construction procedure for the possibility of off-track implementation.

Several overseas electrification construction programs have been able to use specialized on-track equipment to bore the foundation holes, pour the concrete, and erect the catenary poles. On this project, many of those operations will have to use off-track equipment and methods wherever possible. Such operations as erection of a cantilever assembly, headspan construction, stringing or clipping in the wire, and alignment adjustment require the use of the track, and it must be reserved for these operations. Basic construction scheduling is being approached at this point on the basis of these steps:

1. Establish the priorities for projects on the basis of trip-time enhancement in each of several operating segments.
2. Identify site-specific project elements that permit no alternatives to preemption of the track.
3. Establish durations of track preemption on the basis of unit productivity.
4. Schedule those interruptions of service so that the track is available for the maximum time possible.
5. Analyze these results and adjust the construction stages and procedures accordingly.
6. Repeat the process until all project elements are established within program goals.

To aid this effort over the shorter term, the Track-Access Simulator will be used. This consists, in essence, of using stochastic computerized simulation to test the construction schedule by quantifying the maximum extent of each train's schedule-time degradation, while also identifying other windows in track use that would be available for such things as logistical support of ongoing projects or routine on-track maintenance, such as correction of track geometry and catenary inspection.

Last but not least, phase-in and cut-over plans will have to be developed for the electrification program as it is constructed and becomes operational. It is certainly recognized that the conversion of existing rolling stock and delivery schedules for new equipment will play a large role in these future scheduling plans.

The Railroad Revitalization and Regulatory Reform Act set travel-time goals of 2 h 40 min between New York and Washington and 3 h 40 min between New York and Boston. Electrification plays a major role in reaching those objectives. The same act stipulates that these goals be met by February 1981 at a maximum cost of $1.9 billion. The plans for those working on the project are to have history record that the goals were achieved.

Comment

Per Erik Olson, ASEA, Inc., White Plains, New York

The cost for the eventual future conversion from 11 kV 25 Hz to 12.5 or 25 kV 60 Hz is based on the market projections of future traffic demands. The figures mentioned were based on 14-car trains every 15 min in both directions. In spite of the fact that the National Passenger Railroad Corporation (Amtrak) has recently been involved in efficient promotional activities, the statistics indicate that the 4 to 6-car Metroliners, operating at 60-min intervals along with the longer and slower trains, are not more than about 50 to 75 percent filled normally. A professional market follow-up is recommended.

As a general comment to the plans of converting the catenary system, I would like to mention that in Europe 32 000 km (20 000 miles) are electrified with 15-kV 16.66-Hz current, and there are no known plans to change this system. Projection of an eventual electrification of the U.S. railroads indicates that 13 000 to 16 000 km (8000 to 10 000 miles) is the most probable length. The track length already now electrified with 11-kV 25-Hz current in the Northeast Corridor is about 2400 km (1500 miles) and, if an increase in power is eventually necessary, it could, based on European experience, be made at a lower cost by supplying some extra inverter stations of a type now available that is based on solid-state technology. We generally have difficulty in understanding the need for 3000-MW power for the future Northeast Corridor network. By comparison, the total power installed in the Swedish State Railways network, which has an electrified track length of 11 000 km (7000 miles), is 285 MW, in spite of the fact that this network is very spread out—a total north-south distance of 2400 km (1500 miles).

To make an electrified railroad competitive with other means of transportation in the future, every effort has to be made to optimize the system approach and not to overbuild the installation so that the system can never be competitive.

Author's Reply

The reference to 14-car trains every 15 min relates, of course, only to the peak-hour service, and any comparisons must relate to existing peak-hour services.

A major benefit of the Northeast Corridor Improvement Project will be the extension of high-speed status to all intercity passenger trains, which is expected to generate a considerable increase in passenger travel in major corridor segments. The increase in capacity of the power supply in the Northeast Corridor is just an incidental part of the main task of replacing all the existing 25-Hz installations in order to achieve the reliability objectives of the Railroad Revitalization and Regulatory Reform Act. The overall cost for a replacement 25-Hz system is much greater than the cost for a new 60-Hz system. Conversion of the European networks operating at 15 kV 16.66 Hz is not likely to be considered as long as the fixed installations continue to be operationally satisfactory without excessive maintenance cost.

The prospective increase in capacity of the electrified power-supply system for all routes south of New York is from the existing 240 MW available to about 325 MW in 1981 and to about 465 MW in 1990. This is comparable to the 320 MW that were available in 1970 before the recent failures and retirements of obsolete generating equipment. This larger capacity is required by the increase in train-kilometers and by the considerable increase in power demand caused by high acceleration rates and cruising speeds and by an increase in heating and air-conditioning loads. Some increase of capacity will be required between New York and New Haven, and new power-supply installations are required for the extension of electrification from New Haven to Boston, but the total capacity would be less than 700 MW rather than the 3000 MW suggested by Olson.

The Swedish State Railways, which travel fewer annual train-kilometers and have lower train densities, acceleration rates, and cruising speeds than the proposed eastern U.S. electrified network, would naturally require a lower power-supply capacity. Present work on redesigning the Northeast Corridor electrification systems is being undertaken on the basis of optimized system design that is consistent with cost-effective selection of electrical equipment. Funding constraints do not provide any opportunity for constructing excess capacity beyond the levels essential for normal and emergency-feed requirements on this high-density line, which includes several commuter-train networks and substantial freight-train operations.

Utility Service to Electrified Railroads

Blair A. Ross, American Electric Power Service Corporation, Lancaster, Ohio

During the past decade American railroads have expressed considerable interest in electrification, but no major electrification commitments have been made except for the extensions in the Northeast Corridor.

It is assumed that a railroad operation of significant size will be served at 60 Hz and probably either 25 or 50 kV. The economic advantages and proven performance of the 25 to 50-kV commercial-frequency power-delivery system appear to favor this type of service for future electrified operations. This assumption is supported by a number of North American and foreign technical and economic studies.

When the supplying utility develops a service proposal for prospective railway service, it must consider the electrical characteristics of the railroad load; the effects of the new load on the utility's facilities; the effects of the load on other customers of the utility; the direct and indirect costs and investments required to serve the railway; and the regulatory, rate, contractual, and billing considerations involved in meeting the railroads' service requirements. The electric railway load has several service characteristics that are unique in regard to cost of service and technical aspects. The service agreement with the railroad must recognize and resolve the economic and service aspects of the railroad's electrical needs in a manner that is acceptable to the railroad, the supplying utility, and the interested regulatory agencies.

IMPACT ON THE UTILITY SYSTEM

The railroad's power demands affect the utility system's phase balance and voltage, voltage dips, possible parallel ties with utility facilities under certain service conditions, feedback harmonics, and ground return effects. The reduction of the electrical effects to technically acceptable levels may in many cases involve substantial investments on the part of the utility system or changes in the location or characteristics of the electrical service facility.

Phase Unbalance

The single-phase railroad load, which is never perfectly balanced because of train diversity, imposes an unbalanced load on the utility system, particularly on the line or lines from which the single-phase load is fed. This unbalanced loading creates negative phase-sequence currents, which have a more serious effect on generating equipment than on any other utility apparatus. The amount of negative phase-sequence load that a generator is capable of carrying is principally a function of the heating of the slot wedges and rotor body ends. Depending on their design and the length of time they are subjected to an unbalanced load, generators can absorb varying amounts of negative phase-sequence currents. American equipment manufacturers have published data indicating that, operating at rated voltage and rated load, generators are capable of carrying a 5 percent negative phase-sequence current continuously. British and Japanese design permits up to a 10 percent negative phase-sequence current, although in neither country has the amount of unbalanced loading resulting from railway electrification exceeded 5 percent.

Since the power demand from the railroad would be connected to the overall transmission system, the negative phase-sequence currents would affect different generators in different amounts; those electrically closest to the supply points would be subjected to the larger amount of unbalance. Computer programs are available to translate train movements into power demand in kilowatts. Their use can permit the design of an electrification system that can keep the phase unbalance from exceeding the allowable limit by proper sectionalizing and selecting the correct transformer size.

The computer can be programmed to read out the railroad's power demand by substation locations and by selected time intervals, both for normal railroad operation and for abnormal operations, such as after derailments. Thus, the maximum demand, maximum unbalance, and the time of either or both can be determined. These may or may not normally occur simultaneously and may or may not coincide with the peak load for the utility system. To determine whether the phase unbalance exceeds the limits, the railroad load pattern must be compared with generating schedules at all times of the day.

Voltage Unbalance

The single-phase railroad load can cause voltage unbalance between phases that can overload or damage three-phase equipment that belongs to other customers or the utility. The unbalanced voltage is most troublesome to polyphase motors, in which it can cause overheating. Although the standards of the National Electrical Manufacturers Association give no permissible limit for unbalance, a 5 percent unbalance is generally recognized as the tolerable maximum. Foreign practice has been to limit this unbalance to 3 percent, except in France, where higher limits (in some cases as great as 7 percent) have been allowed in rural areas. From a technical viewpoint, the primary effect of the unbalanced voltage appears to be the probable, but unproven, loss of life to the customers' motor insulation.

Voltage Dips

The sudden impact on electric demand posed by a heavy train can cause an objectionable dip in voltage levels on the supplying utility system. This objectionable dip generally occurs when the train crosses a phase break. The problem has been encountered in Japan and France, but in most cases the system's short-circuit capacity that is required to correct for the effects of phase and voltage unbalance will also correct for sudden dips.

Phase Breaks and Parallel Operation

To limit the effects of phase unbalance a utility will generally place adjacent railroad substations on different phases. This method of service, known as the center-feed system, has the advantages of providing the best distribution of the railroad load between phases and of avoiding the establishment of a single-phase tie between two points on the utility system. A phase break is generally established midway between the supply substations.

Although it is very desirable from the viewpoint of the utility, the center-feed system presents a major disadvantage for train operations when the phase break between substations occurs on a major grade. When freight locomotives are working at maximum output, e.g., on a steep grade, the loss of power to each locomotive unit as it crosses the phase break would create momentary changes in tractive effort that would produce objectionable slack actions in the long freight trains.

These momentary changes in power would inevitably cause trains to break in two. Therefore, if a grade is too long to be supplied from a single substation, it may be necessary to operate two or more adjacent supply points in parallel that are served from the same phase, despite the problems presented to the utility system. The French National Railways operates several stations in parallel as standard practice, and this apparently has not caused significant power-system problems. The principal advantages to the railroad's power-delivery or catenary system of tying adjacent supply substations together with a transformer at each end are that

1. Current loadings on the catenary system are reduced, thereby decreasing the chances of voltage drops and system losses;
2. In case of a transformer or transmission-line outage, supply continuity is assured, whereas under the center-feed system there is a short dead period while the associated automatic transfer switching is taking place; and
3. The objectionable effects of phase breaks are moved to a location where the voltage is at its maximum strength rather than at its weakest.

Many of the objections to the establishment of a parallel point-to-point tie with the utility system can be eliminated if proper relaying and fault-sensing equipment is installed.

Harmonics

The harmonics generated by locomotives with silicone-controlled rectifiers, although they present notable problems to railroad signal systems, are as a general rule effectively reduced by the natural system capacitance to a point at which they do not affect the facilities of the utility. French and British experience has confirmed that harmonic effects are minor in nature and that they have not affected the apparatus of the utility or of other customers.

CHARACTERISTICS OF RAILROAD POWER DEMAND

At today's traffic levels, the electrified railroad's power demand presents potential national energy requirements of 72 to 108 PJ (20 to 30 billion kW·h). At the level of 27 Tg (30 million gross tons) annually that is generally considered sufficient to justify electrification, annual energy requirements of 1.75 to 2.25 TJ/km (800 000 to 1 000 000 kW·h/mile) may be anticipated.

Assuming the approximately 32 000 km (20 000 miles) that today carry about 60 percent of the nation's rail traffic undergo electrification, the railroads will create an annual demand for about 72 PJ (20 billion kW·h), with a peak national demand of about 3000 MW. Traffic growth could increase this market to more than 108 PJ (30 billion kW·h) on the same 32 000 km of track. In the nation as a whole, the demand imposed by railroad electrification will probably be less than 1 percent of the national peak demand.

The demand of a typical 800-km (500-mile) railroad in the country with occasional short gradients of 0.5 percent or less is estimated to be from 80 to 120 MW for a single-track line and from 140 to 180 MW for double-track lines. Main-line grades of more than 1 percent may result in demands as great as 100 MW in an electrified zone of less than 160 km (100 miles). In planning the electrification of operations with grades, care must be taken to coordinate the amount a train is hauling and the operating schedules with the general demand on the electric system.

Typical railroad load factors improve as the length of track electrified increases and, therefore, as the number of supply points increases. An 800-km electrification project might be served from 15 to 30 delivery points, depending on the voltage of the catenary and the operating conditions. Load factors on lines that have sufficient traffic density to justify electrification have varied from 55 percent to more than 70 percent for a 650 to 1000-km (400 to 600-mile) double-track route. The power factor for railroads served by several delivery points will be a lagging factor of 0.85 to 0.90.

The impedance of the catenary system will, in most cases, limit the supply capability of 25-kV catenary system stations to 25 to 35 MW and of 50-kV stations to 40 to 50 MW. Power factors may vary from as low as 10 percent, under the most adverse starting conditions with only one train in the service section, to as high as 85 to 90 percent. In recent studies, the load factor of individual stations has been found to range from 10 percent to slightly more than 40 percent.

Railroad officials indicate that there will probably be two or three 6-MW (8000-hp) locomotives per train. On level track, each 6-MW locomotive would be capable of moving about 2 Gg (2450 tons) at 130 km/h (80 mph) or 3.5 Gg (3800 tons) at 105 km/h (65 mph). Maximum train demands of 25 to 30 MV·A may occur when 7 to 9-Gg (8000 to 10 000-ton) freight trains are operated at speeds of 110 km/h (70 mph) and more. The average use of energy by a train depends on speed, frequency of speed changes or stops, acceleration rates, and the grade. Recent studies indicate that the average requirement is 60 to 75 kJ/Mg·km (25 to 30 kW·h/1000 ton-miles).

The electric locomotive that is expected to provide power in the 1970s and 1980s will be a six-axle, six-motor locomotive that has a solid-state rectifier and 6 to 9 MW of power (8000 to 12 000 hp). The locomotive will present a power demand at the pantograph that is about 20 percent greater than its rail power and a capacity demand of 8 to 12 MV·A. The modern locomotive with a solid-state rectifier operates at a lagging power factor that varies from less than 10 percent standing still to 85 to 90 percent at maximum power output.

RAILROAD SERVICE REQUIREMENTS

The service requirements of railroads with respect to service reliability and regulation of voltage are comparable to the requirements of most industrial customers. Railroads can generally tolerate power interruptions of short duration (up to 60 s); this will permit motor-operated air-break switches to operate without adverse effects. Therefore, in most cases, the use of automatic air-break switches and sectionalized power lines should provide an adequate quality of service.

Railroads can also tolerate considerable variations in the supply of voltage without adverse effects. As a general rule, voltage regulation that is acceptable to other customers will be acceptable for railroad loads. In the few instances in which this is not the case, load-tap-changing transformers at the supply substation provide a technical solution.

Rates and Service Arrangements

Service considerations and arrangements for providing power to electrified railroads will be influenced by economic conditions, policies of the railroads and utilities, regulatory and legal considerations, facility costs, contractual requirements, and rate structure and billing considerations. Following are some thoughts and suggestions that may serve as guidelines to assist in developing service agreements.

As a general rule, railroads have a poorer load factor than the average utility customer. This is especially true if each substation is treated as an individual billing or metering point. Unless regulatory approval can be secured to provide special treatment for railroads by considering the impact on the overall system rather than on the individual delivery point, the development of appropriate electric service rates may present significant problems.

Since, unlike the demand of conventional industrial customers, the railroad's demand point moves with time as the trains move from substation to substation, the development of service arrangements equitable to both the railroad customer and the supplying utility may require a departure from the usual practices and concepts of utility service and pricing.

Costs related to providing the railroad's power requirements are incurred in four major areas. The railway service tariff must be designed and applied to recover costs in the areas of

1. Energy (principally fuel and production expenses), including provision for losses to the utility system as a result of single-phase loads;
2. Demand, including some type of minimum demand and careful selection of the billing period (e.g., 15 min, 1 h), as well as consideration of the time and duration of peaks if extensive commuter or passenger operations are involved;
3. Dedicated utility facilities (i.e., charges associated with new utility facilities, such as transmission lines or switchgear required exclusively for service to the electrified railway); and
4. Other utility expenses, which should be covered by a separately stated charge that provides for automatic or periodic adjustments to cover changes in such costs as fuel, labor, materials, services, taxes, and interest (as far as is permitted by applicable utility regulatory agencies and legislation).

Contractual Arrangements

The railroad electrification service contract must be a long-term agreement (20 years or more). The contract should include appropriate cancellation provisions and provision to reduce the power costs if there are improvements in the load factor and power factor. In general, the contract should be comparable to other power service contracts with large industrial customers in order to avoid difficulties in securing regulatory approval.

A major electrification project will usually involve securing electric service from a number of different utilities. Because of franchise and other considerations related to the different service areas (including, in most instances, different regulatory agencies), the cost and details of service will differ among individual utility suppliers. Because of variations in the number of supply points, differences in the financial structures and costs of the utility systems, and differences in railroad load factors and effective railroad load diversity, the separate tariffs negotiated with a single railroad by individual utility suppliers will not, in all probability, be identical in structure or price level. At the same time, it would be desirable for all service agreements to be similar in format and general billing procedures.

A significant obstacle to the establishment of uniform procedures for railroad service by a number of utilities is the possibility that any concerted action taken by several utilities to establish uniform service procedures might raise questions about antitrust activities.

THEORETICAL COST OF SERVICE

The development of a theoretical cost for electric service involves the major components of the service rate and their anticipated typical costs. It must be recognized that actual service costs will be greatly influenced by major variations in construction costs, capital structure, cost of capital, fuel costs, differences between public and investor-owned utilities, allowable rates of return, the rates (under existing industrial tariffs) to which the rail service rate must be compared, system operating costs, and characteristics of the service area and load.

This simplified analysis includes estimated costs for new generating capacity, transmission system, fuel, and other utility costs. The actual cost of generation may be reduced if there are existing facilities to which greater capacity is added, but this varies. Likewise, the allowable rate of return, tax, and debt-equity ratio components of the assumed 18 percent carrying charge will actually vary from 14 percent to 22 percent or more.

1. Fuel costs (coal-burning plant). If the plant's power production is 23.3 MJ/kg (10 000 Btu/lb) of coal and its heat rate is 2.75 MJ/MJ (9400 Btu/kW·h) with a transmission system loss of 7 percent and coal costs of $22/Mg ($20/ton), then the fuel costs are 2.78 mils/MJ (10 mils/kW·h).
2. Capital investment carrying charges. Assuming the cost for a coal-burning generating unit for service in 1982 is $550/kW—the Federal Power Commission (1) has estimated $574/kW and Northern States Power Company, in its first quarter 1977 report to its shareholders, estimated $544/kW for units to be placed in service in 1981 to 1983—with an 18 percent carrying charge on the utility investment and a reserve factor of 15 percent as well as an investment in the transmission system of $100/kW with the same 18 percent carrying charge and a 60 percent load factor for the railroad, then the total investment cost is 6.94 mils/MJ (25 mils/kW·h).
3. Administrative and general expenses. Assuming the administrative and general overhead expenses run about 3 percent of the fuel cost of 2.78 mils/MJ and the investment carrying charge of 6.94 mils/MJ, then these expenses amount to 0.28 mils/MJ (1 mil/kW·h).
4. Total cost for delivered power. Adding the fuel cost, the investment carrying charges, and the administrative and general expenses gives a total cost of 10 mils/MJ (36 mils/kW·h) delivered to the railroad substation.

CONCLUSIONS

When limitations with respect to voltage unbalance and single-phase loading are observed, a railroad's single-phase load can be served without harmful effects to the utility system's generating or utilization equipment that is currently in service. The provision of a supply of electricity to the mobile loads of a single railroad at a number of different locations, in most cases by several utility companies, poses a number of problems concerning rates, regulatory tariffs, and legal obligations that have not previously been encountered by American utilities.

The electrification of North American railroads requires a recognition of both utility and railroad problems and a willingness on the part of utilities, railroads, and government to consider all the issues involved. These issues include changes in operating techniques and new concepts with respect to rate structures and contractual arrangements.

REFERENCE

1. Factors Affecting the Electric Power Supply, 1980-1985. Federal Power Commission, Dec. 1, 1976.

Canadian Railway Electrification Study: Phase 1

E. R. Corneil, Canadian Institute of Guided Ground Transport, Kingston, Ontario

The Canadian Railway Electrification Study was commissioned by the Railway Advisory Committed and funded through the Canada Department of Transport's Transportation Development Agency to (a) bring into sharper focus the time frame in which it might be expected that electrification of significant portions of Canadian railways is likely to occur and (b) develop and describe a program of investigation, research, and development designed to permit a smooth transition to effective electrified operation at that time.

It was not intended that the study resolve the question of whether electrification will, or should, take place; the terms of reference required the presumption that it will occur at some future time. However, the study has provided considerable background information that would be necessary to make a decision concerning rail electrification, and it aids in identifying additional studies that would be necessary to such a decision. The study examined a number of factors, including

1. The future supply and costs of hydrocarbon fuels for railway operations in Canada;
2. A comparison of the technical features of diesel-electric and electric locomotives, including a comparison of capital and operating costs;
3. The future supply and costs of electric energy for railway traction;
4. The technical and cost features of high-voltage overhead catenary;
5. The effects of inductive interference on signaling and communication systems, including a discussion of the nature of the interference and design factors that affect the degree of interference generated;
6. System operating considerations;
7. The requirement for an operational prototype for the Canadian situation;
8. An economic evaluation for a specific, but typical, 650-km (400-mile) segment to determine the importance of numerous factors on both the financial return and the optimum timing for electrification;
9. An examination of rail traffic volume, with projections for the future for main-line track of both the Canadian National Railways and the Canadian Pacific Ltd. and the development of a possible implementation sequence for electrification of roughly 15 300 track km (9500 track miles) over a 30-year period;
10. Identification of some implications of rail electrification;
11. Consideration of the scale and nature of the capital financing required for electrification and its impact on the Canadian economy; and
12. Identification of the additional study necessary to resolve both technical and financial questions and the steps and time required to complete a prototype operating system.

ENERGY SUPPLY AND COST

If the future supply of diesel fuel to the railways could not be guaranteed, then the requirement for electrification of the rail network would become essential. This presumes that the railways continue to be an essential part of Canada's transportation system, that alternative railway fuels (such as hydrogen or coal-derived products) are not available, and that an adequate supply of electric energy is available.

After reviewing statements concerning petroleum supplies in Canada and allocation policies of the federal government, we concluded that Canadian railways will not be crippled by a lack of diesel fuel within the next 50 years. However, on the basis of limited world petroleum supplies, and the projections of crude oil prices, as shown in Figure 1, we must conclude that the relative price of petroleum-based fuels will rise faster than the general inflation rate would suggest. The projected world oil price suggests a price escalation rate 4 percent greater than the general inflation rate. This would lead to the projected diesel fuel costs shown below in terms of 1975 Canadian dollars (1 L = 0.26 gal).

Year	Cost ($/L)	Year	Cost ($/L)
1980	0.163 to 0.205	1995	0.297 to 0.372
1985	0.198 to 0.249	2000	0.361 to 0.454
1990	0.242 to 0.304		

In Canada, electricity is provided by provincially owned or regulated supply authorities. Each supply authority establishes its own price structure. Naturally, the demand load factor (the average demand divided by the peak demand during, for example, a 30-min period) will significantly affect electric costs. Hence, to provide a reasonable picture of the comparative costs shown in Table 1, we assumed a 650-km segment of track carrying 18 gross Tg/year (20 million gross tons/year) with substations at 65-km (40-mile) intervals, an energy consumption of 11.7 kW/gross Gg·km (17.1 kW/1000 gross ton-miles), and a power factor of 85 percent. As traffic levels increase, the load factor increases, thereby reducing the unit energy cost.

Rather than using individual substation metering, the possibility of system metering has been considered. This would involve connecting individual substations to a railway-owned distribution line from a single supply authority. Significant improvement in the load factor is possible, accompanied by a consequent reduction in the unit energy cost, as shown in Table 1.

Projections of the electric authority's generation capacity and the electrified railway's electric demand reveal that the railway load will be a relatively small portion of the total generation capacity. The annual growth of electric demand averages 6 to 7 percent for all of the supply authorities considered. As the table below illustrates, the railway demand might be considered significant only for Calgary Power, since the rail electrification would be spread over several years, there being a roughly 5-year construction period before the first impact of the demand.

Utility	Average Demand in 2000 (MW)	Percentage of Generating Capacity
Hydro Quebec	84.0	<1
Ontario Hydro	273.0	<1
Manitoba Hydro Electric Board	95.0	2
Saskatchewan Power Corporation	151.0	6
Calgary Power Ltd.	479.1	14
British Columbia Hydro and Power Authority	504.8	8

Calgary Power and Alberta Power both supply electric energy to the province of Alberta through an interconnected system. Although in Alberta the candidate rail lines for electrification lie solely within the distribution area of Calgary Power, the interconnection of supply authorities would reduce the importance of the rail load on the Calgary Power system.

Projections of the price increases for electric energy reveal that the strong base provided by hydraulic and coal-based power generation and the continued development of efficient nuclear and coal-fueled power generation will result in a price-escalation rate that is lower than that for petroleum-based fuels. The need to conserve petroleum fuels, which are used for domestic and commercial heating, demands that the price escalation of electric energy be slightly less than that of petroleum fuels.

LOCOMOTIVES

We examined the design and performance aspects of the electric locomotive in detail, considering the similarities and differences between the electric and diesel-electric locomotive. Significant improvements in the North American diesel-electric locomotive are possible, and current developments will provide units that more closely match the performance of the modern electric locomotive. The performance of modern European electric locomotives is outstanding. However, the lighter axle load, lesser maintenance requirements, and other features of the European electric locomotive would make it unsatisfactory for Canadian service. We concluded that current electric locomotives built in North America could be used in Canadian service but that all available units are a long way from the optimum. However, it is clear that a unit designed specifically for the Canadian application could be built today.

Improved train performance is commonly claimed for electrically powered trains on the basis that they provide greater power per unit of train mass. Figure 2 illustrates the importance of adhesion to the tractive effort and the use of power for various axle-power ratings. Curve a, with an adhesion of 40 percent, roughly represents the maximum adhesion available with good track conditions and suitable locomotive design. Curve b (28 percent) represents a more realistic scheduled speed for a well-designed electric locomotive. There is an indication that adhesion decreases with increasing vehicle speed.

Figure 1. Projected prices of crude oil.

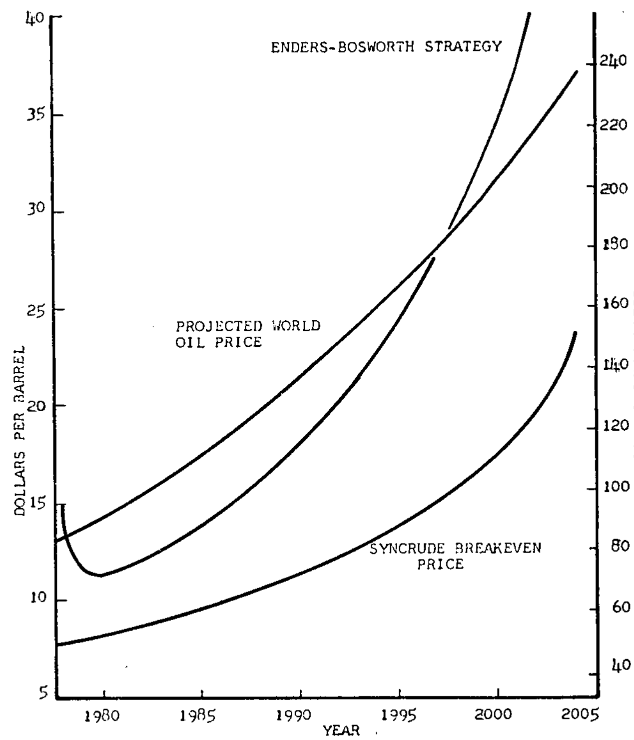


Table 1. Unit energy costs for various load factors under individual substation metering and system metering.

Load Factor (%)	Hydro Quebec[a]	Ontario Hydro[a]	Manitoba Hydro Electric Board	Saskatchewan Power Corporation	Calgary Power Ltd.	British Columbia Hydro and Power Authority
Substation metering						
25	0.65	0.69	0.60	0.64	0.84	0.72 to 0.81
20	0.79	0.82	0.70	0.68	0.99	0.88 to 1.01
16.7	0.92	0.94	0.80	0.73	1.14	1.04 to 1.21
14.3	1.04	1.07	0.90	0.77	1.29	1.20 to 1.41
12.5	1.17	1.19	1.00	0.82	1.43	1.36 to 1.61
11.1	1.31	1.32	1.10	0.86	1.58	1.52 to 1.81
10	1.45	1.44	1.20	0.91	1.73	1.67 to 2.01
System metering						
50	0.36	0.44	0.40	0.35	0.46	0.40
33.3	0.47	0.57	0.50	0.43	0.61	0.56
25	0.59	0.69	0.60	0.47	0.76	0.72
20	0.70	0.82	0.70	0.52	0.90	0.88

Note: All values except load factors are expressed in cents/megajoule (1 MJ = 0.27 kW·h).
[a] Price may be slightly lower depending on the high-voltage feed level.

This is a function of track characteristics and locomotive suspension design. Curve c attempts to illustrate this effect of speed.

Note on curve c that a 635-kW axle can produce full power at speeds exceeding 34 km/h (22 mph). However, a 1500-kW axle cannot produce full power until the vehicle's speed exceeds 96 km/h (60 mph). Diesel-electric locomotives can also provide this improved performance, if that is an objective of train scheduling. Improved wheel-slip controls can raise the adhesion levels of diesel-electric locomotives to values that are only marginally lower than the adhesion levels achieved by the finest of electric locomotives. However, the diesel locomotive will continue to be restricted in power per axle to a level that may be below the optimum for most Canadian operations. The electric locomotive, on the other hand, will not be power restricted.

After reviewing the design aspects of the catenary system, including the consideration of materials, we recommended the use of the British Insulated Callender's Construction Company Ltd. catenary, illustrated in Figure 3. The proposal includes a copper contact wire with an aluminum cable steel-reinforced (ACSR) messenger wire, and an ACSR ground return wire on the mast. The operating voltage would be 50 kV, with 25-kV operation in restricted areas, such as tunnels. The power capacity of the standard catenary system would be up to 45 MW, with a substation supplying up to 90 MW in a center-feed connection. Mast material would be selected on the basis of price and local conditions. A mast setback of 3 m (10 ft) from the center line of the track, with an increase to 3.7 m (12 ft) on severe curves and in areas of heavy snowfall, was recommended.

Kendall's paper in this report discusses signaling and communications. He provided much of the background information on this topic for our report. We examined sources of interference, results of interference, and their effects on equipment selection.

SYSTEM OPERATION

Electrification does not imply that diesel-electric locomotives will disappear. Local operations and branch-line operations will be diesel powered. The conversion to electrified main-line operation would occur at a pace that would preclude the necessity of scrapping or selling diesel units.

Because of the relation between power and adhesion requirements for electric locomotives on most main-line tracks, the train power would exceed 820 W/Mg (1 hp/ton), and in most cases it would correspond to the level currently used on express trains. Simulations reveal that train schedules for a variety of typical trains would be almost identical. Electrically powered trains would operate with the same track speed limits and the same downgrade restraints. On climbing grades, the greater power would reduce the schedule time required. The more uniform operation would permit some increase in track capacity.

The power demand of a typical train over a typical terrain, using the European control strategy, is shown in Figure 4. The variation in electric demand will cause problems for the supply authority. The variation of single-phase load on the utility's three-phase system can create a phase imbalance. The severity of the problem depends on connection techniques, significance of the load, and the control strategy.

The electric locomotive can draw full power only after it attains a relatively high speed. The power to an individual locomotive can be limited by a central dispatcher using carrier signals. This would allow a central dispatcher to control the system's power demand without seriously degrading train performance, thereby achieving significant savings in power costs. Although this central control would seem undesirable to members of the Canada Department of Transport, we believe that it can be shown, by simulation, that applications of central control would not usually be noticed by train-operating personnel.

The lack of an internal combustion engine would reduce the cost of locomotive maintenance in an electric operation. Also, the weight of the electric locomotive per unit of power is less, and the total weight carried by the track would typically be reduced by 3 to 5 percent. This can reduce track maintenance costs. The reduced energy and maintenance costs and the greater reliability of operation provide added incentive for electrification. The increased capital cost and the costs of catenary maintenance tend to offset the cost advantages indicated above. Repair after derailment would become more complex.

ECONOMIC EVALUATION

The cost implications of rail electrification require a relatively sophisticated economic analysis to identify the effects of time, traffic growth, capital and operating costs, and so on. As a preliminary step toward economic evaluation, it was necessary to develop traffic projections for each segment of main-line track. The relatively long span of time involved (approximately 30 years) required the identification and evaluation of long-term factors. Population trends, resource development, and historical rail traffic records were considered in developing the projections. Figure 5 illustrates a typical

Figure 2. Locomotive adhesion for various axle-power ratings.

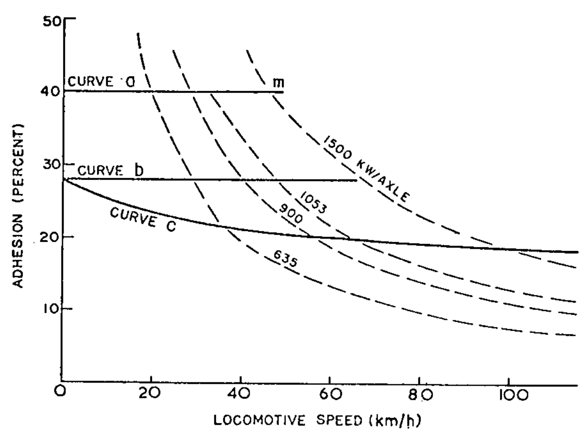
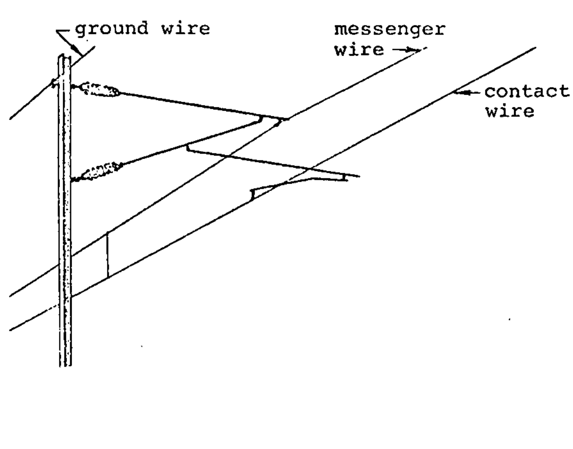


Figure 3. Sagged simple catenary with steel column masts.



traffic projection for a specific track segment. Note that the study projection is conservative, compared with the projection used by the railway for planning purposes. This was true of all study projections used.

Further detailed consideration of a 650-km track segment included simulations of train performance, actual train patterns over a 1-year period, derailments and other traffic restrictions, and a survey of modifications to physical structures that electrification would require. From this detailed information, the cost figures shown below were generated. As has been discussed in detail in the full report, the costs are derived from long-term intercept values; note that the fuel and energy costs are not expressed strictly as 1975 prices. The annual operating costs were as follows.

Item	Cost ($000)
Savings	
Diesel fuel	7 943
Diesel maintenance	4 008
Track maintenance	336
Subtotal	12 287
Costs	
Electricity	5 013
Electrical maintenance	908
Catenary maintenance	1 000
Subtotal	6 921
Total annual cost savings	5 366

The initial capital costs were as follows.

Item	Cost ($000)
Costs	
Electric locomotives	13 932
Fixed plant (catenary, signaling maintenance facilities, and so on)	75 869
Planning	5 000
Savings	
Diesel locomotives	15 120
Subtotal	94 801
Total initial capital costs	79 681

The cost of a locomotive fleet for a different traffic mix is based on a detailed analysis of locomotive cost estimates provided by General Motors. It is interesting to note that the capital cost of the locomotive fleet is essentially independent of the locomotive type, as illustrated below.

Type of Locomotive	Number of Axles	Number of Units	Unit Price ($000)	Total Cost ($000)
Diesel units	6	40	560	22 400
Low-power electric	8	16	1167	18 672
High-power electric	8	15	1447	21 705

This is specific to the particular terrain characteristics, which include controlling grades of more than 1 percent, and a higher concentration of eastward traffic load. On most other segments, the capital cost of an electric fleet would tend to be lower than that of a diesel-electric fleet because the high-powered locomotives would be more effectively utilized.

Financial aspects were examined in a general way only, since the pertinent parameters for any given railway link depend on regional and local conditions. At the scale of investment that electrification implies, commercial viability must be judged on the specific terms of the corporate institution considering the investment.

Methodology

The research involved development of a methodology rather than a determination of the commercial viability of electrification. Within this methodology, the direction and relative magnitude of the impact of variations in selected cost and financial parameters were examined. The economic valuation procedure explores the basic premise that, under conditions of increasing real prices of petroleum in relation to other energy sources and of increasing traffic densities, eventual electrification of a substantial portion of the Canadian railway system would seem inevitable. The optimal timing for such a conversion will be dictated by projected changes in current operations and the values of financial parameters.

Figure 4. Typical power demand at the substation.

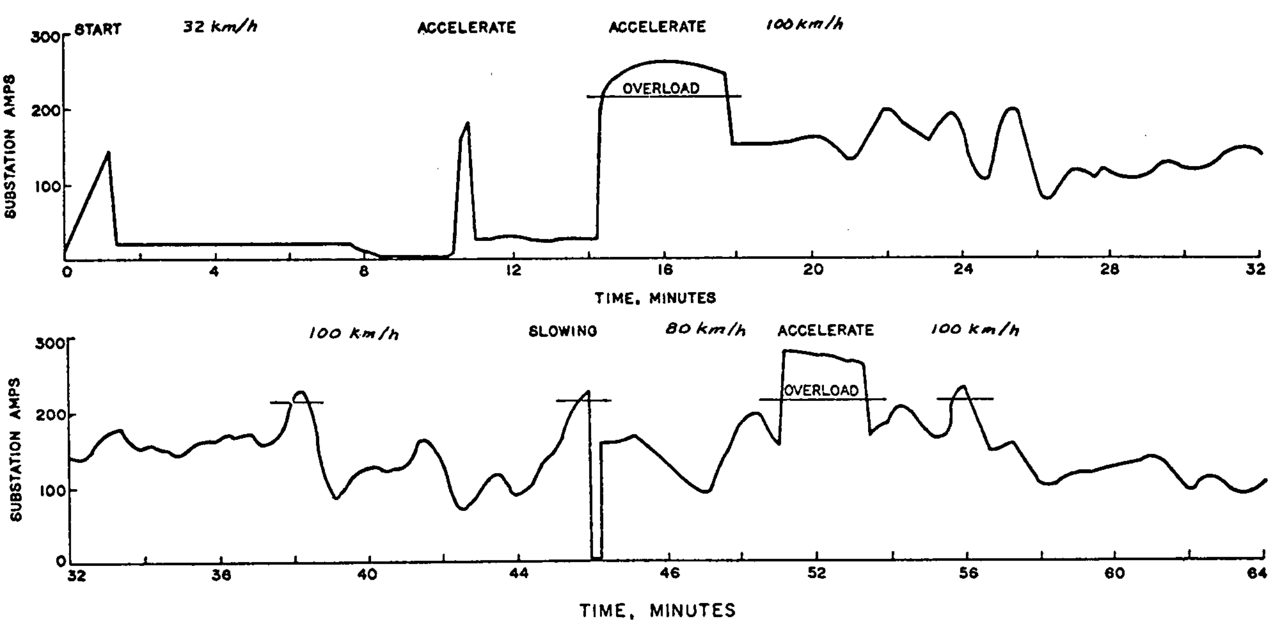


Figure 5. Typical traffic projection for a track segment.

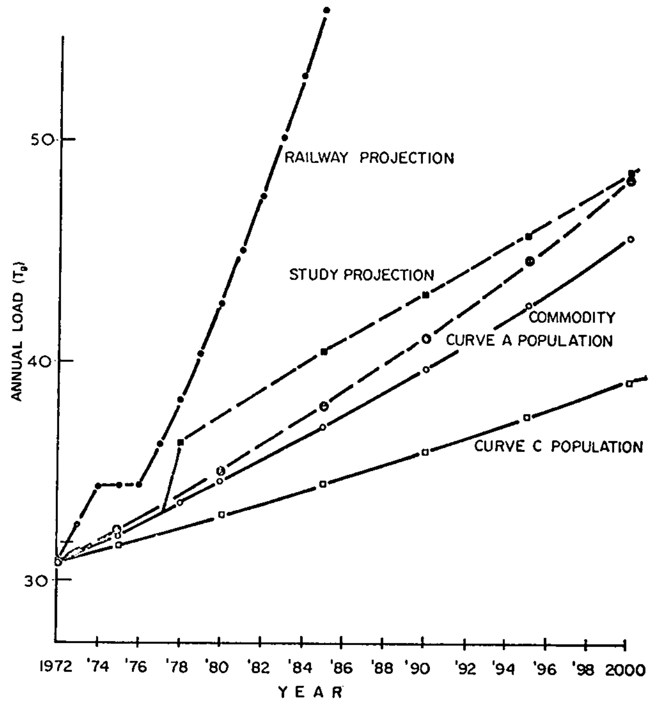
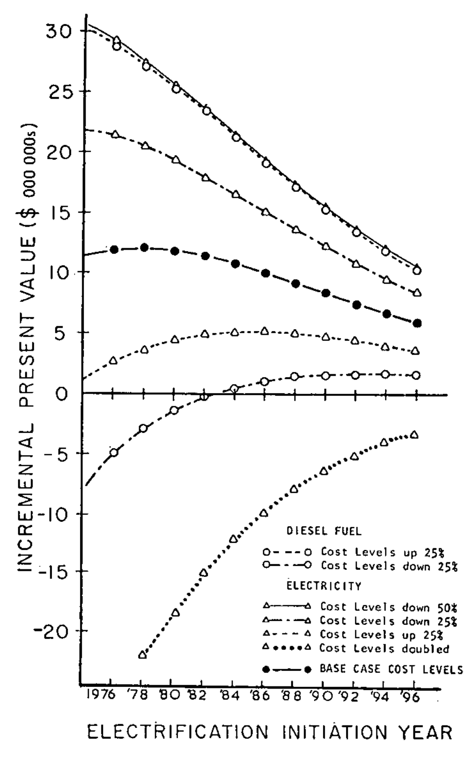


Figure 6. Effect of variations in energy cost and year of initiating electrification on the incremental present value.



Since available discounted cash-flow methodologies do not address themselves adequately to these aspects, it was necessary to develop a new valuation model that incorporates differential cost escalation and traffic growth. The model calculates an incremental present value (IPV) of cost savings.

The value of the gross savings from electrification that accrue to the railway company may, however, be greater or less than the simple IPV calculated by the model. There are a number of factors that are not addressed in the analysis. The most important of these concerns the distinction between first-order direct-cost savings and incremental advantage to the railway. No account is taken of the impact that electrification would have on the firm's marketing policies, rate structures, and overall financing costs or of indirect costs and savings that may accrue to other areas of the firm as a result of electrification. Thus, it is important that evidence of a clearly positive IPV not be interpreted to imply that the railway companies should embark on an immediate program of electrification.

The parameter groups investigated include financial parameters, parameters under control of the government, traffic characteristics, and some measures of cost escalation. In addition, sensitivity to base-price levels of individual components was examined.

Sensitivity to base levels of traffic volume is important in the selection of specific candidates for electrification since it implies that there is some traffic threshold beyond which electrification is attractive. With a base-year traffic level of 18 gross Tg/year (20 million gross tons/year), electrification within a few years would seem advantageous, while it appears that lines carrying substantially more traffic should be electrified immediately. The effect of a pattern or path of traffic growth is substantial. With low growth, the IPV would remain negative into the mid-1980s. On the other hand, very large initial growth levels that taper off more severely are characterized by a strongly positive IPV, and substantial cost is associated with delay.

Cost Escalation

The estimation of the impact of cost escalation on electrification is complex. Since they are determined by economic forces far removed from the corporate management, escalation rates are linked both to each other and to most of the other parameters of the model. Analysis was restricted to general parameter categories. In general, since the benefit from electrification is in savings in operating costs, increasing levels of cost escalation tend to increase the overall benefit. In addition, if there are higher escalation rates, operating cost savings of substantial magnitude are generated sooner, thus advancing the optimal timing for electrification. Similar effects are produced by a greater differential between the general cost-escalation rate and that applicable to operating cost components, e.g., diesel fuel.

Of all of the parameter groups investigated, prices of diesel fuel and electricity were found to have by far the most important impact on economic viability. Figure 6 plots the model's output for variations in the prices of diesel fuel and electricity. The base-case cost levels indicate the IPV of all the costs and savings over a theoretically infinite time period as a result of electrifying the hypothetical territory of 650 km. Each dot shows the IPV for a specific year in which electrification might be initiated.

Thus, for example, if electrification of this theoretical territory were initiated in 1978, the IPV for the entire stream of future savings, appropriately discounted, would amount to approximately $12 million. If electrification were deferred until 1996, the IPV of the future savings would be reduced to approximately $6 million. Thus, the methodology and model respond to the question of when might (or should) electrification occur. Obviously, from a savings standpoint, it should be initiated about 1980, if the base case used only included real input for a specific operating segment. It is apparent what would happen, however, if energy prices were to be different from those used in the base case. If diesel fuel prices were higher by 25 percent, electrification should begin immediately, and the indicated IPV would be in excess of $30 million.

Net savings in energy and locomotive maintenance provided the major component of operating cost savings, while catenary and other fixed-plant expenditures provided the major component of capital costs. Since catenary, transmission lines, and other infrastructure capital costs are location specific, they must be estimated individually for each candidate for electrification.

The results of the financial analysis clearly indicate that a positive equivalent-present-value cost savings can be attributed to the electrification of some segments of the Canadian railway system. The analysis also indicates however that, although an investment in electrification may be economically attractive (have a positive IPV) at 14 to 18 Tg (15 to 20 million tons), it might not be considered commercially attractive. The model can only evaluate the total benefits from cost savings. It cannot tell how they will be distributed. If strong consumer and political reactions left the railway with only a small part of its total traffic, the change might be in the national interest but unprofitable to the enterprise that would normally make the investment.

It is important to note that a major capital commitment may be a dangerously disproportionate burden if traffic drops or any one of a number of other factors becomes adverse. The burden accepted is immediate and relatively definite; the benefits are indefinite and distant in time. In effect, electrification exchanges the variable costs of fuel and labor for the fixed cost of conversion to electrification. This increases sensitivity to cyclical swings in traffic, as well as to defects in the traffic forecast, and therefore increases the risk of corporate vulnerability at times of economic downturn.

A PLAN

On the basis of the traffic projections and the economic analysis, a plan was developed to implement electrified operation on 15 300 km (9500 miles) of track over a 30-year period. Initially, the high-traffic lines, which carry more than 36 gross Tg (40 million gross tons) annually, would be electrified. Later, the threshold traffic level would decrease as the system expanded and electric operation was possible over increasing distances. The plan calls for an initial prototype operation, implemented on existing main-line track that currently carries substantial traffic. The many tasks required to implement such a prototype operation were identified, and a critical-path analysis was used to indicate bottlenecks and to eventually develop an estimate of the time required to implement the prototype. A minimum duration of 5 years, considering the severe constraints of the Canadian winters and the public participation required in certain decision steps, was projected.

CONCLUSIONS

Such a brief presentation cannot hope to cover the detail of a 764-page report. In the Canadian situation, it appears clear that the benefits of electrification will not be derived solely by the operating railways. Electrification would result in a reduced escalation of rail costs over the long term and would provide benefits derived from a reduced reliance on foreign oil, which suggests that rail electrification should be a joint venture of the federal government and the railways. The construction process, which involves a high proportion of relatively unskilled labor, would provide additional benefits during a period of high unemployment, such as the one we are facing at the present time. However, railway electrification is not a simple process. The long payback period makes the financial aspects less attractive.

Railways are faced with a number of alternative methods to increase rail productivity, and all they require is capital. However, we believe that North American railways can benefit significantly from rail electrification, in much the same way that other railways around the world have. On some rail lines, traffic is already approaching levels that justify electrification. As traffic increases, the interference caused by trackside construction becomes more severe. Electrification should therefore occur before critical levels have been reached. Thus, in the Canadian situation, if electrification is to occur, it cannot begin too soon. We suspect that the United States is facing the same situation.

Comment

Per Erik Olson, ASEA, Inc., White Plains, New York

The adhesion values used in this report may be too modest. If we at ASEA understood the figures correctly, the suggestion was made to use not more than 635 kW/axle, which gives 20 percent adhesion. A study carried out by Canadian Pacific Ltd., using a Swedish locomotive on the Norwegian State Railway in mountain areas, found that the average adhesion achieved was about 30 percent and could be increased (1). Use of the ASEA RC4 locomotive in the Northeast Corridor has clearly verified that adhesion levels above 30 percent can be used with an individual early warning system like that on the ASEA locomotive.

Author's Reply

After reviewing the source data from the Canadian Pacific study (1) and discussing the results with railway personnel who are responsible for dispatching trains, we concluded that, until substantial North American experience has confirmed the high adhesion capability of European locomotives under North American conditions, it would be too optimistic to assume that adhesion levels of more than 28 percent can be achieved. Research personnel have suggested that the figure should be higher, but some members of the Mechanical Department have suggested much lower figures and are concerned about the effects that high-adhesion locomotives will have on wheel and track wear. There is no agreement.

Since adhesion characteristics may have important consequences on the economics of electrification, it is better to assume a lower value, recognizing that the benefits may be increased as experience permits the use of higher values. A full-scale prototype railway operation under typical operating conditions would provide the experience necessary to establish an acceptable level for dispatching purposes.

The matter of the optimum locomotive axle power is an area that requires further investigation and is specific to the rail system under investigation. For Canadian railways, 635 kW/axle is too low, but we suspect that 1500 kW/axle is too high. The overload capability of the electric locomotive further complicates this study.

Comment

J. K. Leslie, Canadian Pacific Ltd., Montreal, Quebec

What are the relative advantages and disadvantages of 50-kV and 25-kV operation, from the operation point of view?

Author's Reply

The size of catenary wire may be dictated by considerations of wire strength or by current capacity. The lightest practical catenary, on the basis of strength, would typically carry slightly more than 600 A. At 25 kV, such a catenary would limit train power to roughly 8.9 MW (12 000 hp) and impose severe restrictions on train spacing. A 50-kV catenary, with twice the power capacity, would entail fewer restrictions on train power and operation.

To avoid the train restrictions, a 25-kV catenary would be designed to handle more current. However, increased current requires larger wire sizes, which increases the cost of the 25-kV catenary. The increase in wire cost would, in most cases, be much more significant than the additional costs encountered in providing the electrical clearance and insulation required for the 50-kV system.

The current capacity of locomotive pantographs would require the use of three or four pantographs to handle the current demand for an 11.9 to 17.9-MW (16 000 to 24 000-hp) unit train (16 locomotive axles) operating at 25 kV. A 50-kV supply would reduce the number of operating pantographs required, thus reducing the dynamic interaction of the catenary with multiple pantographs. The reduced dynamic interplay in turn reduces the loss of contact and hence the loss of unit power and electric arcing, which reduces problems of train dynamics and catenary and pantograph contact wear.

The loss of voltage due to the impedance of the catenary wire is proportional to the distance from the supply point and the current carried. If the permissible voltage drop is limited, for example, to 10 percent of the nominal supply voltage, then a 50-kV substation might end feed a 32-km (20-mile) segment of catenary, but a 25-kV substation could only feed a 16-km (10-mile) segment. Thus, the 25-kV system requires twice as many substations and twice as many phase breaks. On the basis of substation and utility feed costs, the 50-kV system provides lower costs per kilometer.

The initial cost of constructing the 50-kV catenary system would be significantly lower than the cost of a 25-kV system, except in areas that require extensive public works related to tunnels and bridges. The operational effects of properly designed 25-kV and 50-kV systems would not differ significantly. The lower number of phase breaks of the 50-kV system would decrease the number of times the locomotive power had to be reduced to zero during a train run. The relative safety of 25 and 50-kV systems suggests no advantage—both are lethal, and both require comparable protection for wayside wire structures.

Comment

J. K. Leslie

How does central dispatching reduce the power demand and hence the cost?

Author's Reply

Locomotives can be equipped with remotely operated power-limiting circuits as part of the normal power-control system. Each locomotive unit can be adjusted to respond to its unique code. This is similar to the practice used in robot midtrain power systems.

The coded limiting signals may be transmitted by radio or as carrier signals on the catenary system. Thus, it is possible to limit the power demand of each locomotive from a central power-control center. The train dispatcher in a centralized traffic control (CTC) territory is able to monitor the progress of individual trains within his territory from a central panel. The power control center should be made part of the CTC display or located immediately adjacent to it.

The electric demand charge is based on the peak power required over a certain period, typically 30 min, on a monthly basis. The power control center would display the system's instantaneous power demand, and an audible and visual alarm could indicate when the demand exceeds a preset level. The power dispatcher (perhaps the train dispatcher) could take action to reduce the power demand on appropriate locomotive units in order to limit the 15-min demand peak. This might involve reducing the power demand by 20 percent on a heavy train climbing a gradient at high speed, thereby slowing that particular train for a short period of time—only a few minutes.

Reply

Blair A. Ross, American Electric Power Service Corporation

It is believed that, although the use of central dispatching to reduce demand is valid in theory, it may be questionable in practice and would require careful analysis to determine whether the restraints on railway operation are worth the power-demand savings.

Comment

Keith Chirgwin, Garrett Corporation, Torrance, California

In relation to Figure 2, in which tractive effort was plotted against speed, and specifically with regard to curve c (poor rail conditions), I would like to ask:

1. How was this curve arrived at, i.e., what are the conditions or assumptions behind it?
2. What is the significance of the curve as far as locomotive operation is concerned?
3. How does this curve compare with similar curves

published by European locomotive suppliers that show higher values of tractive effort?

Author's Reply

Curve c in Figure 2 begins at 28 percent adhesion at 0 km/h. This point was selected after reviewing the data obtained in tests of the ASEA RC2 locomotive by Canadian Pacific Ltd. during the winter of 1970-1971. During these tests, the adhesion level dropped below 28 percent on fewer than 10 percent of the starts, and the second attempt to start was always successful. This seems to be an acceptable (but minimum) level for train scheduling for a modern electric locomotive of refined design on Canadian railways.

As locomotive speed increases, the dynamic effects tend to reduce the effective adhesion. This, of course, is a function of track structure, rail quality, and vehicle suspension. The curve used is similar to those used by European railways, and it is used for illustrative purposes only.

Canadian railway personnel suggest that the adhesion levels represented by curve c are optimistic. However, the larger wheel diameter, the use of shunt field-traction motors, improved wheel-slip controls, and improved locomotive suspensions all contribute to higher adhesion levels. We believe that levels corresponding to those in curve c can be achieved and would be used for heavy freight trains on Canadian railways after a suitable period of experience.

Curve c illustrates that, at low speeds, the full power of an electric locomotive cannot be used; it is limited by its adhesion. The high-power locomotive (1500 kW/axle) may not be power limited until the locomotive exceeds 96 km/h (60 mph).

REFERENCE

1. G. T. Fisher. Testing of High Performance Electric Locomotives. Paper presented at the ASME/IEEE Joint Railroad Conference, Jacksonville, Fla., IEEE Paper C 72-941-8-1A, March 14-15, 1972.

Technological Issues

Locomotive Costs: A Railroad Electrification Issue

Merton D. Meeker, Jr., General Electric Company, Erie, Pennsylvania

In any railroad electrification project, the acquisition and maintenance costs of the electric locomotives are, of course, important considerations. Specifically, the costs of ownership of electric locomotives compared with those of the diesel-electric locomotives they will replace are very important.

In analyzing relative acquisition costs, we can draw information from those railroads that have significant experience with both diesel-electric and electric operations. Furthermore, we can examine the similarities and differences between electric and diesel-electric locomotives in order to identify factors that influence their relative costs. Considered together with the economic life of the two kinds of vehicles and the relative fleet sizes required to do the same job, these factors will provide a means to weigh the relative capital costs of the two kinds of motive power. In analyzing maintenance costs, we can again draw on the experience of existing railroads and also compare logically the two kinds of locomotives to arrive at reasonable conclusions about relative maintenance costs of electric and diesel-electric locomotives.

We can get some insight about acquisition costs from a 1976 report (1) that surveyed many of the railroads of the world and a number of locomotive manufacturers. The report found that a typical 2.24-MW (3000-hp) six-axle U.S. diesel-electric freight locomotive delivers about 1.9 MW (2550 hp) at the rail and costs $500 000, or $261/kW ($196/hp). In both the United States and Europe, the typical 3.73-MW (5000-hp) electric locomotive costs between $800 000 and $1 million and the typical 5.22-MW (7000-hp) electric locomotive costs between $1 million and $1.5 million. Averaging these, one would arrive at a cost of approximately $241/kW ($180/hp) for the straight electric locomotive, or about 92 percent of the cost of the diesel electric on the basis of power. It is worthwhile to look at several factors that can affect the prices of these two types of locomotives.

PRODUCTION VOLUME

Nowhere in the free world are electric locomotives produced in a volume comparable to the production of diesel-electric locomotives in the United States. Hence, the present price levels for electric locomotives do not reflect any economies due to volume. What kind of volume might we expect in the future?

There is general agreement among many who have studied the subject that about 10 percent of the U.S. railroad lines have a sufficiently high density to be candidates for electrification. This 10 percent covers about 35 000 km (22 000 miles) and carries approximately 50 percent of the total U.S. traffic. It has been estimated that the electric locomotive fleet required to handle all of this traffic would be between 3500 and 4000 units. The electrification of these 35 000 km would probably take more than 20 years. Hence, production of electric locomotives averaging 150 to 200 units annually will be required when electrification in the United States really gets going. That volume would provide for a reduced cost/unit both through the efficiency of repetitive production of a given design and the production efficiencies inherent in continuous manufacture of any product. Although it is true that production volume for electric locomotives will probably never approach the production volume of diesel electrics, it can benefit from the same economies that make the present diesel-electric locomotives manufactured in North America one of the most cost-effective products in the world.

Let us examine briefly the similarities and differences between the electric and diesel-electric locomotives. The principal item of equipment that relates specifically to the diesel-electric locomotive is, of course, the diesel engine. The unit cost of the engine is greatly affected by volume since the manufacture of the engine requires substantial metal-working operations, which lend themselves to automation as volume permits. The principal parts that are uniquely associated with an electric locomotive are mostly pieces of equipment that are built up through assembly and do not necessarily lend themselves to the kinds of economies that can be achieved through automatic machining. Considering the rest of each locomotive—the common parts, including the locomotive platform, cabs, trucks, wheels and axles, and traction motors—it is easy to see that, if the electric locomotive is kept similar in form and function to the present diesel, both the electric and the diesel can benefit from economies of scale. Hence, although the probable production of electric locomotives will be in the range of 200 units/year, whereas diesel-electric locomotive production is in the order of 1000 units/year, when production of the electric locomotive approaches 200/year it should have the benefits of economies comparable to those achieved with today's diesel electrics.

TRENDS IN COSTS OF MATERIALS

Costs of the materials are certainly a principal factor in the total cost of a locomotive. There is one major area in the equipment of an electric locomotive in which the cost is going down, despite the inflation in cost of practically all other materials. This area is that of solid-state electronics, both for power and for signaling. Increasing use of power thyristors, diodes, and such static control devices as microprocessors to replace engines, generators, contactors, and relays can only produce cost savings. We are all familiar with this trend in such products as electronic calculators. The General Electric Company has announced a new method of semiconductor manufacture called thermomigration for the production of high-voltage, high-current power semiconductors at substantially lower cost than was possible with older methods (2). And a Univac computer that sold for $2.5 million 25 years ago can now be duplicated for far less than $500 on a single board (3). The electric locomotive certainly enhances the capability for applying solid-state devices.

The expected useful life of a piece of equipment is certainly important in considering its total ownership costs. There is no question that the actual useful life of both diesel-electric and electric locomotives is significantly longer than the nominal economic life attributed to them. Many diesels are running more than 20, even 30, years. On the other hand, as Table 1 shows, many electric locomotives have run more than 50 years. The New York Central System's S-class locomotives are still in operation after 70 years, and 106 of 139 GG-1s are still operating. The old locomotives of the Chicago, Milwaukee, St. Paul and Pacific Railroad Company and 1920-vintage Mexican locomotives were still operating when a decision was made to cease electrified service. Throughout the world, 30 years seems to be the accepted figure for the economic life of an electric locomotive, while 15 years is the accepted economic life of a diesel-electric locomotive.

An electric locomotive can be manufactured with two or three times the continuous power rating of a diesel-electric locomotive. This is, of course, because the electric does not have to carry its prime mover on its back. Also, by exploiting the thermal capabilities of electrical apparatus, the electric locomotive is capable of short-time power ratings that are double the continuous rating. This is not possible for the diesel electric. The question then is, How large a fleet of electric locomotives is required to do the same job as a given number of diesel-electric locomotives? There is no simple answer to this question. For high-speed manifest freight service over relatively level terrain, it may be possible for one electric locomotive to replace as many as three diesel electrics. On the other hand, in heavy freight service over extremely difficult terrain with sustained need for high tractive effort, one electric locomotive may be capable of replacing only 1.5 diesel-electric locomotives. In general, one electric will probably replace two diesel-electric locomotives.

A further consideration is that, when an existing railroad route is electrified, the diesel-electric locomotives that had previously been used on that route must be accounted for. This should not be a problem, since attrition alone on the rest of that railroad's system would normally require more replacement locomotives than those released by the electrification. Looking at it in gross numbers, the diesel-electric fleet in the United States comprises about 30 000 locomotives, with nearly 1000 needed every year just as replacements. As mentioned previously, approximately 4000 electric locomotives would be required over the next 20 years if all of the promising routes were electrified. That would result in an average rate of acquisition of 200 electric locomotives each year. Hence, attrition can more than handle the diesels displaced. Further, more than sufficient time will be available to plan for the use of these diesels, since the time for electrification on any given project will be a minimum of 3 years from decision point to operation.

MAINTENANCE

It is generally agreed that the maintenance cost of a fleet of electric locomotives will be significantly lower than the maintenance costs on an equivalent fleet of diesel-electric locomotives. Widely different figures have appeared in print; some suggest that maintenance of electric locomotives is as much as two-thirds the maintenance cost for diesels, and others suggest that it is as low as 20 percent of the maintenance cost of diesels. A general consensus appears to be that the maintenance cost of a fleet of electric locomotives is approximately one-third the maintenance cost of the equivalent fleet of diesel-electric locomotives. Much of the difference in the figures quoted results from different interpretations of the costs that are applicable to maintenance. As was

Table 1. Life spans of electric locomotives.

Railroad	Locomotive Type	Power (MW)	Year Placed in Service	Year Taken out of Service	Life (years)
New York Central System		1.64	1906	–	71+
New York, New Haven and Hartford	EP-1	1.06	1906	1936	30
Railroad Company	EF-1	1.19	1912	1953	41
Butte, Anaconda and Pacific Railway Company		0.81	1913	1967	54
Norfolk and Western Railway Company	LC-1	2.39	1914	1950	36
Chicago, Milwaukee, St. Paul and	Box cab	2.24	1916	1974	58
Pacific Railroad Company	EP-2	2.39	1918	1961	43
	EP-3	3.13	1920	1954	34
New York, New Haven and Hartford Railroad Company	EP-2	2.39	1923	1958	35
Mexican railroads		2.01	1924	1974	50
Norfolk and Western Railway Company	LC-2	3.54	1924	1950	26
Virginian Railway Company	EL-3A	3.54	1925	1960	35
Great Northern Railway Company		2.88	1927	1956	29
Pennsylvania Railroad	P5-A	2.80	1932	1962	30
	GG-1	3.45	1935 to 1940	–	40+
New York, New Haven and Hartford Railroad Company	EP-5	2.98	1954	–	23+

Note: 1 MW = 1341 hp.

pointed out in a recent article (4), "Special care should be taken to insure that all costs associated with maintaining and servicing diesels are compiled. Special maintenance accounts, heavy repairs, and fringe benefits are frequently omitted in manufacturer's cost figures but must be included when comparing different types of motive power."

It is certainly understandable that the maintenance cost for an electric locomotive should be substantially lower than that for a diesel-electric locomotive. The engine-related parts of a diesel-electric locomotive comprise the bulk of the moving, wearing parts and such replaceable renewal elements as fuel and air filters; hence, these are the parts that require by far the greatest amount of maintenance on the locomotive. The parts peculiar to the electric locomotive are, by contrast, generally rugged, static, nonwearing apparatus, such as the power transformer and the thyristor power supply. This equipment is extremely long lived and requires very little maintenance other than a route inspection from time to time. In addition, the electric locomotive requires no time for fueling; therefore, a minimum of service is required between runs. The electric locomotive's maintenance characteristics also permit a smaller inventory of spare parts and an attendant reduction in the carrying cost of that inventory.

As the conversion from diesel operation to electric operation proceeds, no significant investment will be required in new maintenance facilities for the electric fleet. The facilities and equipment needed for the diesel fleet will be more than adequate for the replacement electric fleet. As a matter of fact, if the electrified operation being considered is for a new or rapidly expanding operation in which new maintenance facilities would be required regardless of whether the operation were to continue with diesel electrics or be converted to electric, the investment in an electric maintenance facility would be substantially less. If it were not true for any other reason, it would be true because the fleet of electric locomotives to be maintained at that facility would be substantially smaller than the equivalent fleet of diesels.

Experience on the world's railroads corroborates the significantly lower maintenance expense of electric locomotives and shows general agreement that the maintenance expense for electrics is approximately one-third that of an equivalent diesel operation. At the Railway Systems and Management Association's Conference on Railroad Electrification in September 1973, it was reported that British Rail has found diesel-electric maintenance three times as costly as electric maintenance (5) and that electric maintenance costs on Japanese National Railways were approximately 35 percent those of diesel maintenance (6). French National Railways reported maintenance costs for electrics that were 34 percent of those for diesel electrics in 1970 and 33 percent of those for diesel electrics in 1972 and 1974 (7). It was added that "General introduction of thyristors on electric locomotives ... reduces electrical equipment maintenance by 40 percent." This latter fact results from the replacement of the tap changer, a piece of equipment with many moving, wearing parts, by the rugged static thyristor power supply. Swedish State Railways has reported that in 1971 the cost of electric locomotive maintenance averaged 42 percent of that for diesel electrics on the basis of cost per locomotive kilometer and 18 percent of that for diesel electrics on the basis of cost per megagram-kilometer (6). An article that summarized maintenance costs from a number of domestic studies on both diesel and electric locomotives found that, on the average, electric maintenance costs 30 percent as much as diesel maintenance (4).

There is, of course, no substitute for one's own experience in arriving at the correct locomotive costs to be used in studies leading to such important decisions as that on electrification. Unfortunately, by definition, those who must make the decision do not have their own experience and must depend on that of others. It is important that, in considering each specific route segment, there be an application study to determine specifically what the relative fleet requirements would be for the type of service contemplated. It is also important that each railroad's specific maintenance practices be considered in the determination of the relative maintenance costs.

Summarizing all of these considerations, it seems clear that the wealth of experience throughout the world indicates some general factors that can be used as points of departure. On the basis of an equivalent fleet

1. The costs of acquiring electric locomotives will be about 90 percent of those for diesel electrics, and it is expected that that percentage may decrease in the future.
2. The economic life of the electric locomotive will be twice that of the diesel electric.
3. The maintenance costs of the electric locomotive will be approximately one-third of those experienced with diesel-electric locomotives.

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Maintenance and Capital Costs of Locomotives

Max Ephraim, Jr., Electro-Motive Division, General Motors Corporation, La Grange, Illinois

On the basis of 1975 Interstate Commerce Commission (ICC) data, repairs for some 22 000 diesel-electric locomotives in freight and passenger service totaled \$680 845 000; thus the average maintenance cost for all classes of diesel-electric locomotives was \$30 948/unit. The maintenance cost of particular diesel-electric locomotives will vary with age, distance traveled, duty cycle, and type (turbocharged or nonturbocharged), as well as by manufacturer and railroad.

Maintenance cost data for specific railroads will deviate considerably from the gross averages. For example, a railroad that used 202 modern 2.24-MW (3000-hp) diesel-electric units that had an average age of 3.42 years compiled the following maintenance cost data for 1975: average monthly distance traveled per unit = 17 512 km (10 945 miles), average monthly repair cost per unit = \$1258, average repair cost per unit-kilometer = \$0.072/unit·km (\$0.115/unit-mile), average overhead per unit-kilometer = \$0.128/unit·km (\$0.205/unit-mile), total average repair cost per unit-kilometer = \$0.20/unit·km (\$0.320/unit-mile), and total average annual repair cost per unit = \$42 028. This cost is \$12 000 more per unit per year than the U.S. average because of (a) a higher than average distance traveled per unit and (b) a lower percentage of branch-line and switcher operation.

Because of the difficulty of obtaining maintenance cost data for operating diesel-electric locomotives on a large number of railroads, we have constructed an average annual maintenance cost on the basis of the required ICC inspection and the manufacturers' recommended periodic maintenance procedures for the engine, electrical, and running gear and major overhauls over a 25-year life. The cost data refer to a typical turbocharged, six-axle 2.24-MW locomotive in heavy-duty service that accumulates 20 100 km (12 500 miles) each month. A typical breakdown of maintenance costs into major categories is shown below.

Item	Cost (\$)	Percentage
Engine	13 400	31.3
Lube oil	3 500	8.2
Electrical	5 800	13.5
Running gear	20 000	47.0
Total	42 700	

Using 1975 dollars and the annual distance traveled of 240 000 km (150 000 miles), the maintenance cost is 17.8 cents/km (28.5 cents/mile). A locomotive that accumulated more kilometers would reflect lower costs per kilometer.

There is no established data base for modern electric locomotives in the United States at the present time, so comparisons are difficult to make. However, an estimate can be obtained by constructing a cost on the basis of the required ICC inspection and manufacturers' recommendations for periodic maintenance of electrical equipment running gear. If the annual distance traveled is 240 000 km, the expected maintenance cost would be \$26 000 for a six-axle electric locomotive. This is 11 cents/km (17 cents/mile), or 61 percent of the corresponding cost for a six-axle diesel-electric locomotive.

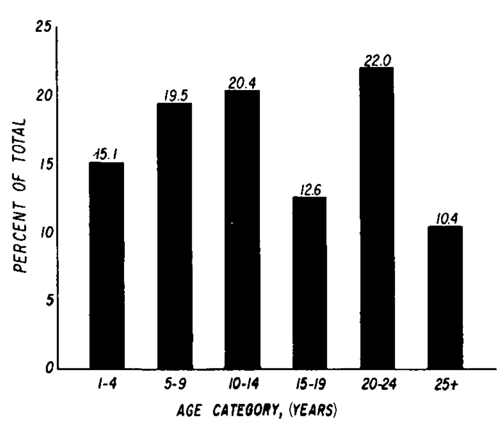
Typical maintenance cost values for the Swedish State Railway fleet of 43 ASEA RC locomotives is about 9 cents/km (15 cents/mile), which is close to the value computed for a six-axle 4.47-MW (6000-hp) electric locomotive. The Swedish locomotive, however, is only in passenger service, which differs considerably from the freight service for which the foregoing figures were developed. The electric locomotive entails about 60 percent of the maintenance cost of an equivalent-weight diesel-electric locomotive in the heavy-duty drag freight service that is characteristic of most U.S. freight operations. If tractive effort is not a limiting factor and locomotive units can be assigned on the basis of the total power needed for the train, it is possible to use a smaller number of electric units than diesel units, thereby achieving a further maintenance cost advantage. For example, if two 4.47-MW electric units can replace four 2.24-MW diesel units, the maintenance cost ratio (electric to diesel unit) would become 0.3.

The capital costs of diesel-electric and electric locomotives are much more difficult to compare, since very few modern electric locomotives have been constructed recently in the United States. On the basis of tractive effort, the price of a six-axle 4.47-MW electric locomotive is estimated to be two to three times the price of a six-axle 2.24-MW diesel-electric locomotive. On the basis of horsepower, the price of the electric is comparable to that of the diesel electric.

In heavy-duty freight service, locomotives are normally sized on the basis of continuous tractive effort to ensure operation over the maximum grade on the line. Therefore, locomotive costs on the basis of tractive effort provide the best comparison between diesel-electric and electric locomotives. In passenger service or special high-speed freight service, in which tractive effort is not a limiting factor and power is the basis for sizing locomotives, comparative locomotive costs should be based on power ratings.

It has frequently been stated that the diesel-electric locomotive has an economic life of 15 years. While the allowable tax depreciation life of the diesel locomotive can be taken to be as short as 11 years, the actual useful operating life can exceed 25 years, although technical obsolescence will dictate savings by replacing locomotives before this time in order to benefit from improve-

Figure 1. Distribution by age of 17 911 diesel-electric locomotives in service on U.S. railroads as of January 1976.



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

Graham S. W. Calder, Brush Electrical Machines Ltd., Loughborough, England

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 Number	Class 87 Electric Locomotive Percent	Class 47 Diesel-Electric Locomotive Number	Class 47 Diesel-Electric Locomotive 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

Edward G. Schwarm, Arthur D. Little, Inc., Cambridge, Massachusetts

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.

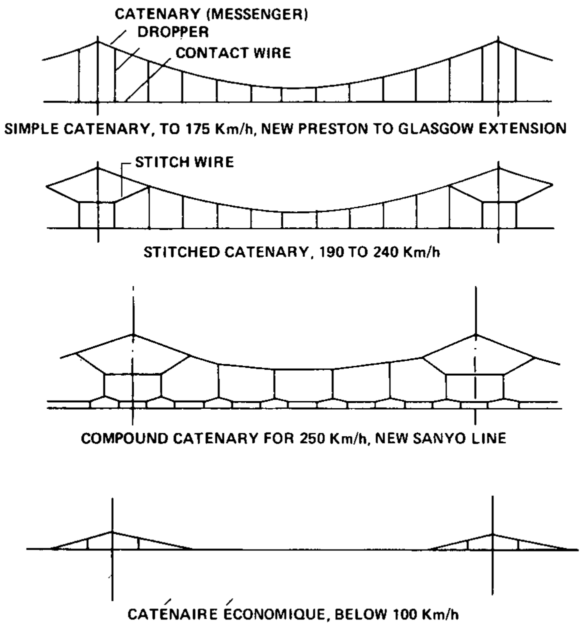
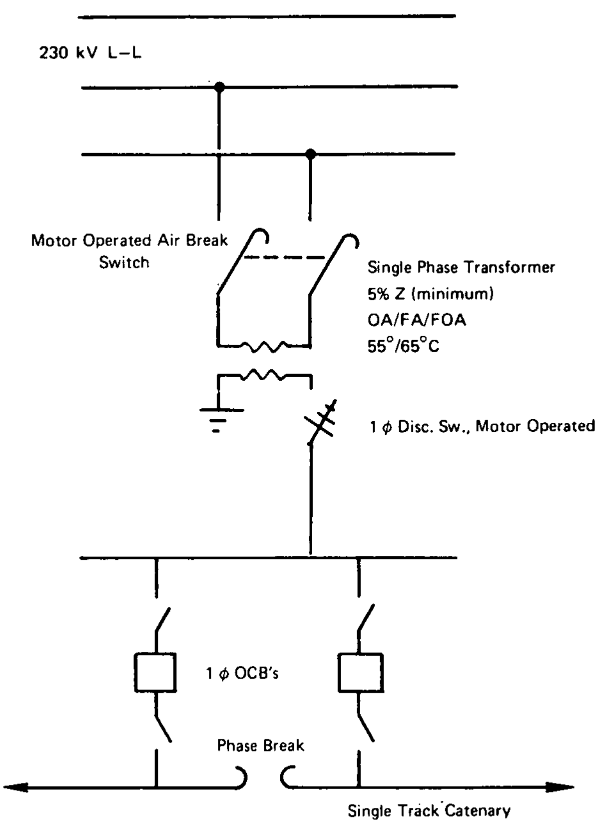


Figure 2. Basic single-transformer single-track substation.



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.

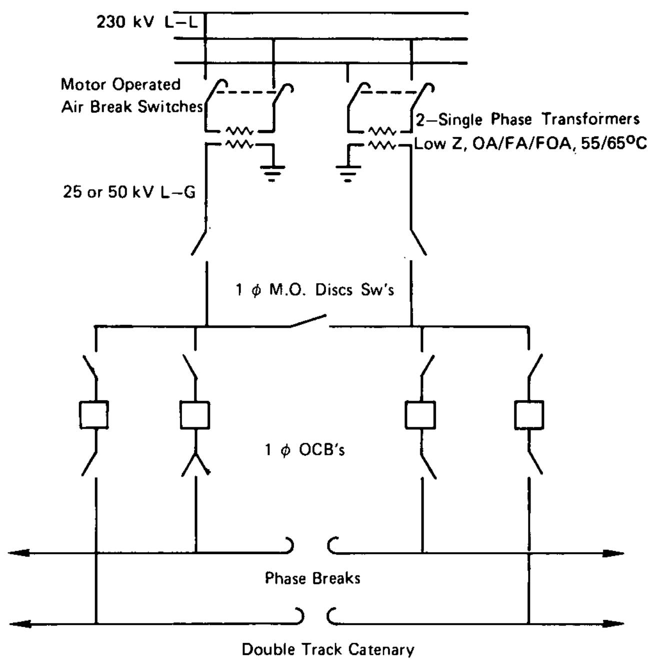
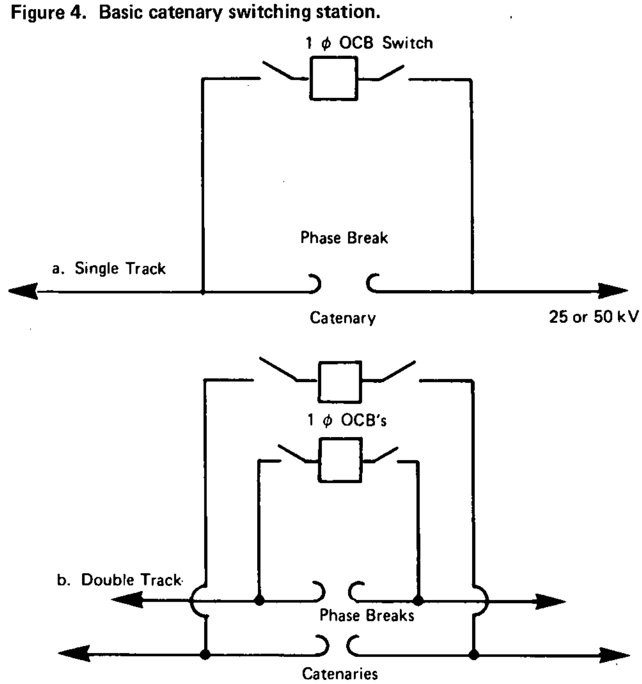


Figure 4. Basic catenary switching station.



$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.

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Interference of Electrification With Signaling and Communication Systems

Hugh C. Kendall, General Railway Signal Company, Rochester, New York

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 therefore cannot be employed in electrified territory. They must instead be replaced by suitable alternating-current track circuits.

The impact of the catenary system on parallel signal and communication circuits will be examined below in detail, along with the consequences of using the track for both return of the propulsion current and detection of trains and broken rails. The costs associated with rendering existing signal and communication systems compatible with the electrification environment will also be identified.

SOURCES OF INTERFERENCE

Signal and communication systems in alternating-current electrified territory must withstand substantial interference effects produced by current flowing in the catenary and the use of the rails to return the propulsion current. These interference effects may be conveniently divided into four categories:

1. Electromagnetic induction—the effect on a conductor produced by varying current flowing in a parallel conductor.
2. Electrostatic induction—the effect on a conductor produced when another conductor has a higher potential than the ground.
3. Rise in ground potential—the effect produced by the use of the ground as a conductor.
4. Metallic cross-conduction—the effect produced by the accidental connection of one conductor to another.

Electromagnetic Induction

Alternating current flowing in the catenary produces an alternating magnetic field around the catenary. The strength of the magnetic field is directly proportional to the current, and it decreases as a function of distance from the catenary. The alternating magnetic field induces an alternating voltage of the same frequency in any conductor that parallels the catenary regardless of whether the conductor is above or below ground. The induced voltage is proportional to the strength of the magnetic field, the frequency, and the length of parallel exposure.

Figure 1 shows the voltage that would be induced in a conductor 1 km (0.6 mile) long that paralleled a catenary carrying a current of 1000 A at 60 Hz, assuming that the propulsion current returns to the substation via a remote-return path. Note that a conductor separated from the catenary by a distance of 9 m (30 ft) would experience a longitudinally induced voltage of approximately 375 V. If this conductor became grounded at one end, an open-circuit potential of 375 V would appear between the other end of the conductor and the ground.

In Figure 1, the effect of the magnetic field produced by the return of the propulsion current was neglected in the interest of simplicity. In reality, this field has an important bearing on the actual voltage that is induced on conductors paralleling the catenary. Figure 2 assumes that all of the propulsion current returns to the substation via the rails. The current flowing in the rails is in phase with the current in the catenary but flows in the opposite direction. The two magnetic fields therefore tend to offset each other in a midway neutral plane. If one were to locate a conductor parallel to the catenary in the neutral plane, no voltage would be magnetically induced in it. If the conductor were located either above or below the neutral plane, the voltage induced in it would vary as shown. At a distance of 9 m from the catenary, for instance, if the conductor were raised to the height of the catenary, approximately 25 V/km (40 V/mile) would be induced in it. This is a substantial reduction from the case seen in Figure 1.

Unfortunately, not all of the propulsion current returns to the substation via the rails. The rails of a track structure are in close contact with the ballast, which creates leakage paths between the rails and the ground. It is not uncommon for the resistance between the rails and the ground to measure less than 1 Ω in a typical track circuit. In an electrified railroad, therefore, a portion of the returning propulsion current leaves the rails and flows back to the substation via a ground path.

Due to the character of the ground as a conductor, the phase angle of the returning propulsion current flowing in the ground path differs from that flowing in the rails, which tends to reduce the neutralizing effect of the ground current field on the catenary current field. Furthermore, the effective ground return path is generally far removed from the catenary, with the depth of the path in the earth dependent on the earth's resistivity and also on the distance between a given locomotive and the substation. When this distance is large, a substantial portion of the returning propulsion current flows in the ground path.

If one were to assume in Figure 2 that half of the returning propulsion current flowed in a ground path at a depth of 75 m (246 ft) below the catenary, with the other half flowing in the rails, it would be reasonable to expect a longitudinally induced voltage of about 125 V/km (200 V/mile) in a conductor that was 9 m away from the catenary. One means of reducing the induced voltage over long distances is to use a three-wire system with autotransformers and a negative feeder, as shown in Figure 3. This arrangement minimizes the induced voltage in the unoccupied sections between the substation and the autotransformers where the return current flows through the negative feeder, and the rail and ground currents are negligible. With an autotransformer that has a 2:1 ratio, the catenary and negative feeder current carry only half of the load current, and the negative feeder effectively shields parallel conductors near the neutral plane.

In the above examples, a catenary current of 1000 A at 60 Hz was assumed. This current might not be exceeded under normal operations on a railroad that has been electrified at 25 kV and undoubtedly would be well above that required in a 50-kV operation. It should be borne in mind, however, that a fault in the propulsion system could create a temporary catenary current of as much as 10 times normal amperage. Under these circumstances, voltages induced in parallel conductors could rise to as much as 10 times their normal values. In the event of a fault, however, the hazards to personnel must still be kept within acceptable voltage limits, and damage or malfunctions in signal or communication equipment must not be allowed to occur. In no event can the safety to railroad operations be compromised under such circumstances.

The effects of electromagnetic induction on conductors that parallel the right-of-way can be reduced to tolerable limits by placing these conductors in shielded cable wrapped with ferrous tape with the shield grounded at frequent intervals. The cable may be either buried or laid in trunking along the right-of-way and should preferably be laid as far as practical from the track. A properly designed and installed cable can reduce the effects of electromagnetic induction by as much as 95 percent. Unfortunately, however, conductors that are not under railroad control frequently parallel the right-of-way. A farmer's fence or local communication lines are typical examples of this. They constitute a hazardous liability to an electrified railroad, and adequate steps must be taken to ensure the proper grounding or shielding of these facilities.

Figure 1. Electromagnetic induction from catenary with remote-return path.

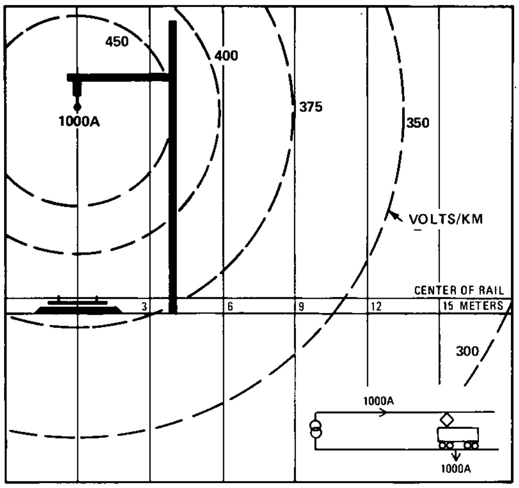


Figure 2. Electromagnetic induction from catenary with rail-return path.

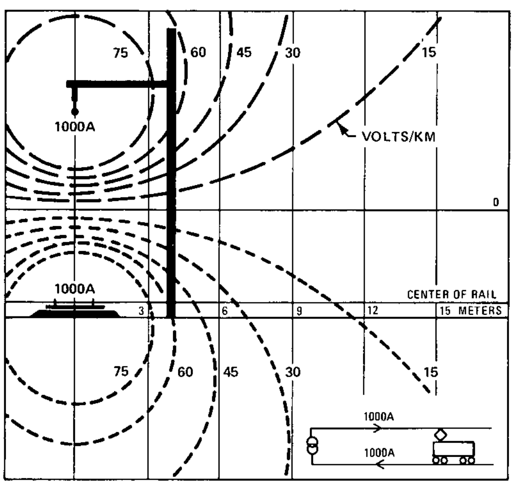
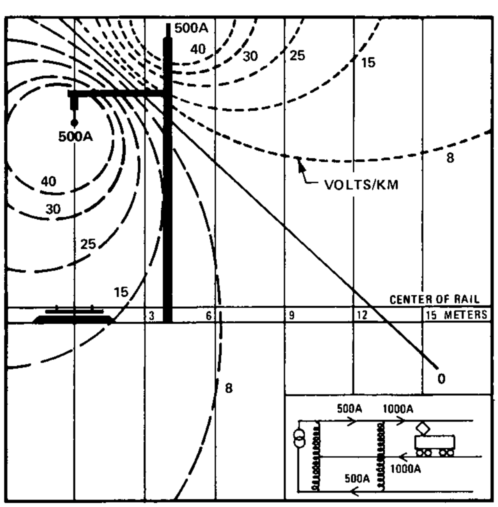


Figure 3. Electromagnetic induction from catenary with negative feeder.



Electrostatic Induction

Regardless of whether current is flowing in the catenary, open-wire lines along the right-of-way that have significant capacitive coupling to the catenary will experience the effects of electrostatic induction by virtue of the fact that the catenary has higher potential than the ground. In the event such lines became open circuited at both ends, it would not be unreasonable to find several hundred volts electrostatically induced in them in high-voltage electrified territory. The potential to which they would rise would depend on the relative capacitance between the lines and the catenary and the lines and ground, as shown in Figure 4. The effects of electrostatic induction on open-wire lines can be eliminated by the use of shielded cable.

Metallic objects on the wayside also have significant capacitive coupling to the catenary and, if ungrounded, could rise to several hundred volts above the ground, creating a shock hazard to personnel. Adequate steps must therefore be taken to see that all such objects are adequately grounded. As in the case of electromagnetic induction, the influence of the electrostatic field of the catenary can extend beyond the right-of-way. A metal

Figure 4. Electrostatic induction from catenary.

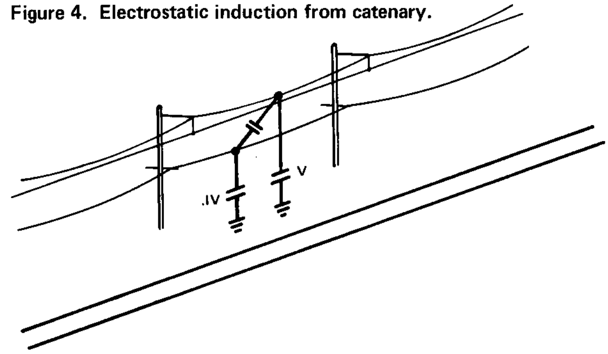


Figure 5. Ground-current conduction.

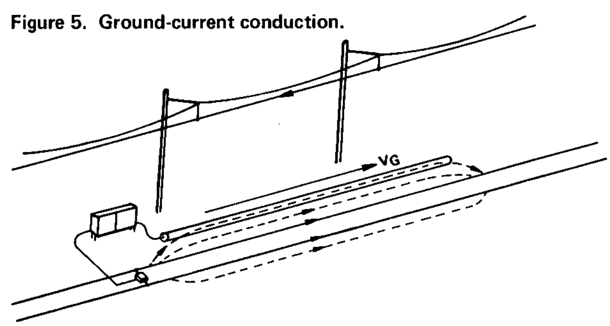
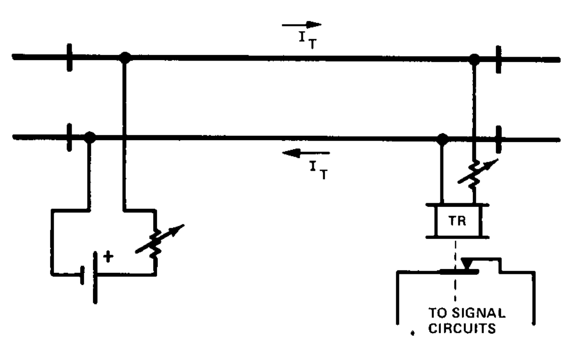


Figure 6. Neutral direct-current track circuit.



roof on a nearby barn or a farmer's fence along the right-of-way could be a hazardous liability to the railroad in the event they were not adequately grounded.

Rise in Ground Potential

Propulsion current returning in the ground path to the substation creates a potential gradient near the surface of the earth. The potential gradient causes foreign current to flow in any conductors that are in good contact with the ground, e.g., track circuits and cable shields, as shown in Figure 5. Track-circuit coupling equipment must be rugged enough to withstand the foreign current that may flow through it. Cable shields must be adequate in conductivity to carry foreign current flowing in them because of the difference in ground potential along the right-of-way. Wayside housings must be grounded to minimize the hazard to personnel due to the difference in ground potential between wayside locations. Equipment in wayside housings must be protected from surges that originate in the cable system because of faults in the propulsion system.

Metallic Cross-Conduction

A catenary energized at 25 or 50 kV and barely 7.5 m (25 ft) above the rails poses a significant hazard to personnel and to wayside equipment in the event of a mechanical failure in the catenary that would cause it to drop and come into contact with elements of the signal or communication system. Conductors mounted on the catenary support poles, wayside housings, signal heads, wayside sensing equipment, and the rails themselves must be thoroughly grounded, and suitable protective devices must be installed in all wayside cases to protect personnel from the consequences of such an accident.

TRACK CIRCUITS

In nonelectrified territory, the neutral direct-current track circuit shown in Figure 6 has been the backbone of railway signaling for more than 100 years. It has proven to be the simplest and most dependable means ever devised to continuously detect the presence of a train between two points on a railroad. Insulated joints are used to isolate one track circuit from the next. The track relay (TR) at one end of the circuit is energized through the rails by a battery at the other end of the circuit. The track-circuit current flows from the positive terminal of the battery through a series circuit consisting of a battery-current-limiting resistor, the upper rail, the relay resistor, the relay coil, and the lower rail back to the negative terminal of the battery. A break in either rail or the failure of the battery, either resistor, or the relay coil will interrupt the flow of current and cause the front contact of the track relay to open.

The effect of the presence of a train on the track circuit is shown in Figure 7. The front wheels and axle of the locomotive shunt the two rails together, robbing the track relay of battery energy. The track-circuit current now flows through the front axle of the locomotive rather than through the relay coil, causing the front contact of the track relay to open.

As mentioned previously, leakage paths exist between the rails because the rails come in contact with the ballast, as shown in Figure 8. For this reason, the length of a neutral direct-current track circuit is generally limited to 1.8 to 2.4 km (6000 to 8000 ft), depending on the ballast leakage conditions.

One means of lengthening a direct-current track circuit is to code the battery energy at one end and use a code-responsive (CR) relay at the other end as shown in Figure 9. The front contact of a code-transmitting (CT) relay is placed between the positive terminal of the battery and the battery-current-limiting resistor. In one type of circuit, the CR relay is operated by coding equipment in such a way that battery energy is alternately applied and removed from the track circuit for approximately equal intervals at a rate of 75 times/min. The CR relay at the other end of the track circuit alternately closes and then opens its front contact in response to the coded energy. A track relay is maintained in an energized condition by decoding equipment as long as the CR relay continues to operate. A broken rail, a train shunt, or a failure of any component in the circuit will cause the CR relay to stop coding and thus cause the track relay to release.

Coded direct-current circuits are used on many railroads in lengths of 3 to 4.5 km (10 000 to 15 000 ft), depending on ballast conditions. They are particularly useful because various types of codes can be employed and the track can be used not only to detect trains but also to transmit power in place of line wires.

In electrifying a railroad, the domain of the track circuit is invaded by propulsion current on its return to the substation. Figure 10 shows an alternating-current track circuit that is suitable for use on railroads that have been electrified using high-voltage alternating-current. Note that the propulsion current flows down both rails in the same direction, whereas the track-circuit current flows down one rail and back on the other. Since insulated joints, if they were not bypassed, would block the flow of propulsion current between adjacent track circuits, an impedance bond is used at each end of the track circuit to form the path for the propulsion current.

As Figure 10 shows, an impedance bond is a center-tapped coil wound on an iron core. The ends of the coil are connected to the rails near the insulated joints, and the center tap is connected to the center tap of a similar bond in the adjacent track circuit. The path of the propulsion current through each half of each bond is in the same direction, that is, either toward the center tap or away from it. On this basis, because of flux cancellation, it encounters a very small impedance in passing from one track circuit to the next. Since the alternating track current flows through each half of each bond in the opposite direction, it encounters an impedance of several ohms. The effect of this impedance is to create a voltage drop across the bond, and therefore between the rails, that is sufficient to detect a train shunt when it occurs.

A vane-like track relay is employed that requires two-phase related sources of energy to operate. One source is called the track phase and is transmitted over the rails. The other is called the reference phase and is transmitted over a pair of wires that run the length of the track circuit. If both sources of energy are present in the two coils of the relay in the proper phase, the front contact of the relay will close. A train shunt robs the relay of the track phase, thus causing the front contact of the relay to open. As with the direct-current track circuit, a failure of the energy source, the reference, or any component in the circuit will cause the track relay to open its front contact.

The alternating-current track circuit is energized at a frequency that is not harmonically related to the odd harmonics of the propulsion power supply. Because of the reactance of the rails, it is desirable to energize the circuit at a frequency that is as low as possible in order to maximize the length of the circuit. On railroads that have been electrified at either 25 or 60 Hz, a track-circuit frequency of 100 Hz has proven to be a satisfactory compromise. At this frequency, circuit lengths of

1.5 to 1.8 km (5000 to 6000 ft) may be used.

On certain railroads that are candidates for electrification, cab signals and overspeed control are used on locomotives. The systems use coded alternating-current in the track to convey information from the wayside to the locomotives. Where direct-current track circuits are used, coded alternating current is superimposed on the direct current. Figure 11 shows a coded alternating-current track circuit that is suitable for cab signaling in alternating-current electrified territory. It is essentially a modification of the alternating-current track circuit shown in Figure 10.

A front contact of a CT relay has been inserted in the track energy feed. The CT relay is operated at various code rates (75, 120, or 180 pulses/min) by the coding equipment, depending on the conditions on the track ahead. At the receiving end of the circuit, coded energy from the track is fed to one of two inputs of a phase-selective detector. Uncoded energy from the phase reference line is fed to the other input of the detector. When energy from the track is present in the proper phase at the detector, the CR relay is operated. When energy in the proper phase from the track is absent, the CR relay is released. As long as the CR relay responds to one of the three code rates, a track relay is maintained in an energized condition by local decoding equipment. Like the coded direct-current track circuit, a train shunt, broken rail, or failure in any component of the circuit causes the CR relay to stop coding and thus causes the track relay to release.

Aboard the locomotive, two receiving coils are mounted ahead of the front axle of the locomotive, as shown in Figure 12. The magnetic field around the rails produced by the track-circuit current induces a voltage in the receiving coils that is amplified and passed on to decoders, which determine the cab-signal aspect to be displayed in the cab as well as the speed-limit threshold of the overspeed governor. The actual speed of the locomotive is determined by a tachometer generator driven by an axle of the locomotive. If the speed of the locomotive exceeds the speed-limit threshold of the overspeed governor, an audible warning is sounded in the locomotive cab. If the engineman fails to take action within a prescribed time period, the locomotive's brakes are automatically applied until the speed of the locomotive is below the speed-limit threshold.

CONVERSION TASKS

The following tasks must be accomplished in rendering

Figure 7. Neutral direct-current track circuit with train shunt.

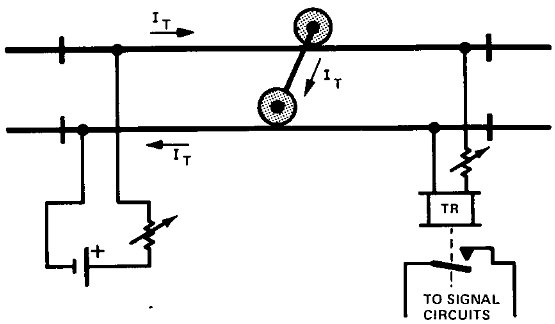


Figure 8. Ballast leakage.

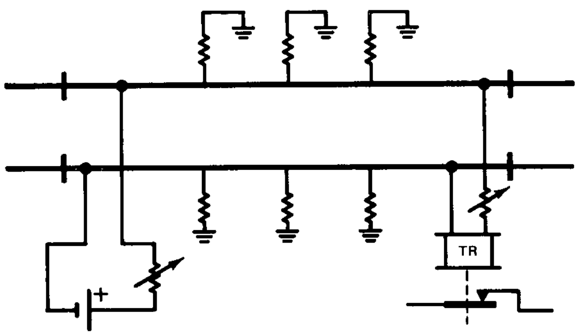


Figure 9. Coded direct-current track circuit.

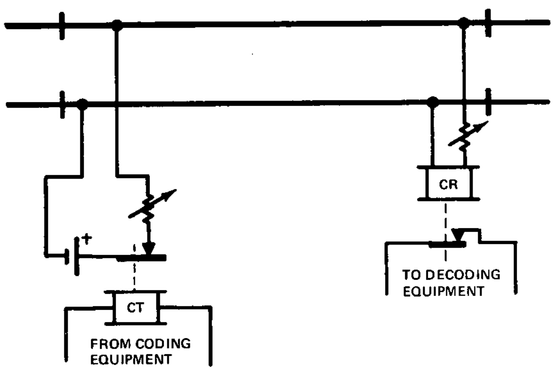


Figure 10. Two-phase alternating-current track circuit.

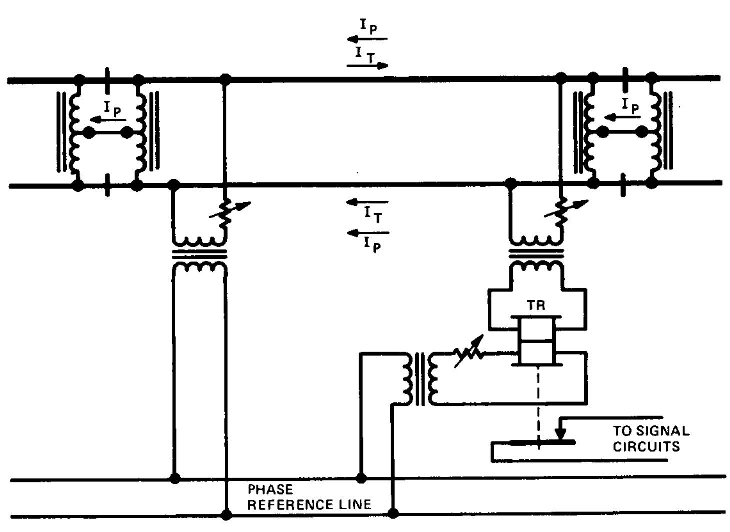


Figure 11. Two-phase coded alternating-current track circuit.

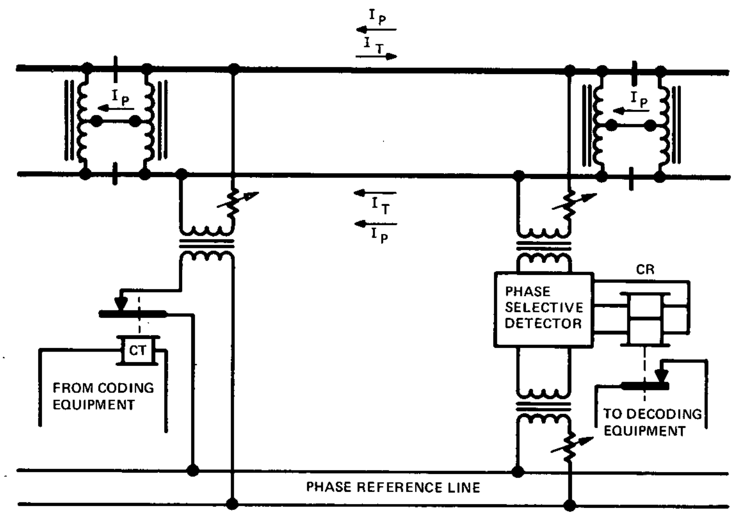
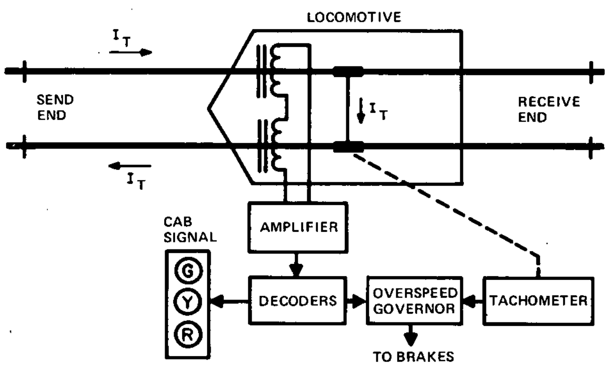


Figure 12. Cab signals with overspeed control.



existing signal and communication systems compatible with high-voltage electrification at either 25 or 60 Hz.

1. Neutral or coded direct-current track circuits must be replaced by either two-phase continuously energized or coded double-rail alternating-current track circuits that have impedance bonds. Experience has shown that a track-circuit energization frequency of 100 Hz can be used satisfactorily in these circuits for operating lengths up to 1.5 to 1.8 km (5000 to 6000 ft). Means must be provided to generate energy at the track-circuit frequency and to transmit it in a metallic circuit the entire length of the railroad.
2. Open-wire signal and communication circuits along the right-of-way must be replaced by shielded cable that is either buried or laid in trunking as far away from the track as possible. The interconnection of various elements of the signal system requires access to circuits in the signal cable at roughly 1.6-km (1-mile) intervals. This requirement in some respects precludes the use of a joint signal-and-communications cable. Communication circuits are generally designed for the long haul and, since they use relatively low signal levels, it is preferable not to open the cable any more frequently than is absolutely necessary. It is therefore customary to use two separate cables, but these cables can be buried in the same trench or duct running the length of the railroad. The use of cables requires that cable repeaters be installed at appropriate locations along the right-of-way to maintain satisfactory signal-to-noise ratios.
3. Instrument housings, signals, wayside detection devices, switch machines, and all other metallic objects along the right-of-way must be adequately grounded. In addition large metallic objects, fences, or wire lines that are off the right-of-way but relatively close must be either grounded or suitably coordinated with the propulsion power supply.
4. Surge arrestors and other protective devices must be installed in wayside cases to protect personnel and equipment if the propulsion power supply becomes faulty.
5. Signal cases and bungalows along the right-of-way must be supplied with power for battery charging, track-circuit energization, environmental control, and other purposes. In nonelectrified territory, a single-phase power circuit is conventionally carried on the open-wire signal and communication pole line along the right-of-way. With the elimination of the pole line, alternate arrangements for signal power must be made. One alternative would be to provide a signal power line carried on the catenary poles and energized from a substation. The signal power line would be operated at a voltage 25 to 50 percent that of the catenary voltage and insulated to withstand the effects of electrostatic induction on the catenary in the event the signal power line became open circuited. Transformers would be used at each signal location to step the power down to 110 or 240 V.
6. Rail bonding and cross bonding must be adequate to support both the propulsion and signal systems. Since traction bonds are required, this task is generally considered to be a part of the installation of the propulsion system.
7. If switch circuit controllers are used to shunt the rails, they must be suitable for heavy duty to withstand the possible unequal flow of propulsion current in the two rails.
8. Centralized traffic control systems generally use direct-current coding systems to convey commands to field locations and to receive indications from the field. The code lines parallel the railroad for very substantial distances without a break and could therefore have a relatively high exposure to interference effects produced by the propulsion system. In some cases, these code lines will have to either be broken and replaced by direct-current code repeater stations or be converted to carrier operation.
9. Signals that are now mounted on wayside poles would be obscured in some cases by the catenary support structures; such signals would require relocation to achieve adequate visibility. In addition, some signals are mounted on signal bridges that will have to be raised

to permit the catenary to be installed.

10. The conversion of the signal and communication systems for electrification would involve the handling of substantial quantities of high-grade electrical equipment, housings, and cables along hundreds of kilometers of right-of-way. The movement, storage, and protection of this material during installation are an important task.

11. Cab signals are used on some railroads in nonelectrified territory. In these cases, a coded 60-Hz signal is superimposed on the direct-current track circuit. In the event of electrification, the locomotive-carried equipment would require conversion for operation at the new 100-Hz coded track-circuit frequency.

12. Highway-crossing warning systems frequently use overlay track circuits to detect the presence of trains in the approach sections. In addition, motion detectors and constant-warning-time devices are employed in certain installations. In general, this track-connected equipment was designed for use in nonelectrified territory in which direct-current track circuits are employed. Under electrification, this equipment will usually require either modification or replacement to enable it to operate in the presence of 100-Hz track current and the higher harmonics of the 60-Hz propulsion current flowing in the rails. Since the number and complexity of highway-crossing warning systems on railroads vary widely in different parts of the country, the task of converting this equipment for electrification is generally considered as a separate item.

COSTS OF CONVERSION

During the past 5 years a number of railroads have conducted electrification studies. Some of the results of these studies have been made public, particularly those from the Consolidated Rail Corporation studies. Representative costs per kilometer for the conversion of signal and communication systems can be summarized as follows for a double-track railroad that is to be electrified at 25 to 50 kV 60 Hz:

Item	Cost ($)
Signal cable	4 000
Communication cable	3 000
Cable trenching and splicing	16 000
Signal power line and transformers	2 100
Impedance bonds	4 500
Moving signals	1 200
Prewired cases (track-circuit control)	12 000
Cabling and grounding of cases and signals	2 400
Modifications to hotbox detectors	300
Carrier repeaters and terminations	2 000
Material handling and security	3 000
Fence grounding	300
Testing and miscellaneous	2 000
Total	52 800

The above figures do not include the costs associated with the conversion of track-connected equipment associated with highway-crossing warning systems, since the number of such systems per kilometer varies widely in different parts of the country. Also not considered are the costs of compatible track circuits within interlockings or those associated with sidings, since the quantity would depend on the layout of a particular railroad.

Comment

A. H. Carter, Bell Laboratories, Whippany, New Jersey

Kendall has discussed the interference effects produced in railroad signal and communication systems, noting that special problems are presented by the proposed conversion to 25-kV 60-Hz electrification. Interference with telecommunication systems is also likely to occur as a result of two factors.

First, at 25 Hz, interference is largely confined to the railroad right-of-way because it is produced solely by currents flowing in the catenary, the rails, and the earth. The commercial power system does not provide a path for current flow because it is electrically isolated from the catenary. The conversion to 60-Hz commercial power, on the other hand, will give rise to a proliferation of the interference in the local power distribution network and may necessitate inductive coordination extending beyond the right-of-way. The severity of the problem will depend on the extent to which the locomotive's rectifier harmonics flow back into the alternating-current network where communications and power lines are together on joint-use utility poles or in common trenches.

The second source of concern has to do with the wave shape of the induced currents. The action of the locomotive rectifier produces currents rich in harmonics of the fundamental power frequency. More harmonic energy lies in the voice-frequency band of telephone circuits with 60-Hz power than with 25 Hz; thus the noise generated is expected to be correspondingly greater. Experience has shown that the noise problem is manageable if the interfering system's I·T product is less than about 20 kA (the I·T product is the product of the total current and the telephone influence factor, a dimensionless quantity that describes the frequency distribution of the harmonic components of the rectifier current within the voice-frequency spectrum, weighted according to the response of the telephone set and the auditory characteristics of the user). Predictions based on limited measurements of wave forms of locomotive rectifiers give I·T products that are an order of magnitude higher for 25-kV 60-Hz systems, implying an increase in noise levels of approximately 20 dB. Such an increase would undoubtedly entail inductive coordination or mitigation requiring modification of both railroad and telephone systems in many situations.

At present the Bell System is engaged in a program to assess the magnitude of the potential problem. As a first step, measurements of rectifier current and induced voltage are being made in cooperation with the Muskingum Electric Railroad, which operates E-50 locomotives on 25-kV 60-Hz power. The results of these studies will be reported through the TRB Committee on Electrification Systems.

Reply

Blair A. Ross, American Electric Power Service Company, Lancaster, Ohio

Carter comments that 60-Hz electrified railways interfere with commercial telecommunication systems, as well as with railway signal and communication systems, and that this must be recognized. As was indicated in the discussion, the locomotive rectifiers are the primary source of the interference. The problem of harmonic reflections into the power system is, as a general rule, mitigated to a considerable extent by the inherent capacitance of the commercial power network; if this is not sufficient, filtering capacitors can be installed at the railway substation. Further, it is believed that proper use of neutralizing transformers in the telecommunication system or booster transformers and return feed on the railway can, in considerable measure, eliminate harmonic problems or reduce them to tolerable levels.

Impact of Research and Development on Railroad Electrification

Frank L. Raposa, Transportation Systems Center, U.S. Department of Transportation, Cambridge, Massachusetts

The 1974 report of the government and industry task force on railroad electrification (1) concluded that electrification is the only available alternative to diesel-electric operation and that railroad electrification offers the only feasible means to use coal or nuclear energy for intercity movements of general freight and passengers. However, the investment required is not so attractive as to cause immediate conversion of the nation's rail system from diesel-electric to electrified operation, particularly considering the present state of railroad finances. By contrast, enormous savings were possible at the turn of the century by converting from steam to electric motive power, and even greater savings were realized in the 1940s by converting from steam to diesel-electric motive power.

Electrified operation has its place in the nation's rail system, not as a replacement for diesel operation but as a partner in the effort to provide the most efficient means of transporting freight and passengers. It is generally accepted that, above a certain level of traffic density, electric traction provides lower operating costs. However, it is essential that the traffic forecasts predict with some assurance that the route will maintain sufficient density over the life of the traction equipment to justify the large capital investment.

Specific conditions may make electrification more attractive financially. For example, the availability of low-cost hydroelectric power, the short-term high-power demands of mountainous routes or schedules with frequent acceleration requirements, and the requirement to eliminate emissions in tunnels and urban areas are characteristics that were influential in the decision to electrify specific routes in the United States and Europe.

Other conditions have the effect of forcing a decision to be made concerning electrification. The scarcity of fuel and the limitations on diesel-engine development are two cases in point. It should be emphasized that the scarcity of fuel does not imply that fuel is not available to the railroads of the United States. Their consumption makes up only a small percentage of the total oil consumption and could always be accommodated, but the uncertainty about the cost of fuel affects the capability of the railroads to develop long-range growth plans. The upper limit on diesel locomotive power appears to have been reached, just as it was with the steam locomotive. Railroads now use up to 12-unit consists for the very long trains. Attempts to increase engine power have resulted in losses in reliability and higher maintenance costs. The electric locomotive, with its higher power density and overload capability, gives the railroads the capability to offer increased service as the economic demands of the market develop.

The Railroad Revitalization and Regulatory Reform Act of 1976 is expected to result in a major reassessment of electrification and its impact on railroad operations in the United States. A direct impact is the major rehabilitation by the National Railroad Passenger Corporation (Amtrak) of existing electrification and the extension of electrification to cover the entire Northeast Corridor (Washington to Boston) for high-speed passenger operations. Specific provisions of the act enable the Consolidated Rail Corporation (Conrail) to request from the Secretary of Transportation a federal guarantee for loans for funds to electrify high-density main-line freight routes. Other railroads have informally notified the Federal Railroad Administration (FRA) that they wish to apply for electrification funding under other provisions of the act.

A sector of the Conrail track that has been given consideration for electrification is the route from Pittsburgh to Harrisburg, which has the highest traffic density in the United States. Because the Conrail route from Harrisburg east to the Northeast Corridor (run by Amtrak) is already electrified, the new wiring represents an extension of electrification. Upgrading of the Northeast Corridor will force Conrail to decide between upgrading of current electrification equipment and replacing the existing electric fleet with a diesel fleet. It is probable that the decision to continue electrified operation would include the recommendation to extend electrification from Harrisburg to Pittsburgh.

Site-specific studies are required to determine whether there are other routes that would be better served by electric traction. It is not the purpose of this report to expound on the methodology of evaluating motive-power alternatives in an electrification feasibility study. Suffice it to say that each application must be examined very carefully to assure that the multitude of design and cost factors are estimated with sufficient accuracy to make the result convincing. The uniqueness of each site study is reflected in the relative influence of such factors as fleet size, energy costs, and the effect on public works, all of which can have a major impact on the investment decision.

Electrification of U.S. railroads could begin immediately if the existing technology from the European, Russian, and Japanese rail systems were adapted. This assumes that design variations resulting from the uniqueness of U.S. railroads are minimal. However, the long-term implications deserve further attention. Careful consideration should be given to the constraints imposed by adapting existing equipment, particularly if a commitment is made to large-scale electrification in the United States. At the other extreme, it would be unwise to put off electrification until a major evaluation of technological requirements is completed. There are no technological breakthroughs on the horizon that would make obsolete an electrification system that used current technology. If feasibility studies determine that electrification of a sector is justified using the current technology, it should be implemented.

Research and development for the near- and mid-term periods (5 to 10-year payoffs) should be designed to achieve a maximum return on investment. This research and development should consist primarily of the assessment and development of technology to define, evaluate, and improve equipment that could be used in current and planned electrification systems in the United States.

TOPICS FOR RESEARCH AND DEVELOPMENT

Conversion to electrification requires a significant capital investment that must be recovered through savings in operating costs and in obtaining service improvements. Because electrification affects the heart of the railroads, the risk of failure must be virtually eliminated. The near- and mid-term research and development topics identified in this paper are directed toward reducing that risk and obtaining a higher return on investment.

Systems Analysis and Engineering Studies

Prior to and early in an electrification program in the United States, systems analysis and engineering studies must be carried out on a number of problems common to all railroad properties, problems that have reduced the credibility of conventional feasibility studies. Among the problems that will require such work are the following.

1. Review and adaptation of technology developed abroad—Because railroad electrification has progressed further in Europe and Japan than in the United States, studies of foreign technology must be carried out to determine their applicability to railroad operations in the United States. This analysis should include delineation of the similarities and differences in equipment, construction, and operation; assessment of the alternatives, including adaptation of foreign technology to meet present operational requirements of U.S. railroads; and adaptation of U.S. requirements to make use of foreign technology as is. Equipment studies should include the testing and evaluation of foreign locomotives and fixed-plant equipment on U.S. properties and test facilities and the evaluation on foreign properties of locomotives designed to meet U.S. requirements.

2. Comparison of electric with present diesel-electric operation—Economic feasibility studies typically compare the electric and diesel-electric alternatives under conditions of equal service and reliability. Further quantitative study should be made of the gains and losses in service speed and reliability in conversion to electric operation. Operational changes designed to optimize the benefits of electrification should be evaluated. Problems in the management and maintenance of a dual fleet (if there is partial electrification of a railroad), the limitation of the electric fleet to main lines that are wired, the extra change requirements, and the reduced use of diesel locomotives should be evaluated. The reliability of each alternative as it affects service to the shipper should be quantified, considering both the above factors and reliability of railroad and utility equipment.

3. Interfacing between railroads and electric utilities—The supply of thousands of kilometers of electrified railroads from adjacent electric utilities raises many problems that require study and resolution at an early stage. These problems include whether or not to build dedicated transmission lines paralleling the railroad, whether to reinforce weak utility systems or employ artificial phase-balancing methods, and how to handle phase breaks between adjacent utility companies.

Electrification Standards

Standards must be prepared for electrification facilities to ensure that they are safe, are compatible with other services, and use reasonably uniform equipment. Standards committees should be formed and made responsible for turning the recommended practices into sets of standards as use and review establish their validity. A start must be made in the preparation of standards long before designs for equipment are frozen for major production, since time is required for standards to be reviewed by public agencies and by industry groups before their acceptance. Standards are required in the following areas:

1. Telecommunication interference—Standards must be prepared to define the maximum harmonic current and voltage environment in which wayside train control, communications, and public telecommunication facilities should operate. Tests must be run on controlled facilities, such as the U.S. Department of Transportation's Transportation Test Center, and on electrified facilities that are already operating. Until these standards are written and approved, designers of electric locomotives and wayside facilities cannot be assured of compatibility.

2. Voltage unbalance in the electric utility system—The largest single-phase load that can be provided for railroad service from an electric utility system is limited either by negative-sequence current in the utility's generator or by the maximum voltage unbalance at the supply bus car. Standards for negative-sequence current have already been set by the Institute of Electrical and Electronics Engineers, but standards are still required for voltage unbalance. The maximum voltage unbalance is generally limited by the overheating of induction motors operating from the source of the unbalanced voltage. In addition to the preparation of standards, extensive testing is required to ensure that the standards are not overly conservative.

3. Current harmonics in the locomotive—Locomotives that use phase-controlled rectifiers will produce harmonics in the catenaries, resulting in potential telecommunications interference. The harmonics can be controlled within the locomotive by filters and other design measures that generally add to the cost of the locomotive. Standards for the acceptable percentage of harmonic current at the locomotive are required to guide locomotive manufacturers and to assure railroads that buy such locomotives that the potential interference is at a controlled level. This will entail extensive testing of sample locomotives in controlled test situations and in-service electrified systems.

4. Current harmonics at the interface with the electric utility—Maximum allowable levels for harmonics at utility interfaces have been set in European countries but not in the United States. Standards peculiar to railroad service must be set and must be confirmed by calculations and tests to ensure that they are reasonable.

Current harmonics in a utility can produce resonances with alternating-current capacitor banks and high-voltage cables, resulting in possible failure.

5. Nominal voltage levels for catenary—At the present time alternating-current voltages of 25 and 50 kV are being considered as standards. These levels should be formalized in a standard, and levels for direct current and higher voltages should also be established. Setting standards early in the electrification program will prevent selection of inappropriate voltages, ensure interchangeability of equipment between railroads, and provide economies of scale as a result of higher production levels. These voltage levels should be researched to ensure that they are reasonable and adequate to handle future growth in U.S. electrification.

6. Substation and catenary voltage limits—To ensure the compatibility of electric locomotives and multiple-unit cars in operation on any electrified railroads in the United States, standards must be set for the maximum and minimum limits of voltages that rolling stock will encounter from catenary operation. Manufacturers of electric locomotives and multiple-unit cars now set voltage limits at which their equipment will operate either at full performance or at reduced performance. Considerable cooperation will be required from industrial manufacturers, consulting engineers, and railroad operators before these limits can be formalized into a standard.

7. Mechanical and electrical clearance—Clearance distances must be set between rolling stock and catenaries, between catenaries and adjacent structures, along surfaces that provide insulation, and for electrical equipment installed within rolling stock. These clearance standards are fundamental to the development of the whole electric railroad industry and must be used uniformly by all railroads in the United States.

8. Electrical safety—Safety standards must be formulated for personnel working on rolling stock, catenaries, substations, repair shops, and all other locations that may expose them to high voltage. These standards must include grounding methods, fault detection, equipment tripping, emergency operation, and all other aspects of electric railroad conditions. These safety standards should be generated by the combined effort of the railroad industry and organizations that work in the safety field.

9. Reliability of system and subsystem equipment—Standards are required for specifying, testing, and applying measures of reliability, e.g., mean time between failures and mean time to repair. In addition, preliminary standards should be generated for electric locomotives and as many subsystems as possible, including traction motors, motor-alternator sets, rectifier sets, transformers, and train control systems. Extensive testing will be required to correlate measures of reliability with railroad service demands and to obtain coefficients of reliability for use in the standards.

10. Test methods—Standard test methods must be developed for all types of electric railroad system and subsystem equipment to ensure uniformity among manufacturers in quoting prices and delivering equipment to railroad customers. Development of such standards for testing will be a major effort that will require the cooperation of industry and railroad representatives over several years. In some cases, existing test methods can be adapted to railroad purposes, but testing will be required to confirm the validity of proposed standard test methods.

11. Methods of measuring energy—Measurement of energy at the interface between utilities and electric railroads is complicated by the presence of harmonics and regeneration. Standards must be set for the methods and the specific types of metering equipment that will be used as a basis for measuring the energy the railroad pays for. In cases in which energy charges are based on metering at more than one point, the equipment involved in the summing system must also be included in the standard. Electric utility committees are addressing the problem of measuring energy for industrial rectifier loads, where the same conditions prevail as for railroad service.

Improvement of the Interface With the Utility

The nature of the railroad's electric load is unique and will require connection to the electric utility at a capacity level sufficient to make the impact on the utility unobservable. This will require the utility to provide larger than normal reserves of generation and transmission capacity. The capital cost of investment in this and the transmission-line extensions required will probably be either passed on to the railroad as connection and reinforcement costs or rolled into the rate structure. Research and development should be initiated to reduce the impact of the utilities' capital costs on the energy costs of the railroads.

1. Reducing peak demand—During the past several years, industrial and commercial users of electricity have been able to make reductions in both peak demand and total energy used by applying digital computing equipment to control the time and amount of power use. It seems probable that similar techniques applied to an electrified railroad might reduce peak demands either at individual substations or on a single utility by all substations connected to that utility. Better control of the fleet, both in limiting the power demand and fleet management, can result in better load factors and reduced demand charges if improved computer and centralized traffic control techniques are developed.

2. Improvement of phase balance—Traction power on the catenary is a single-phase electric load. It has been the practice in the United States to operate the railroad load from three-phase to one-phase frequency converters in such a way that the railroad load, when reflected back into the electric utility, represented a balanced load. However, since this conversion equipment represents a significant addition to the cost of electrification, three-phase to one-phase converters should be used only where the utility grid cannot accept direct connection of the single-phase load.

Operation of the railroad's single-phase load from the three-phase electric power system must consider the impacts of the unbalanced load on the electric system. If the unbalance is large, it must be taken into account that the unbalanced current flowing through the system alternator stators causes rotor heating and that unbalanced currents cause unbalanced transmission voltages, which causes similar heating of motors on the line. These impacts generally require the power system to have significantly more power available than the railroad requires.

If a synchronous three-phase machine is operated at the point of connection of the railroad load, the machine will provide a path for negative-sequence currents paralleling the paths through the three-phase network. Such a machine will reduce the magnitude of negative-sequence currents in the utility network, but the machine must be sized to accept the unbalanced currents safely. Various circuits that use static inductors, capacitors, and transformers can connect a single-phase load to a three-phase source in such a way that the three-phase source perceives a balanced load. If it can be verified that these types of equipment are economically attractive and meet the conditions of variable loading and a variable power factor, it may be practical to have three-phase to single-phase conversion without rotary equipment or active components.

3. Reactive power reduction—The propulsion circuits of locomotives that operate from 25 or 50-kV 60-Hz catenary must include some type of power conditioning to convert power collected from the catenary to a form suitable for the traction motors. Each of the types of power conditioners produce a lagging power-factor load. Many power conditions produce complex current wave forms that have many harmonics. The lagging reactive current produces voltage drops in the catenary that limit the distances between feeders. The harmonic currents flowing in the catenary can produce interference in communication and signaling circuits near the railroad.

Capacitors or filters on the locomotives can reduce interference, reduce lagging reactive currents, and reduce harmonic currents. However, the amount of correction that can be accomplished through capacitors is limited. It is common practice for utilities in the United States to use capacitors to correct the power factor on transmission and distribution lines. Automatic or manually controlled switching is used to connect the correct number of capacitors. The disadvantage of assuming full responsibility for power-factor correction at the wayside is the poor utilization of equipment. Research and development are required to develop a dual system that provides the desired correction with the least capital investment.

4. Regenerative power management—Regeneration of electric power back into the catenary to decelerate an electric locomotive has been considered as a method to conserve energy and assist in braking. Regeneration must be researched and all of the problems, costs, and benefits determined to arrive at a policy for large-scale electrification. The problems at the interface with the utilities must be explored and resolved so that there is a clear understanding of the nature of energy regenerated to the utility.

Catenary Improvements

Automated Catenary Installation

The amount of catenary installed in the United States in the last 40 years has not been sufficient to preserve and update the installation techniques and skills developed in the first quarter of the century. Furthermore, the techniques developed were labor intensive. Significant savings can be achieved if labor costs, which represent more than 50 percent of the capital investment in catenary, can be reduced by using automated equipment that is track mounted. Research and development are needed to determine the degree of automation that will be most cost-effective for large-scale catenary installation in the United States and to develop the necessary equipment to demonstrate that capability.

The installation of foundations and pole setting are labor-intensive tasks in which mechanization can significantly reduce the cost, e.g., through the use of a work train equipped with augers, backhoes, and mechanized pole-setting equipment. This approach is reasonable when "work windows" of 2 to 3 h are available. When soil conditions are poor, the time required for blasting, pile- and casement-driving operations, and pouring concrete for gravity foundations lowers the installation rate significantly. It is then more reasonable to separate the drilling and pole-setting tasks or to perform the work by using road-or-rail vehicles that do not block the track as much or by using off-track equipment only.

The use of a train for large-scale stringing of catenary appears to be necessary even though stringing 1.6 to 3.2-km (1 to 2-mile) lengths requires long work windows. Mechanization to increase the speed of stringing and to perform the stringing in one pass is desirable. Final adjustment is a labor-intensive task for which little mechanization has been developed. Experience in design and installation will lead to improvements in this area.

Economical Catenary Design

The railroad electrification anticipated in the United States will most likely develop in two areas—high-speed passenger service and high-density main-line freight service. European experience offers proven catenary designs that are particularly appropriate for upgrading high-speed passenger service and initiating electrified freight service in the United States.

The bulk of U.S. electrification will involve freight service on which the conventional design may prove to be an overdesign in terms of speed requirements. The large capital investment in catenary and installation labor makes it prudent to examine alternative designs that can provide satisfactory performance at lower cost. Potential savings can be achieved by simplifying the design of components, reducing the quantity of materials, and reducing the number of components and using alternative materials. Research and development should identify and evaluate unproven catenary designs that could provide significant reductions in equipment and labor costs.

The simple catenary and trolley wire should be evaluated for low-cost designs. Specific variations that would reduce arcing and wear of trolley wire need to be evaluated, including reducing the sag by reducing span length, increasing wire tension, suspending wire from springs and dampers, adjusting wire height to offset the change in wire slope as pantographs pass supports, and improving the pantograph.

Locomotive and Multiple-Unit Motive Power

Improved Adhesion

The wheels of a locomotive reach their adhesion limit on the rails and start to slip if the locomotive is exerting its maximum tractive effort at speeds below the power limit or if the locomotive is braking at any speed at braking rates that exceed the power-limited tractive effort. The adhesion limit is lowered by wet or icy rails and by higher speed.

Most wheel-slip control systems are additions to the locomotive propulsion plant. These control systems operate by monitoring changes in the speed of individual wheels in comparison to the average speed, sudden drops in the traction-motor current, or acceleration of individual wheels. The monitors initiate a reduction of current to one or more motors or a reduction of braking effort to one or more wheels. The current or braking effort is then restored in some prescribed way to the level of sustained adhesion. The ideal wheel-slip control system would control only the slipping wheels and maintain full power on the rest. Most phase-controlled thyristor rectifier arrangements do not lend themselves to individual motor control, particularly if the rectifiers are arranged sequentially to reduce the reactive power load.

The object of research and development in this area should be to raise the average adhesion limit by at least 25 percent by considering, for example, correlation of the theory of adhesion with experimental measurements, study of the theory of micro-slip adhesion, determination of parameters for use in control-system design, development of rugged but sensitive sensors for use on motor and wheel shafts, development of circuits for use with the sensors to indicate relative wheel velocities and accelerations, and design of propulsion control systems. The results should be applicable to both alternating- and direct-current traction-motor locomotives.

Improving Power Density

The productivity of a locomotive is limited by the maximum tractive force it can exert at low speeds and the power the propulsion plant can deliver at high speeds. A fixed amount of power can be traded off between tractive force and the maximum speed of the locomotive by changing the gear ratio. The tractive force at low speed is always limited by adhesion.

Alternating-current squirrel-cage traction motors of up to 1.1 MW (1500 hp) can be built for axle or truck mounting. Alternating-current synchronous motors can be built with stationary field windings in the Lundell construction or in the brushless-exciter form. The motor can also be built as a two-stage motor in a single frame for operation at synchronous speed. The cascaded motor will then permit the injection of small speed-changing signals for adhesion control of individual motors, even though a single main converter plant is used for economy.

Research and development are required on advanced types of propulsion systems, including such candidate systems as inverter-driven synchronous traction motors and inverter-driven asynchronous traction motors. Some of the primary goals of research and development in this area should be greater power and productivity of the locomotive without an increase in its weight, improved truck dynamics through reduction in the motor weight for a given level of power, reduction in motor maintenance and levels of harmonics and electromagnetic interference (EMI) through the use of brushless alternating-current traction motors.

Regeneration in Electric Locomotives

Regeneration of electric power to the catenary to decelerate an electric locomotive has been considered as a means to conserve energy and assist in braking. Regeneration of power from a motor to the supply line has been used for many years with direct-current motors supplied from motor/generator sets or from rectifiers. When the direct-current motor must be decelerated rapidly or reversed, the field current is manipulated to make the direct-current motor act as a generator and the kinetic energy of the motor and its load is pumped back to the source.

There are four problems with regeneration on railroad equipment. First, the actual energy savings are relatively low compared with the total amount used—perhaps 10 to 20 percent. Second, the propulsion control system must be more complicated so that it can handle the regeneration requirement. Third, the substations must be equipped to receive power from the catenary when there are no other trains on the same catenary section to absorb the power. Fourth, the locomotive or powered car must still be equipped to handle the full braking function with dynamic braking if the car is not able to regenerate in a particular operating mode.

The areas of research and development that must be considered are determination of how much energy can be recovered by regeneration, evaluation of the costs and benefits, development of equipment for the locomotive or multiple-unit car to handle regeneration, and development of braking systems that will incorporate all of the modes (traction, dynamic, and regenerative) to match all operating conditions.

Control of Power Harmonics and EMI

Thyristor control of the traction motors on electric locomotives may cause severe electrical noise within the locomotive and produce harmonics of the supply frequency in the catenary-wire and substation currents. These harmonics cause interference in trackside signal and communication circuits, in nearby telephone circuits, and in the utility and supply system to the railroad.

Compared with multistep tap-changing transformers on the older alternating-current locomotives, the consequence of using thyristor control and 60-Hz catenaries will be greater induction over a higher frequency spectrum. The methods that have been used to try to control interference include installing power filters on the locomotives, burying all of the wayside signal and communication circuits, installing waveform-shaping active filters on the locomotive, and using power harmonic filters at the substations.

The areas of research and development that must be considered are methods to reduce EMI by using wayside railroad and public communication facilities, techniques to minimize the interference from power semiconductor circuits on controls and signal equipment on locomotives, methods to reduce radiated EMI, and methods to reduce the generation of power harmonics on the locomotive and their transmission through the substations. The primary results of research and development in this area will be the establishment of design guidelines to reduce the effects of power harmonics and EMI, the establishment of standards for acceptable levels of interference, and the development of construction and grounding techniques that provide protection to equipment susceptible to the interference.

IMPACT OF RESEARCH AND DEVELOPMENT ON THE ECONOMICS OF ELECTRIFICATION

Historically, electrification has been considered primarily for the investment gain, since implementation on routes with high traffic density offers an attractive return on investment. The relative capital and operating-cost structures for a railroad with high traffic density are shown below; these summaries are presented to indicate the direction and emphasis of any proposed research and development effort. The capital cost summary shows a relatively even distribution of costs over three of the principal elements—locomotive, catenary, and power supply (2).

Item	Percentage of Total Costs
Catenary costs	21
Utility and substation costs	27
Connection (30 percent)	
Utility reinforcement (40 percent)	
Railroad substations (30 percent)	
Signaling, control, and communications costs	12
Engineering and design of fixed plant	9
Other fixed capital costs	10
Locomotive costs	21

The operating cost summary indicates that about half of the transportation expenses (energy costs) can be affected by research and development (2, 3).

Accounting Item	Percentage of Total Cost	Percentage Affected by Research and Development Related to Electrification
Maintenance of roadway and structure	10	1
Maintenance of equipment	20	5
Transportation expense accounts	65	30
Traffic, miscellaneous, and general expenses	5	–

A summary of the estimated benefits and costs for the hardware-related items described above is shown in Table 1. These benefits and costs have been analyzed and determined for a specific plan of electrification, described elsewhere in detail (4). The near-term research and development can be achieved and brought to the implementation stage in 5 years with the funding indicated; the mid-term research and development can be implemented in 10 years with the funding indicated. The negative numbers represent savings that can be achieved in the operating and capital costs (note that the capital cost for regenerative power management indicates an equip-

Table 1. Estimated costs or savings of research and development.

Research and Development Area		Costs or Savings as a Percentage of Operating Costs	Costs or Savings as a Percentage of Capital Costs	Cost of Research and Development as a Percentage of Cost Savings
Number	Description			
	Near-term			
1	Reduction of peak demand	-6	-6	0.5
2	Improvement of phase balance		-7	1
3	Reduction of reactive power	-3	-2	2
4	Automated catenary installation		-2	15
5	Motive-power wheel-slip control	-1	-4	5
6	Harmonic and electromagnetic interference control		-2	5
	Mid-term			
7	Regenerative power management	-4	+1	2
8	Economic catenary design		-2	5
9	Improvement of locomotive power density	-0.5	-2	10

Table 2. Impact of research and development projects on major areas of cost savings.

Project	Research and Development Area: Near-Term Results 1	2	3	4	5	6	Other	Mid-Term Results 7	8	9	Other
Wayside equipment technology											
Development of substation equipment for power factor control[a]	X	X	X				X				X
Improved transformer design[a]	X					X	X				
Wayside energy storage[b]	X	X	X			X		X			X
Load and fault discrimination							X				X
Improved alternating-current switchgear[a]							X				X
Improved voltage regulation			X				X				X
Modular substation design[a]											X
Reduction of substation electromagnetic interference						X	X				X
Upgrading signal and communication equipment[a,b]							X				X
Establishment of signal and communication interference limits[a]						X	X				X
Application of fiber optics to signaling and communication[a]											X
Catenary technology											
Phase-break design[a]		X					X				X
Catenary design standards[a]				X			X		X		X
Breakaway catenary-suspension design									X		X
Evaluation of the trolley wire configuration				X			X		X		X
Corrosion effects of diesel-electric exhaust							X		X		X
Evaluation of alternative conductor materials[a]							X		X		X
Evaluation of improved pantograph wear-strip materials[a]							X		X		X
Pantograph shoe standards							X		X		X
Evaluation of servo-operated and two-tier pantographs[a]							X		X		X
Development of vandal-proof insulators[a]							X				X
Reduction of rail bond impedance[a]							X				X
Development of emergency safety standards[a,b]							X				X
Locomotive technology											
Conversion from diesel electric to electric							X				
Hybrid locomotives							X				X
On-board battery power											
Development of alternating-current traction motor[a,b]	X	X	X		X	X	X	X		X	X
Electric traction test facility[b]	X	X	X	X	X	X	X	X	X	X	X
Evaluation of traction-motor suspension concepts[a,b]					X		X			X	X
Improved performance and reliability of direct-current traction motor systems[a]	X		X		X	X	X	X		X	X
Development of harmonic filter systems			X			X	X				X
Development of variable frequency power control[a,b]	X	X	X		X	X	X	X		X	X
Transformer coolant alternatives[a,b]							X				
Wheel-slip sensors[a]					X		X			X	X
Skid-bar insulation and rooftop safety standards							X				X
Multiple-unit and multiple-locomotive connections and controls[a]							X				X
Modular controls							X				X
Development of auxiliary power[a,b]							X				X

[a]Under way with industry funding. [b]Under way with government funding.

ment cost associated with implementation).

Considerable benefits can be achieved with the near-term research and development, particularly in the areas of the interface between the utility and the substations and railroad and motive power improvements. The potential savings in capital and operating costs for some applications may be as large as the savings achieved in conversion from diesel-electric to all-electric operation. In such cases the return on investment could be expected to double. It would appear that one of the significant benefits of near-term research and development for any application would be to provide leverage in reducing the risks of electrification.

The cost savings identified are not directly additive since it is not appropriate to assume that all of the research and development benefits can be obtained simultaneously. For example, a reduction in peak power demand will reduce the benefits that can be obtained from research and development to obtain reactive power reduction. Likewise, improvement of motive power density can reduce the locomotive fleet and thereby alter the reactive and regenerative power benefits. It is estimated that the total benefits, if all the research and development areas listed in Table 1 were successfully completed, would be cost savings of 15 to 20 percent. These savings would result primarily from reduced capital investment. To obtain the maximum benefit from this research and development, it should be completed before or be concurrent with implementation of electrification.

The research and development costs are also shown as percentages of the cost savings. The ratio of benefits to research and development costs can be constructed to measure the leverage of research and development. This ratio can also be used to order the priorities for possible projects. Since the leverage for such areas as automated catenary installation and locomotive power density is low, research and development in these areas should be considered only in the light of whether a major commitment to railroad electrification in the United States is to be made. Improved locomotive power density appears to be a critical element in the successful operation of high-speed rail passenger service, and research and development in this area may be requisite to successful implementation.

PLANNING RESEARCH AND DEVELOPMENT

The major areas of research and development for which significant benefits in cost savings could be obtained have been identified above. Table 2 shows the impact of specific research and development projects on these major areas. Setting priorities for candidate projects should reflect the number of areas affected by an individual project. For example, development of an electric traction test facility and traction motor affects most of the research and development areas and therefore represents a high-priority candidate project.

Although a significant portion of the research and development listed is under way, there has been no focus to this work to date. It is essential that an overall electrification research and development program be developed that defines the roles of industry and government and that will focus present and future research and development to achieve the greatest benefits from electrification. The FRA's Office of Research and Development has been assigned the responsibility for railroad electrification research and development and should be expected to provide such a focus.

The primary source of the individual research and development topics identified in this paper was a series of government and industry workshops, sponsored by the FRA's Office of Research and Development, that had as their objective the identification of candidate research and development projects that could significantly benefit railroad electrification in the United States (4). The topics have been screened to eliminate high-risk projects or those that would produce insignificant benefits. The topics presented in Table 2 represent only a partial listing, and continual updating and extension are required to reflect the changing state of the art.

CONCLUSIONS

There are no technological breakthroughs on the horizon that would make obsolete an electrification system that used the present technology. Selected research and development projects that could be implemented in the next 5 to 10 years could result in significant cost savings to both the capital and operating cost structures of an electrified railroad. The research and development costs in most instances represent a very small percentage of the cost savings that could be obtained. Specific electrification research and development projects have been shown to affect many of the areas for which cost savings have been estimated. This research and development consists primarily of the assessment and development of technology to define, evaluate, and improve the equipment, systems, and procedures to be applied to current and planned railroad electrification.

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Comments on Technological Issues

Comment

Per Erik Olson, ASEA, Inc., White Plains, New York

In discussing the economic life span of electric and diesel-electric locomotives, several figures were mentioned. Actual studies of about 1000 electric locomotives belonging to the Swedish State Railways indicated that more than 50 percent of the fleet in use in 1976 was more than 25 years old; the percentages are shown below.

Age of Locomotive (years)	Electric Locomotives		Diesel-Electric Locomotive
	SJ71	SJ76	EMD76
5	94	92	85
10	90	83	65
15	82.5	76	45
20	69	66	30
25	56	51.8	10

Comment

E. R. Corneil, Canadian Institute of Guided Ground Transport, Kingston, Ontario

During the discussion of the issues, Mr. Cogswell suggested that the Canadian study differed from previous studies in considering that energy-cost savings were more important than maintenance-cost savings. The following points related to this observation should be taken into account.

1. We cannot agree that electric locomotives of equal axle power will engender only 60 percent of the maintenance costs of a diesel-electric unit. The increased power of the electric locomotive increases the wheel wear. The additional cost of the higher power components, such as the traction motors, will increase the costs of parts. The additional electronic equipment increases maintenance and parts costs. Typically, workers in the electric trades must have a higher skill level and therefore earn higher wage rates than those whose work is related to diesel-engine maintenance. After careful analysis by railway locomotive maintenance personnel, including a review of maintenance records of electrified railways in both Europe and North America, we adopted our figure of 75 percent.
2. The cost of maintaining the electric supply and catenary adds to the maintenance cost of the electrified system.
3. The ratio for replacing diesel-electric with electric locomotives is dependent on terrain. In mountainous territory, only 1.25 diesel-electric units may be able to be replaced by one electric unit, whereas in flat terrain (grades of less than 0.6 percent) the ratio may be as high as 3 to 1. In our analysis, we used a ratio of 2 to 1.
4. Energy prices are difficult to define. Canadian crude oil prices are rapidly approaching world price levels. Railway diesel fuel costs are already substantially higher than those quoted a few months ago. The diesel fuel prices used in the study were based on projections of world crude oil prices. On the other hand, prices of electric energy are not as high in Canada, although they are projected to rise at approximately the same rate that U.S. projections suggest. Again, costs of fuel and electric energy are specific to the region. Hence, energy savings may be lower for railway lines in some areas.

Each analysis can therefore result in variations in the significance of various factors. Maintenance costs are less uncertain than energy costs, and their absolute values are much lower. In the Canadian study, the sensitivity analysis revealed that energy costs were the most important operating parameter and that maintenance costs were less important.

Comment

Richard V. Cogswell, Federal Railroad Administration

The accounting system prescribed for railroads by the Interstate Commerce Commission (ICC) is rather complex and requires the use of an instruction book in order to fully understand where and under which headings all the costs associated with locomotive maintenance are to be found. The uninitiated will assume that all entries in account 311 (locomotive maintenance) cover all the costs associated with locomotive maintenance. Nothing could be further from the truth. Account 311 does represent about two-thirds of the total locomotive maintenance costs.

Major costs not found in account 311 include supervision, old-age and retirement payments, unemployment taxes, daily locomotive inspections and servicing, and the utility costs of running a maintenance shop. To be totally accurate, part or all of accounts 301, 302, 304, 332, 335, 388, and 400, as well as accounts for old-age and retirement taxes and unemployment insurance must be added to the entries found in account 311. When these direct costs are factored into those given in the presentation by Max Ephraim, the average maintenance cost quoted increases from \$30 000/year to about \$45 000/year.

It is difficult to understand why maintenance costs for a fleet that averages only 3.42 years old are quoted at the beginning of the paper, while a life span of 25 years is referred to shortly thereafter. A 3.42-year-old diesel has hardly had its first power-assembly change, much less an engine overhaul, generator replacement, or any of the major overhaul work usually performed by the railroad later in the life of the unit. Objectivity would dictate using the average maintenance cost over the expected life of the locomotive and not the first 3.42 years. Detailed studies of locomotive maintenance costs by many railroads have shown that the average annual maintenance cost of a 2.24-MW (3000-hp) diesel-electric locomotive over its expected life is about \$65 000 in 1975 dollars, rather than the \$42 000 quoted.

Several major railroad studies have confirmed the breakdown of maintenance costs by percentages shown, but only for new locomotives. These studies have shown that when the unit reaches an age of 15 years the prime mover and its associated subsystems consume nearly 65 percent of the maintenance costs. Again, objectivity would demand a more realistic figure if a locomotive life of 25 years is to be used.

Reply

Max Ephraim, Jr., General Motors Corporation, La Grange, Illinois

Cogswell is correct in noting that ICC account 311 does not include all of the maintenance costs associated with locomotive operation. However, because of the method of accounting, it is not feasible to accurately assign the aggregate costs of the several other accounts to the freight and passenger locomotives. His assumption that account 311 represents about two-thirds of the total locomotive maintenance costs is subject to debate.

The example I gave of the maintenance costs of 202 modern 2.24-MW (3000-hp) diesel-electric locomotives represents one of the few sets of data available to us and was presented to establish the current magnitude of maintenance costs incurred by modern diesel motive power that incorporates the improved low-maintenance features that were not available in older motive power. Even if data were available on locomotives that are 25 years old, they would not represent the costs associated with current designs. Because of the scarcity of accurate maintenance cost data, the maintenance costs constructed for available 2.24-MW diesel-electric locomotives were used to establish a basis for comparing diesel-electric and electric locomotive costs on a relative basis.

Mr. Corneil is correct in stating that the use of more power per axle on electric locomotives will result in increased maintenance costs for the wheels and traction motors of electric locomotives. At the present time, no data are available to establish the probable increase in costs that will result from this higher power rating per axle. In the absence of data, maintenance costs for electric locomotives were not increased for this effect.

Comment

Laurie D. Tufts, Canadian Pacific, Ltd., Montreal

The subject of electric and diesel-electric maintenance costs of modern high-power locomotives is a subject of great controversy in all feasibility studies being conducted on railroad electrification in North America. A committee of the American Railway Engineering Association (AREA) reported (1):

> Actual maintenance costs for main-line thyristor-controlled electric locomotives are nonexistent in North America today. Studies by many railroads and the U.S. Department of Transportation indicate that an electric locomotive can be maintained for about 40% of the high-horsepower diesel. Any reduction in fleet size must be applied to the 40% figure to arrive at a cost per gross ton-mile; thus, if one electric were to replace two diesels, the cost per gross ton-mile would be about 20% of what it now costs with diesels. Since this ratio is unique to each railroad, no attempt will be made to assign a maintenance cost per gross ton-mile for electric locomotives.

European figures indicate that electric locomotive maintenance costs about 30 to 35 percent that of a diesel-electric locomotive on a unit basis. On the basis of the AREA figures and European experience, the figure of 75 percent cited by Mr. Corneil appears high.

REFERENCE

1. Electrification Economics. AREA Bulletin, Proc. Vol. 75, No. 646, Jan.-Feb. 1974, pp. 642-651.

Comment

TRB Committee on Electrification Systems

As is indicated by the comments of a number of contributors and by the papers presented, the subject of locomotive maintenance for diesel-electric and electric locomotives is a subject of considerable controversy. Committee examination indicates that past experience and studies have estimated the costs of maintenance of electric locomotives at 60 to 75 percent that of diesel locomotives on the basis of individual units and from 30 to 50 percent that of diesel-electric locomotives on a fleet basis. As is indicated in the papers and comments, it appears that the principal area of cost savings is in the diesel engine and its associated auxiliary systems.

Comment

Robert B. Ryan, Mitre Corporation, McLean, Virginia

Throughout the discussions at this conference only minimal attention has been paid to the energy savings that could be achieved by regenerative braking systems on electrified railroads. In view of the facts that, from approximately World War I to the early 1950s, the Chicago, Milwaukee, St. Paul and Pacific Railroad Company obtained 12 to 15 percent energy recovery from electricity generated by descending trains applied as a supplemental power source for ascending trains and that regenerative braking has a long history of use, why is this technical area not being pursued by the railroads, governmental agencies (particularly the Transportation Systems Center of the U.S. Department of Transportation), or industry?

There is apparently little or no interface with research programs under way at the Energy Research and Development Administration, in which such simple devices as flywheels have been proposed to equalize the imbalances that would be caused by the intermittent electrical feedbacks created by regenerative braking at basically unscheduled points in the overall electric demand cycle.

Reply

Richard A. Uher, Carnegie-Mellon University, Pittsburgh

In a study on energy savings by regeneration on a proposed electrified railroad between Harrisburg and Pittsburgh, which was completed at Carnegie-Mellon University in July 1977, we found that under the present operating practices the regeneration savings amounted to 9 percent in energy and 7 percent in energy cost. The results were based on hauling 51.5 gross Tg/year (56.8 million gross tons/year) in each direction. This represented about a 16 percent return on the investment of adding regenerative capability to the electric locomotive. It was found that almost all savings occurred in the Johnstown-to-Altoona portion of the line and a section from Pitcairn east about 40 km (25 miles). These areas were characterized by steep grades.

The results of this study indicate that both steep grades and heavy traffic are required for regeneration to be cost-effective. There are not many railroads that can justify regeneration in terms of the rate of return.

Issues Discussed in Workshop

Conference participants were invited to submit, at the workshop held on the last day, written comments on any topics they believed had not been fully covered in the prepared papers and comments on those papers. This section contains the statements that were submitted and, in some cases, comments in reply.

Comment

E. R. Corneil, Canadian Institute of Guided Ground Transport, Kingston, Ontario

There were several issues that we identified in the Canadian study.

1. Economic evaluation requires increased confidence in the projections of energy costs, both for diesel fuel and for electric energy. These factors are the most important among the operating cost factors in an electrification study. The costs of maintenance are relatively insignificant in comparison. In terms of capital costs, identification of the factors that increase these costs and ways to reduce the costs of catenary, public works, and signal modification would be valuable.
2. Electrification in the European manner implies shorter trains. Benefits, both technical and economic, can be gained by reducing the loads of the larger, heavier trains—the long unit trains of North America. Electrical demand is reduced, the demand factor improves, and energy costs therefore go down. The effects on the utilities become less important, and some saving in capital costs can be achieved. Are the railways prepared to adapt their system of operation, reducing train power levels to 6 to 9 MW (8000 to 12 000 hp) in order to achieve these benefits?
3. The major technical problem will be the interconnection of rail electrification and the utility systems. Alternatives include individual substation connection (with possibly serious effects on energy costs), the use of Scott transformers, and a railway transmission line to provide a single point of connection. This technical area requires additional study to investigate the significance of some of the utility problems Blair Ross identified.

Reply

Myles B. Mitchell, Federal Railroad Administration; Blair A. Ross, American Electric Power Service Company, Lancaster, Ohio; and Richard A. Uher, Carnegie-Mellon University

One might well take issue with the statement that "the costs of maintenance are relatively insignificant in comparison" to energy costs. Historically diesel locomotive maintenance has been roughly equal to the annual energy (fuel) cost per unit. Electric locomotive maintenance is estimated to cost 30 percent as much as diesel maintenance (on the basis of equal power). Therefore, maintenance savings are very significant.

The second item, which advocates running shorter trains in order to reduce demand charges, is controversial and may only prove economically sound under certain circumstances. The economics would depend on the nature of the power distribution system used as well as on the cost of the extra employees needed to run shorter trains.

The third item is not so much a technical problem as an economic one. However, it certainly is a problem that must be addressed in site-specific terms, so that the economics can clearly be determined. The Canadian electrification report did find that energy costs play a significant role in determining the cost-benefit of electrification. There does not appear to be any major technical problem associated with the interconnection of rail electrification and the utility system for which there are not already proven solutions based on European or other foreign experience.

Comment

Cecil E. Law, Canadian Institute of Guided Ground Transport, Kingston, Ontario

There are three frequently made criticisms of rail electrification that I find particularly misleading.

The first of these is the statement that, since railways use only 3 to 4 percent (A. D. Little says 1.6 to 2 percent) of petroleum fuels in the United States and 5 to 6 percent in Canada, and since electrification would only save about half this quantity, electrification will not be a major saver of petroleum energy. The fallacy in this is that, since we are talking about future savings, past ratios are of little significance. Since the impact of a severe petroleum shortage will be reflected in higher fuel prices and perhaps outright rationing, there will be a significant reduction in the use of automobiles, long-haul trucking, and the use of oil and gas for heating and power generation. The reduction in the first two will (we hope) satisfactorily reduce the base of petroleum use, and automobiles and trucks will have to be replaced by the more efficient form of transport, the train. The third will further reduce the base and add demand to the rail share. We would then be dealing with a 30 or 40 percent reduction in base fuel use along with a tripling or quadrupling of rail use. This new share of use would result in savings of 7 to 13.3 percent, quite a significant amount, particularly since the reduction is entirely in foreign exchange. For Canada the change is even more impressive: 21.4 to 40 percent. (This assumes that the railways are only half electrified in either case.)

The second point relates to return on investment. People are always talking about projects that will return 30 to 40 percent before taxes. (If such a return were available, one should borrow money to carry them out!) But projects costing a few million dollars are not to be considered in the same breath as new investment of such magnitude that it alters the very nature of the business. An investment of 1 or 2 percent of the company's capital, whatever its rate of return, will have no discernible effect on corporate profit. An investment that represents 25 percent or so of total corporate investment and produces a return of 15 to 20 percent after taxes (the apparent return for a large-scale electrification project) represents 3 to 4 percent added return on the total corporate investment; this is about 2 to 3 times what most railroads are carrying now. If Henry Ford had been as slow to move as we are, they would still be making buggy whips in Detroit!

My third complaint concerns the time span of investment in electrification. It will take at least 5 years to get a major electrification program started and about 20 years to complete the conversion process. Spreading the total investment required over 20 years not only reduces the average annual investment to a manageable $50 million to $100 million for most major railroads, but it also ensures that the last few years' investment will be generated by the profits from the first few years' investment.

If there is indeed a fuel crisis coming (and only a fool would say that is not highly likely) or if electrification is otherwise inevitable, then the sooner one begins, the better off he will be in strictly financial terms, to say nothing of the greater ease (reduced interference) in making the change.

Reply

Richard A. Uher, Carnegie-Mellon University

Law's comment on petroleum conservation is interesting since it incorporates the idea of a modal shift from highway to rail as a result of electrification. However, the figures he quotes are dependent on a hypothetical situation that represents rather extreme circumstances.

Comment

Herbert G. McClean, Transport International California, Carmel, California

If the federal government wishes to encourage electrification, it should help to minimize the economic and technical risks. Some railroads have expressed interest in being the second railroad to electrify. We can understand this attitude and why shareholders applaud it. It may be helpful to recall why dieselization was introduced so successfully.

In about 1945, there were 100 class 1 railroads, many of which were facing bankruptcy, whereas today our 10 major railroads are profitable. Thirty years ago, diesels could be tried and proven by a small investment. One train, like the Denver Zephyr operating 1600 km (1000 miles) a night, could establish reliability and economy.

Electrification, on the other hand, involves a big initial investment. The diesels' return on investment often exceeded 25 percent; money was plentiful; interest rates were only 3 percent; and banks offered 8-year financing. Banks insisted on manufacturers' standards since, in default, a repossessed locomotive was suitable for resale. All 100 railroads therefore had the same locomotive. Experience was pooled; spare parts, servicing, and training were simplified; and the cost of diesel locomotives was kept low.

Today's price for a six-axle 2.24-MW (3000-hp) freight locomotive weighing 180 Mg (200 tons) is around $600 000. This is only $3.33/kg ($1.50/lb). A standard box car costs $2.22/kg ($1/lb) and a transit car $22/kg ($10/lb). To my knowledge, modern European six-axle electric or diesel-electric locomotives sell for more than $1 million. And they weigh only 115 Mg (125 tons) or $9/kg ($4/lb). I know they have much higher power ratings. European railroads stress passengers and speed. Here we stress freight and profit. Our railroads need assurances to minimize the economic and engineering risks.

In a recent A. D. Little study for the Consolidated Rail Corporation, estimated electrification costs for 10 different divisions were compared with costs in similar studies by General Electric for the United States Railway Association. The annual traffic densities ranged from 48 to 149 Tg·km (33 million to 102 million ton-miles), and the cost estimates differed accordingly. These differences, as well as unsolved engineering problems, will only be resolved, I believe, by a first trial of electrification. The Northeast Corridor reelectrification represents a special case and is designed for passenger service, so it will not give all the answers.

To minimize the risk, I believe the federal government should make a grant sufficient to cover the cost of electrifying a typical average length of freight railroad that covers terrain of average climate and grade and has average traffic density and typical traffic imbalance. The experiment could test and compare U.S. and foreign practice, use catenary suitable for freight speeds but modifiable for higher passenger speeds, set limits of telecommunication interference, and test locomotives of various wheel arrangements, axle loads, and control schemes.

It is essential that the railroads themselves, not some department of government, do this job. A grant of $150 million for this purpose would still be a small grant compared with the $11.8 billion that has been provided for mass transit grants in the last 5 years.

Comment

Robert B. Ryan, Mitre Corporation, McLean, Virginia

I should like to put forward a few thoughts on the neglected topic of energy policy. First, I wish to stress that I am speaking as an individual, not as a representative of the Mitre Corporation, which has prepared studies for the Federal Railway Administration, particularly in connection with the Northeast Corridor. I am not an electrical engineer or a railway man but a geologist.

As a geologist I do not need additional evidence to convince me that the energy crisis is real, that our fossil fuel resources are finite, and that our oil resources (on which we depend to operate our railroads) are strictly limited. We have heard here the views of electrical engineers, members of the financial community, officials of the federal government, and representatives of the electric power industry and the railroads. All the points these speakers have made are accurate, but in my view the subject has been incompletely covered. All the technical and economic points made here would become completely academic if choosing electrification becomes necessary for the survival of the American railroads. Much of the conventional economics of the past (on which many of the presentations here have been based) may be completely altered by the geological facts and new economics of a true energy shortage.

It is only a matter of when we run out, not whether we do or not. This depends heavily on our current, mind-boggling rate of consumption. Other speakers have stressed that the railroads use 2 percent or 4 percent or less than 2 percent of our national annual fuel consumption. But let us convert that 2 percent into cubic meters over the years, given an ever increasing appetite for crude oil, and then superimpose an Arab embargo, an event not unlikely in the light of Middle Eastern geopolitics in the past few years, and we find that 2 percent will be translated into a rather large number of cubic meters of oil.

The energy agencies of the U.S. government with which I have had professional contact, primarily the Federal Energy Administration and the Energy Resource and Development Administration, are very much concerned with the problem of switching from oil and natural gas to coal. Both the utilities and major fuel-burning industries will be affected. I have not heard the vital topic of fuel substitution or fuel switching as it affects a policy of electrification brought up by any speaker at this conference. Yet it may well be the most important event to occur in U.S. industries within the next decade. Switching to electric traction may not be an option; it may well become a necessity. At this moment there is considerable federal emphasis on the feasibility of conversion of utility and industrial boilers from natural gas or fuel oil to coal. The railroad industry represents a significant component of the transportation sector of our economy that has a capability to convert from oil to coal. An order to switch may well carry an immediate advantage and will certainly carry a long-range advantage.

The Burlington Northern, for example, could bring some of its magnificent old coal-burning articulated trains out of storage or out of the museums. The Norfolk and Western Railway Company may have a Y-6 in its future as well as in its past. Although as a longtime railroad enthusiast I would welcome such a trend, I do not believe either the economists or the master mechanics would view this with a large amount of pleasure. But by using coal-fired electric power generation, these great railroads could again burn coal to haul coal.

I have not seen a coal-burning airplane or automobile, although I saw some in Japan immediately after World War II. I do not believe that the maritime industry will convert its marine boilers to coal, but the utility industry will. New construction will be for coal, and the industry is now under considerable pressure to convert its boilers from gas or petroleum to coal.

Another point not mentioned is that all of the alternative energy sources in various stages of development or suggested as substitutes for reliance on expensive imported crude oil and its products (solar power, geothermal power, and most importantly nuclear power) do not produce oil but electricity. Plentiful electricity in an era of shortage of oil is not going to do the railroads any good unless they have electric locomotives, catenary, and all of the infrastructure to operate electrified trains in place. The future prices of increasingly scarce domestic crude oil or increasingly costly imported crude oil cannot be forecast with authority. Their supply can. I do not believe we can use the facts and the cost studies of the past as a basis for a sound decision about the costs of operations in the future. I do believe, as some speakers have mentioned, that the cost of coal will very likely follow the cost of oil (possibly lagging a bit), and the cost of electricity to run locomotives may well be no cheaper than that of oil. Other advantages in the areas of power and maintenance have been competently discussed.

But now let us look at an area that has not been discussed—government policy. Special taxes may be levied; measures may be taken to allocate our scarce oil to those sectors of our economy in which there is no possible substitution. In the transportation sector this would primarily involve the private automobile and the motor bus, trucking, and airline industries. Since electric locomotives can substitute for diesels, in a crunch they may have to. Then the electrified railroads will have a large menu of potential power sources from which to choose, but coal will probably still be the primary power source.

Therefore, I firmly believe that, given the facts that alternative energy technologies are designed to produce electricity, that oil is a finite resource of constantly increasing cost, and that there is a more than even chance that the United States may be subject to another embargo, electrification would be a sound investment to ensure that the railroads could operate independently of either domestic or foreign oil. This is an aspect of the railroads' operational future that the bookkeepers and economists cannot define. In fact all of us have a problem in defining this issue. Do we have 10 years of oil left or 20 or 30 or 40 or more? A great deal of this depends on the rate at which we use it; far less depends on the rate at which we find it. If we are using it faster than we are finding it (and we are), then we have to import still more. At a certain point, (a) the balance-of-payments deficit involved in a massive dependence on foreign oil may become intolerable for any government and (b) we will then enter that never-never land that cannot be predicted by previous experience—the behavior patterns of government regulatory agencies involved in allocations, rationing, and a controlled distribution of an increasingly scarce natural resource.

We began running out of oil on the day we first started using it. It is the rate at which we are running out of oil that is the focus of this discussion. This rate depends on the rate at which we consume it, the price, geopolitics, and, to a lesser extent, the rate at which new fields are found. New fields will be found, but as man goes farther offshore or farther into the Arctic to find his new fields, oil will become more and more expensive. Laws of scarcity, supply, and demand have always operated that way. When we start to manufacture oil the costs will be high, whether we are using the Athabaska Tar Sands, the shales of the American West, or coal.

Earlier we heard a very well-made case against the coal-slurry pipeline and its potential impact on the railroads, particularly the Burlington Northern. However, let us look at this from a national point of view. Slurry pipelines will probably be powered by efficient electric-motor-driven pumps. If we must move our coal by the most energy-efficient system, is not an electric-powered slurry pipeline more efficient than a diesel-electric unit train that burns oil? On the other hand, an electrified railroad would be burning coal to move coal or burning sunshine or nuclear power to move coal. Should we run into another geopolitical crisis like that in 1973 (but probably many times more unpleasant), we may find a governmental fuel-oil allocation process based on what we might call the survival of the fittest. I know that the railroads, as an energy-efficient transportation system, would be allocated oil, but I have an uneasy feeling that, under those circumstances, an electric-powered railroad would continue to operate while the oil-powered competition would find itself with at least drastically curtailed capability. We have heard of diesels that can match the electric in longevity and even surpass the GG-1 in service life. Will their last 5 or 10 years be spent in museums?

I would like to suggest a rather disquieting analogy. Do you remember the time shortly after World War II when the railroads were in the process of converting from steam to diesel, and coal-burning steam locomotives were still very much around? John L. Lewis called a major coal strike. Those railroads that had already converted to diesel power continued to operate, but those that depended on coal for fuel were shut down. An oil embargo could have similar consequences.

Comment

Blair A. Ross, American Electric Power Company, Lancaster, Ohio

There have been a lot of studies done on oil prices in this country. This has always been and will continue to be a pivotal question for the railroad manager and for practically all Americans. The first conclusion one reaches in working with oil prices, as I have done for about 5 years, is that they are artificially set up, perhaps more so than the price of any other commodity we have. We have seen the sudden price advance in 1973 brought about by the conflict between Israel and the Arab nations, in which the oil producers essentially quadrupled the price of world oil overnight.

I think most people agree that oil was probably significantly underpriced, although at that time the Arab countries were getting a lot of money and the oil companies' profits looked pretty nice. But, they raised the price and oil from the Middle East is now about \$84.30/m^3 (\$13.40/bbl). There are some constraints, interestingly enough. The Soviet Union now is selling more and more oil on the world market for hard currency. As the price goes up, there is a limit to how much more the Arabs can charge.

The railroads have said they will pay 7.9 to 8.9 cents/L (30 to 34 cents/gal) for domestic oil, but Arab oil would not be available for 7.9 to 8.9 cents/L. If oil from the Middle East were, let us say, \$79.25/m^3 (\$12.60/bbl), which I believe is a little less than the current price, that would amount to 7.9 cents/L right at the oilfield. Then it is shipped over here in a big tanker, which costs about 0.8 cents/L (3 cents/gal) or \$7.55 to \$9.40/m^3 (\$1.20 to \$1.50/bbl). That brings the cost up to 8.7 cents/L (33 cents/gal). Then you have to refine the oil, which costs about \$15.70/m^3 (\$2.50/bbl), another 1 cent/L (4 cents/gal). The cost is now on the order of 9.7 to 10 cents/L (37 to 38 cents/gal). But, you say to yourself, I am getting it for 8.4 cents/L (32 cents/gal). That is because you are operating in an interesting market environment. The U.S. government has told the oil companies that the old domestic oil must come in at \$44.00 or \$50.00/m^3 (\$7.00 or \$8.00/bbl). Working forward would give 5.3 cents/L (20 cents/gal), plus a refining cost of about 1 cent/L (4 cents/gal), plus a much reduced transportation charge of 0.3 cent/L (1 cent/gal). This should result in a cost of 6.6 cents/L (25 cents/gal) for domestic oil. But there is not going to be much domestic oil left. So we have a completely artificial situation in which, if you were competing on the world market today for oil or railroad diesel fuel, the U.S. price would be 11 cents/L (42 cents/gal).

What are the controlling constraints on coal and oil? The constraints on coal basically are the ability to get the investment to mine it, permission from the government for the coal to be mined, and the decision of investors to invest and open these mines. At certain prices there are plenty of reserves that would be worked. At certain prices, people will enter into and go out of the coal market. Therefore, the coal market will probably go forward in price at a rate comparable to that of American inflation, but I do not think it will go forward as fast as oil. The cost of utility construction over the years presents a similar case. If you can tell me what the inflation rate in the United States will be, I can tell you what the construction cost of a unit will be in 1990. But this whole sector of the economy will presumably move forward uniformly.

Right now some studies show that oil prices may reasonably be expected to go up at an annual rate of about 8 percent, and electric energy prices will rise annually by about 6 percent. I do not think we will see a stabilizing of either price. This has certainly been the case in the last 5 years. I am afraid that each one will continue to move upward, but I continue to feel that electricity will rise at the lower rate because, as mentioned, it has a variety of sources. The cost of nuclear plants may well become stabilized. Some people think that their costs have reached a plateau and will stay there for many years, particularly if licensing procedures and other such regulations are eased a little bit and if we are able to develop a standardized plan.

Participants

Addie, Albert N., General Motors Corporation, La Grange, Illinois
Addison, K. W., Electrack Inc., Washington, D.C.
Alexander, Thomas R., Canada Department of Transport, Ottawa, Ontario
Alston, Liviu L., International Bank for Reconstruction and Development, Washington, D.C.
Anania, Peter V., Fischbach and Moore and L. K. Comstock, Landover, Maryland
Anderson, E. P., Southern Pacific Transportation Company, San Francisco
Angold, John A., Atchison, Topeka and Santa Fe Railway Company, Chicago

Baldwin, Robert D., Booker Associates, Inc., Fort Washington, Maryland
Barker, Allan R., Laramore, Douglass and Popham, Chicago
Berland, Abram, Fepasa-Ferrovia Paulista S.A., São Paulo, Brazil
Berti, Roland J., Union Pacific Railroad Company, Omaha
Birkett, Barry, James F. MacLaren Ltd., Willowdale, Ontario
Bizzul, Ash, Joslyn Manufacturing and Supply Company, Chicago
Bolla, Wayne F., Illinois Central Gulf Railroad, Chicago
Breeze, Robert F., National Passenger Rail Corporation, Washington, D.C.
Buck, Richard J., Unified Industries Inc., Alexandria, Virginia
Burd, Steve A., Association of American Railroads, Washington, D.C.

Calder, Graham S. W., Brush Electrical Machines, Ltd., Loughborough, England
Campanelli, John J., Exide Power Systems Division, Woodbury, New Jersey
Campos, Murilo A., Fepasa-Ferrovia Paulista S. A., São Paulo, Brazil
Carmichael, Kenneth M., Canadian Transport Commission, Ottawa, Ontario
Carter, A. H., Bell Laboratories, Whippany, New Jersey
Chirgwin, Keith M., Garrett Corporation, Torrance, California
Clarke, Lyle, Kentron Hawaii, Ltd., Washington, D.C.
Clarke, Walter J., Sverdrup and Parcel and Associates, Inc., Port Washington, New York
Cogswell, Richard U., Federal Railroad Administration, Washington, D.C.
Conly, Richard T., Jr., American Rail Systems Company, a division of Fischbach and Moore, Inc., Bala Cynwyd, Pennsylvania
Corneil, E. R., Canadian Institute of Guided Ground Transport, Kingston, Ontario
Courtemanch, Edgar E., National Railroad Passenger Corporation, Washington, D.C.
Cowell, James M., National Railroad Passenger Corporation, Washington, D.C.
Craven, E. R., Burlington Northern, Inc., St. Paul

Dawalibi, Farid, Shawinigan Engineering Company, Ltd., Montreal, Quebec
DeGennaro, Richard E., Consolidated Rail Corporation, Philadelphia
Duffield, Norman A. T., General Electric Corporation, Manchester, England
Duffy, Terry, Ohio Brass Company, Mansfield, Ohio

Earley, Paul S., L. T. Klauder and Associates, Philadelphia
Ellsworth, Kenneth G., Railway Age, New York
Engel, Albrecht P., General Electric Company, Erie, Pennsylvania
Ephraim, Max, Jr., General Motors Corporation, La Grange, Illinois
Ericson, Helen, New York Journal of Commerce, Washington, D.C.

Ferrante, Daniel J., Electrack Inc., Washington, D.C.
Fishbein, Richard, Kuhn, Loeb and Company, New York
Flohr, Bruce, Federal Railroad Administration, Washington, D.C.
Foley, Ernest P., Gibbs and Hill, Inc., New York
Frasher, Edward P., Consolidated Rail Corporation, Philadelphia
Frazier, George R., Chicago, Milwaukee, St. Paul and Pacific Railroad Company, Tacoma
Freeman, Walter C., Jr., Bell Telephone Laboratories, Whippany, New Jersey

Gannett, M. Clifford, Federal Railroad Administration, Washington, D.C.
Gardrvits, Gerald, Sverdrup and Parcel and Associates, Inc., Port Washington, New York
Gibbons, Eugene F., Eugene F. Gibbons/Henry J. Campbell Consultant Engineers, Garden City, New Jersey
Gilliatt, E. H., Canada Department of Transport, Ottawa, Ontario
Gilman, F. L., Gibbs and Hill, Inc., New York
Gordon, Walter S., Gordon and Cross Engineers, Tacoma
Gowing, M. F., Ohio Brass Company, Mansfield, Ohio
Greenfield, Arthur C., Westinghouse Electric, Washington, D.C.
Gretzinger, A., Slater Products, Hamilton, Ontario
Guarino, Matthew, Federal Railroad Administration, Washington, D.C.
Guinness, Kenelm, Kennedy and Donkin Consulting Engineers, Woking, England

Haile, Edmund F., MCA Engineering Corporation, Baltimore
Hale, Peter, Canadian General Electric, Peterborough, Ontario
Hamberger, Martin G., Attorney at Law, York, Pennsylvania
Hansen, John E., Brotherhood of Railroad Signalmen, Mt. Prospect, Illinois
Harley, Edward T., Consolidated Rail Corporation, King of Prussia, Pennsylvania
Harrison, John A., Federal Railroad Administration, Washington, D.C.
Harvey, C. F., Southern Railway System, Washington, D.C.
Hearin, Jess, General Electric Company, Philadelphia
Hill, Gordon M., De Leuw, Cather-Parsons and Associates, Washington, D.C.
Hoppe, Charles W., Booz-Allen and Hamilton, Inc., Bethesda, Maryland
Hughes, Frank W., Hughes Railway Supplies, Philadelphia
Hursh, Charles, Fischbach and Moore and L. K. Comstock, Landover, Maryland

Innocenzi, Robert A., New Jersey Department of Transportation, Trenton

Jacobs, Marilynne E., Federal Railroad Administration, Washington, D.C.
Jaeger, A., Brown Boveri and Company, Ltd., Baden, Switzerland
Jewell, Hubert H., Jr., National Transportation Safety Board, Washington, D.C.
Jones, Donald T., Copperweld Bimetallics Division, Glassport, Pennsylvania

Kalweit, Burk G., American Trucking Associations, Washington, D.C.
Karman, E., International Bank for Reconstruction and Development, Washington, D.C.
Kelley, William E., Consolidated Rail Corporation, Philadelphia
Kendall, Hugh C., General Railway Signal Company, Rochester, New York
Kitchen, Daniel W., George Beetle Consulting Engineers, Philadelphia
Kitchens, Joel, Bechtel Inc., Washington, D.C.
Knudsen, Clarence V., Michael Baker, Jr., Inc., Harrisburg, Pennsylvania
Kositzky, G. D., Lake Superior and Ishpeming Railroad Company, Marquette, Michigan

Lamphier, Thomas J., Burlington Northern Inc., St. Paul
Lang, A. Scheffer, Association of American Railroads, Washington, D.C.
Langford, Leon D., U.S. Department of Transportation, Oklahoma City
Law, C. E., Canadian Institute of Guided Ground Transport, Kingston, Ontario
Leavy, Robert L., Charles T. Main, Inc., Pelham, New Hampshire
Leslie, J. K., Canadian Pacific Rail, Montreal, Quebec
Levesque, Paul P. E., Shawinigan Engineering Company, Ltd., Montreal, Quebec
Long, Michael, International Engineering Company, San Francisco
Lord, Edward S., Federal Railroad Administration, Washington, D.C.
Love, Mark E., George Beetle Consulting Engineers, Philadelphia
Loy, Harry R., Sanders and Thomas, Pottstown, Pennsylvania
Luscombe, J. S., James F. MacLaren, Ltd., Willowdale, Ontario
Luxford, Terry M., Virginia Research Institute, Inc., Arlington, Virginia

Margolin, Edward, Consultant, Chevy Chase, Maryland
Martin, J. R., Southern Railway System, Atlanta
Maughan, R. C., Maughan Railway Consulting Services, Inc., Montreal, Quebec
McAlpine, Donald, Electrack, Inc., Washington, D.C.
McClean, Herbert G., Transport International California, Carmel
McClellan, James W., Association of American Railroads, Washington, D.C.
McGinnis, Richard G., Bucknell University, Lewisburg, Pennsylvania
Meeker, Merton D., Jr., General Electric Company, Erie, Pennsylvania
Merritt, Robert P., Federal Railroad Administration, Pueblo, Colorado
Michaliszyn, Richard, Canadian National Railways, Montreal, Quebec
Miller, Leon H., International Bank for Reconstruction and Development, Washington, D.C.
Mitchell, Myles B., Federal Railroad Administration, Washington, D.C.
Montague, Peter M., Federal Railroad Administration, Washington, D.C.
Moon, Albert E., Stanford Research Institute International, Menlo Park, California
Muecke, Botho, Sverdrup and Parcel and Associates, Inc., Port Washington, New York
Murray, Robert C., Pennsylvania Public Utility Commission, Harrisburg

Nicholson, Edward F., Port Authority of New York and New Jersey, Jersey City, New Jersey
Nupp, Byron, U.S. Department of Transportation, Washington, D.C.

Olson, Per Erik, ASEA, Inc., White Plains, New York
Osman, J. Russell, Missouri Pacific Railroad Company, St. Louis

Parkhurst, S. W., Newhouse Newspapers, Washington, D.C.
Parsons, Robert E., Federal Railroad Administration, Washington, D.C.
Peerce, William R., De Leuw, Cather-Parsons and Associates, Washington, D.C.

Rangel, John, Illinois Central Gulf Railroad, Chicago
Raposa, Frank L., Transportation Systems Center, U.S. Department of Transportation, Cambridge, Massachusetts
Rappaport, Harry, National Passenger Rail Corporation, Philadelphia
Reistrup, Paul, National Railroad Passenger Corporation, Washington, D.C.
Resor, Randolph R., Association of American Railroads, Washington, D.C.
Reustle, Walter C., American Rail Systems Company, Bala Cynwyd, Pennsylvania
Rewucki, E. J., Canadian Pacific Rail, Toronto, Ontario
Richard, A. Kelly, Virginia Research Institute, Arlington
Roberts, J. T., Southern Railway System, Washington, D.C.
Roberts, Robert H., Modern Railroads, Washington, D.C.
Robertson, William, III, De Leuw Cather and Company, Washington, D.C.

Ross, Blair A., American Electric Power Service Company, Lancaster, Ohio
Ryan, Robert B., Mitre Corporation, McLean, Virginia

Schmidt, Joseph J., National Railroad Passenger Corporation, Washington, D.C.
Schrader, Henry C., Dalton, Dalton, Little, Newport, Washington, D.C.
Schwarm, Edward G., Arthur D. Little, Inc., Cambridge, Massachusetts
Shapp, Milton J., Governor of Pennsylvania, Harrisburg
Shaw, Peter L., Electrack Inc., Washington, D.C.
Shea, R. A., Canadian Pacific Ltd., Montreal, Quebec
Siemens, Werner H., International Engineering Company, San Francisco
Singhal, Ish K., Canadian Transport Commission, Ottawa, Ontario
Smythe, John B., U.S. Department of Transportation, Washington, D.C.
Speh, Paul E., Electromagnetic Compatibility Analysis Center, Annapolis, Maryland
Spink, Frank M., Canada Department of Industry, Trade, and Commerce, Ottawa, Ontario
Srinivasan, R., International Bank for Reconstruction and Development, Washington, D.C.
Stark, J. J., Bessemer and Lake Erie Railroad Company, Greenville, Pennsylvania
Sullivan, John McGrath, Federal Railroad Administration, Washington, D.C.
Swanson, Carl G., Mitre Corporation, McLean, Virginia

Talukdar, Sarosh N., Carnegie-Mellon University, Pittsburgh
Tassin, Y. M., MTE, Montreal, Quebec
Templeton, Patrick A., General Electric Company, Washington, D.C.
Tennyson, Edson L., Pennsylvania Department of Transportation, Harrisburg
Tufts, Laurie D., Canadian Pacific, Ltd., Montreal, Quebec
Tuinstra, William S., Santa Fe Railroad Company, Chicago

Uher, Richard A., Carnegie-Mellon University, Pittsburgh

Van Schaick, E. E., Bessemer and Lake Erie Railroad Company, Greenville, Pennsylvania
Verselle, Richard C., General Motors Corporation, Wayne, Pennsylvania
Vollmar, John R., Louis T. Klauder and Associates, Philadelphia

Waldman, Byron E., U.S. Department of Transportation, Washington, D.C.
Way, George H., Jr., Association of American Railroads, Washington, D.C.
Webb, Joseph W., Daniel-Mann-Johnson and Mendenhall, Baltimore
Wefers, Hans J., Bechtel Inc., San Francisco
Wert, C. F., Westinghouse Air Brake Company, Pittsburgh
Wessells, Daniel, Urban Engineers, Inc., Philadelphia
Whitbred, Willard R., George Beetle Consulting Engineers, Philadelphia
White, David, Bechtel Inc., Washington, D.C.
White, Ronald K., Stanford Research Institute, Menlo Park, California
Wilmot, Douglas G. K., Portec Inc., Oakbrook, Illinois
Wilson, Kendall W., Energy Research and Development Administration, Washington, D.C.
Wise, John, Canada Wire and Cable, Toronto, Ontario
Wofford, Thomas D., Federal Railroad Administration, Washington, D.C.
Woodhead, Gordon E., Electrack Inc., Washington, D.C.

Yatzkan, Irwin, Metropolitan Transportation Authority, New York

Part 2
Annual Meeting Papers

Summary

Liviu L. Alston, International Bank for Reconstruction and Development, Washington, D.C., and Chairman of the Committee on Electrification Systems

In 1977, for the first time, TRB's annual meeting included a session on railroad electrification. Its purpose was to identify some of the main issues that affect railroad electrification and to prepare for a more extensive discussion of these issues at the Conference on Railroad Electrification: The Issues. The papers presented the railroad, economic, financial, and government points of view.

One of the most striking features of the annual meeting session was the apparent enthusiasm for electrification from some members of the audience and the reservations the speakers had about it. The enthusiasm is partly traditional because electrification has in the past been associated with a modern, efficient railway operation. Diesel traction has since been developed, and it has many of the advantages of electrification, with two important exceptions.

First, it uses oil, which, as we are finding out, is a very scarce resource. Diesel traction is, however, in excellent company in this respect since almost all transport derives its energy from oil. In fact, electric railways are the only major means of transport that need not use an oil-based fuel, and this has heightened interest in electrification. However, since U.S. railroads account for only about 2 percent of national oil consumption, the impact of railway electrification on national oil consumption cannot be very significant. On the other hand, electrification could have an important impact on railway fuel costs if, as a result of future price movements, electrical energy became significantly cheaper than diesel fuel.

The second exception is that a diesel locomotive has to carry a small power plant. As a result, maintenance costs for electric traction are substantially less than for diesel traction. But this advantage—and any fuel cost advantage—has to be paid for, literally, by high investment costs in fixed installations. Since these investment costs increase much less than fuel and maintenance costs as traffic increases, the viability of electrification depends on the level of traffic, but the critical traffic density for any railway depends on local conditions.

EXTENT OF ELECTRIFICATION

Since the end of World War II, American railroads have considered that the price of electrification is not worth paying, apart from minor exceptions, although electrification is now being planned by the Consolidated Rail Corporation (Conrail); the results of that exercise will be watched with considerable interest. In contrast, overseas railways have electrified extensively. The percentage of electrified track kilometers is less than 1 percent in the United States but 16 percent in Britain, 29 percent in West Germany, 25 percent in France and the Soviet Union, 40 percent in Japan, 47 percent in Italy, 60 percent in Sweden, and 99 percent in Switzerland. I believe that the issues affecting electrification can be illuminated by an analysis of the reasons for the differences in the extent of railway electrification in the United States and other countries.

The main difference is that U.S. railways are privately owned, whereas other railways are state owned. Because they are private commercial organizations, U.S. railways would electrify only if a financial analysis showed that electrification would be profitable for the railroad. While such analysis is also important for a state-owned railroad, it takes second place to an analysis of the benefits of electrification to the country. There is a suspicion that this economic analysis has sometimes been superficial and based on such global considerations as independence from oil imports. This may well have happened in some cases, particularly for the older electrification schemes. However, modern economic analysis is quite as searching as a financial analysis, except that its objective is to ensure the most efficient use of national resources rather than to increase the profitability of the railway. Thus the economic analysis ignores the impact of electrification on taxes paid by the railway and prices such resources as oil and electric power at their value to the national economy, which may differ from the market price.

Another important issue is the availability of investment funds. Foreign railways rely heavily on government funds, so that, once the economic justification of the project is demonstrated, the availability of financing depends on national investment policies. This can be a mixed blessing, but it has nevertheless resulted in the execution of fairly extensive electrification. American railroads rely on their internally generated funds and the capital market. In general, they are short of funds, particularly for fixed installations, and, since their ability to borrow at any time depends partly on their existing debts, they must be very careful about which projects they borrow for. There are thus many projects competing for limited investment funds, and many give a greater—and generally quicker—return than electrification.

Two suggestions were made that could make electrification more attractive to the private investor. One was the creation of tax-exempt bonds, like municipal bonds. Another was the creation of revenue bonds, which would involve the creation of an entity that would own the catenary, substations, and related facilities and would sell power to the railway at the pantograph. An alternative suggestion was that a governmental authority construct and own these installations and lease them to the railroad. The total investment needed, assuming that about 10 percent of the U.S. railroads' track, which carried about 50 percent of the traffic, were electrified, was estimated by one speaker to be $7 billion.

Cost differences between the United States and other countries arise for several reasons. The United States is pioneering the 50-kV system, which should result in some cost reduction. However, there is very little recent experience with electrification in the United States, and this may well increase the cost of the first few electrification projects. Again, labor rates are different. Probably the most important differences arise in regard to signaling and telecommunications. The electrification of foreign railroads was usually part of a comprehensive modernization program that involved replacement of signaling and telecommunications, including the installation of underground cables. Under these circumstances, the only signaling and telecommunications cost attributed to electrification was the additional cost needed to protect the signaling and telecommunications equipment, including the cable, from interference from the traction current; this typically amounted to 10 to 15 percent of the total cost of fixed installations. In the United States, on the other hand, the railroads already have modern signaling and telecommunications, and these installations now have to be protected. Probably the greatest single factor that would reduce electrification costs would be the development of less expensive techniques for protecting signaling and telecommunications.

The cost of fixed installations, including signaling and telecommunications and clearances for Southern Railway Company's main line, has been estimated at $75 000/track km ($120 000/track mile). This estimate is consistent with a cost breakdown reported by American Railway Engineering Association (AREA) in 1976 (1). It is rather higher than estimates encountered in other countries, but seems reasonable when the above differences are taken into account. Another speaker quoted a price range of $75 000 to $300 000/route km ($120 000 to $500 000/route mile) for the same installations. The route-kilometer cost is greater partly because it may encompass several tracks. This is unlikely to affect the attractiveness of electrification, because the key parameter is the traffic density per track. However, the upper end of the cost range may reflect problems with clearances and other public works; these make electrification less attractive or, to put it another way, require a greater traffic density to justify it. In general, electrification is not thought to be justified in this country for annual traffic densities of less than 36 gross Tg (40 million gross tons), although substantially lower figures appear to be adequate elsewhere; in the Soviet Union, for example, the critical density is 9 to 11 net Tg (10 to 12 million net tons) for a single-track line (2).

Let us now turn to locomotives. Outside North America, the cost per unit of power of an electric locomotive is less than that of a diesel because the electric does not carry a relatively expensive diesel motor. However, the large market available to U.S. diesel locomotive manufacturers has resulted in the production of diesel locomotives at relatively low cost. One would expect that, as the demand for electric locomotives grows, they will ultimately become available at even lower cost; the AREA report mentioned above (1) estimates that an electric would cost $170/kW ($125/hp) compared with $200/kW ($150/hp) for a diesel. However, this necessitates substantial developments in the production of electric locomotives, and meanwhile the railroads are left uncertain as to when electric locomotives will become cheaper than diesels.

BENEFITS OF ELECTRIFICATION

So much for the cost. Let us now turn again to the benefits of electrification, which as we have seen relate primarily to fuel and maintenance costs. The impact of electrification on fuel costs depends on the energy policy and, until its impact on future oil and electricity prices emerges more clearly, there will be considerable uncertainty as to the extent of the energy savings the railroads could achieve by electrification. Of course, these savings could be appreciable if oil prices increase significantly more than electricity prices do.

Maintenance cost savings result because electrification eliminates the maintenance of diesel motors. Furthermore, electric locomotives can be substantially more powerful than the most powerful diesels now available, and they have an overload capacity that diesels lack. For a given level of traffic, there are thus fewer electrics than diesels to maintain. Although additional maintenance costs are incurred on an electrified railway in respect to fixed installations, total traction maintenance costs are substantially less for an electric railway than for one that uses diesel traction. However, a reduction in maintenance costs generally implies a reduction of staff, which may raise labor problems.

A further advantage of electrification is that in certain circumstances it may increase speed, though only to a limited extent. This may result in more efficient use of staff and equipment but, for a freight railway, is unlikely to be very significant unless traffic on the line approaches saturation and electrification postpones major civil engineering works needed to improve capacity.

A common feature of all these benefits is that they accrue slowly, over many years, although the costs have to be paid immediately. There is thus an initial negative impact on the railroads' cash flow, while the railroads have to face the risk that future changes in traffic patterns or energy costs may decrease the benefits.

There are, in sum, several factors that make electrification less attractive in the United States than in other countries. However, the attractiveness of electrification increases with traffic density, and some U.S. railroads carry a very high level of traffic. For example, the average annual traffic density on electrified lines varies in different European countries from 11 to 19 gross Tg (12 to 21 million gross tons), while electrification is being considered in the United States only for lines that carry more than 36 gross Tg. Nevertheless, uncertainties associated with electrification, some of which I have mentioned, coupled with the financing problems, are causing the railroads to hesitate. A demonstration project will be very valuable in resolving some of these uncertainties, and it is to be hoped that Conrail's electrification of the Harrisburg to Pittsburgh line will fulfill this role.

In any event, it is clear that important issues remain to be answered concerning railway electrification in the United States. The objective of this conference is to focus on these issues, define them, and, to the extent possible, assist in resolving them.

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A Railroad View of Electrification

Walter W. Simpson, Southern Railway System, Washington, D.C.

At the outset I would like to clarify exactly what we mean by railroad electrification and to outline briefly the present status of electrification in this country. Electrification does not mean simply using electric power to drive our locomotives. In that sense, America's railroads are already electrified and have been since the diesel locomotive became the primary type of motive power some 25 years ago. The diesel locomotive is a mobile power plant using petroleum fuel to drive a diesel engine that in turn drives a generator or alternator to produce electricity. The electric power is applied directly to traction motors that propel the locomotive.

By electrification we mean the replacement of the internal-combustion engine and generator or alternator by the large-scale purchase and distribution of commercial electric power. Railroad electrification in its simplest form would consist of a power-transmission system along the railroad right-of-way, most likely consisting of an overhead catenary line from which trolley pickups on the locomotive would draw power for the traction motors. It would also require power substations between the generating plant and the catenary system at intervals ranging from 30 to 80 km (20 to 50 miles). Finally, a complete new fleet of electric locomotives would be needed.

Because of the high capital costs of catenary, substations, electric locomotives, and some additional costs that will be discussed later, only the most heavily used railroad lines can even be considered for electrification. The figure that has usually been advanced as a minimum for justifying electrification is 36 gross Tg (40 million gross tons) annually.

On the Southern Railway System, for example, only about 4.5 percent of our track, representing about 18 percent of our total operation in terms of load and motive power, has a traffic density of this level and has ever been considered for electrification. This is Southern's main line from Cincinnati through Chattanooga to Atlanta, a distance of some 775 road km (485 road miles) or 1160 track km (725 track miles). In terms of capital cost, we are talking about \$75 000 to \$90 000/km (\$120 000 to \$140 000/mile) and, including locomotives, a total cost of \$150 million.

Electrification in this country dates back to 1895, when a 6-km (4-mile) section was installed on the Baltimore and Ohio Railroad Company's line at Baltimore. The system continued to grow into the 1930s, when the Pennsylvania Railroad put into operation its 11-kV 25-Hz system. At its peak, electrification in this country covered fewer than 3200 km (2000 miles), and a portion of this trackage is not in use today. More recent electrification projects, if we exclude rapid-transit systems, consist of a 24-km (15-mile) coal-hauling railroad at Zanesville, Ohio, and the 125-km (78-mile) Black Mesa and Lake Powell Railroad installation at Page, Arizona. U.S. railroads are less than 1 percent electrified, in contrast to other major industrial countries—the Soviet Union is 25 percent electrified, France 25 percent, West Germany 30 percent, Japan 40 percent. Some of the smaller countries are totally electrified, such as Switzerland, which has some 14 500 route km (9000 route miles). Italy, Sweden, Norway, and the Netherlands are 50 to 70 percent electrified.

With the rest of the industrialized nations largely electrified and moving even more rapidly in that direction, why has electrification not made more progress in this country? In a nutshell, from the railroad standpoint, any decision to electrify trackage will depend on economic considerations. While I cannot say it positively, I do strongly believe that economic considerations in other countries took a back seat to what could be called the national interest.

ADVANTAGES AND DISADVANTAGES OF ELECTRIFICATION

One uncertainty in considering electrification is the changing pattern of advantages and disadvantages of electric versus diesel-electric locomotives. Another is the state of the art in the developing technology of electric locomotives and power-transmission systems. Two other considerations are the unpredictability of the cost of electric power and the competition of other necessary improvement projects for the capital investment dollars we have available.

A number of railroads in recent years have shown interest in electrification, but to keep things simple I will concentrate specifically on Southern's proposed electrification project. We have been studying the electrification of our Cincinnati-to-Atlanta line for many years, but this study took on added importance at the time the energy crisis produced a rapid escalation of diesel fuel costs. During this most recent period of study, we have made adjustment for the changing costs of electricity and petroleum fuel, the comparative costs of locomotives, traffic projections, and probable maintenance costs. We have not reached a decision, but we know a lot more about how electrification will affect us. I believe much of what we have learned will apply to railroads generally.

The most obvious advantage in electrification is the potential for lower fuel costs. On the surface it would seem more economic to generate power at a central location than in mobile power plants like the diesel locomotive. Far more flexibility would exist in the choice and use of fuel. Coal, nuclear power, and perhaps solar energy are all potentially usable in the centralized generation of power. Diesel-electric locomotives are limited to petroleum fuel, which suffers from uncertain supply and therefore is subject to rapidly escalating costs. Large-scale use of atomic energy or the development of solar energy for power generation are truly considerations for the future. Greater dependence on coal is a very real possibility, since we have substantial coal reserves and the technology exists to use them.

Conserving our petroleum supplies is not really a consideration. Electrification of the high-density rail lines in the United States would enable the country to save some petroleum but not very much. The entire railroad industry consumes approximately 3 percent of the total energy used for transportation—or less than 2 percent of total energy consumption. Much of this would still be used, since only a portion of the railroads are even being considered for electrification. A lot more petroleum could be saved if the utility companies would convert to coal.

About 4 years ago the price of diesel fuel began to escalate while the cost of electric power remained relatively stable. In the last 2 years that situation has been reversed and the costs of electric power have escalated at a more rapid rate than have the costs of diesel fuel. There is still some fuel-cost advantage in electrification, and I expect this to continue, but I am not sufficiently confident that I would care to invest $150 million. My confidence will be diminished still further if we begin to see power costs for industrial users raised in order to make rate increases more palatable to individual or residential users of electricity. I have heard this possibility mentioned by executives from the utility field and also by industrial users.

Another significant advantage is the fact the electric locomotive has a higher rate of utilization and longer service life than the diesel-electric power plants we now have. Instead of the diesel locomotive's internal-combustion power plant with more than 3000 wearing parts, the electric locomotive has step-down transformers and now solid-state control systems. These components are needed to reduce the high-voltage alternating current from the catenary to 600-V direct current for the traction motor. The major component parts of electric locomotives are smaller and lighter than those of our present diesel-electric power plants.

The solid-state power and control package, which consists of thyristors and silicone diodes, is a relatively recent development. This solid-state control system makes possible improved wheel-slip controls and should provide the electric locomotive with considerably greater adhesion at the rails than the diesel locomotive has. Comparisons must, however, take into consideration the research now under way by the diesel locomotive manufacturers to provide diesel locomotives with improved adhesion by using similar solid-state control hardware.

Another factor in the generally superior performance of electric locomotives compared with diesels of the same weight is their ability to deliver short bursts of very high power. This is possible because the electric locomotive draws on a virtually unlimited power supply from the catenary transmission line, while the diesel locomotive is limited to the power output of its self-contained generating plant.

All this adds up to the generally accepted estimate that two electric locomotives will do the work of three diesels. But this advantage is largely offset by the fact that two electric locomotives cost about as much as three diesels. The initial cost thus shows no advantage to either. Elimination of the internal-combustion power plant does tend to reduce locomotive maintenance costs and also to increase availability. It might also extend the service life of the locomotive. In our evaluation we assumed a two-thirds reduction in maintenance costs for electric locomotives and a 30-year life, whereas the normally accepted life of a diesel locomotive (excluding switch-engine power) is 15 to 20 years. These assumptions were based on available literature and the recommendation of locomotive suppliers.

TECHNOLOGICAL CONSIDERATIONS

Another thing to be considered is that the 15 to 20-year service life of the diesel locomotive is partly the result of technological obsolescence. There is no question about our ability to continue to operate the locomotive for 30 years without any extraordinary additional expense, with the possible exception of rewiring and some car-body repairs. If we purchased a sizable fleet of electric locomotives that have a life expectancy of 30 years, we might lose some flexibility in adopting improved locomotives, at least without additional major expenditures.

Another item to be considered is the quality of the design of the present electric locomotive being offered. Only recently have electric locomotives been placed in service that might be considered to include the latest in technology, and these are in service in very small numbers. Improving the existing electric locomotive will take more development money from locomotive manufacturers or the federal government or both. At the present time there is not enough interest from the railroads in electrification to stimulate additional development expenditures.

It is also pertinent that, while we may be reducing locomotive maintenance with electrification, we are getting into another area of maintenance for which we have no experience—maintenance of the catenary. We can estimate what it will cost to maintain the power-transmission system, but we cannot be sure our figures are correct.

We can anticipate other difficulties as a result of running power lines over the rails. The power-transmission system is subject to damage in case of derailment. High-voltage power lines might set up stray currents in the track that could affect our signaling system. In fact, the estimated cost of redesigning the signal system that we used was not very far below the estimated cost of installing the catenary. In addition, high-voltage power lines may interfere with train radio transmissions and might also cause some interference with communication systems in communities in which the track runs right through the center of town.

The lack of flexibility in the use of electric locomotives gives some cause for concern. The track from Cincinnati to Atlanta has a main line to St. Louis and another to Knoxville. These lines will have to be operated with diesel power, which will probably result in some loss of diesel utilization both at Danville and at Harriman Junction. We can also expect some problems and perhaps a drop in locomotive utilization on a number of run-through trains for which motive power belonging to Southern and motive power from other railroads operate interchangeably.

All these problems I am mentioning I believe are solvable. Some of them require intense in-house planning and study; for others we do not have sufficient information to make a decision. In reviewing electrification studies by other railroads, I find that very different numbers are being used in calculating the return on investment. But I do not believe any of us know whether the figures we are using are correct. The problem is that nowhere in the United States is there a high-speed heavy-load electrification system like that we were considering between Cincinnati and Atlanta. The most recent project, the 125-km (78-mile) Black Mesa and Lake Powell Railroad, operates one train, does not have a signal system, and does not traverse heavily populated areas. Like any other business decision, the decision to electrify is based on a number of factors; the most important is the return on investment.

There is, in our judgment, no service or reliability advantage to be gained with electrification. We can run the Cincinnati-to-Atlanta line with diesel locomotives as well as we can with electric locomotives. Therefore we are looking for the return on a $150 million capital investment. There are a lot of other necessary and desirable improvement projects to our railroad that are actively competing for this money—new classification yards, additional centralized traffic control, double-tracking projects; all of these have service as well as cost advantages.

Several years ago, when diesel fuel prices began climbing and the cost of electric power was stable, the rate of return looked very attractive. Now that the cost of electricity appears to have caught up with petroleum prices, it is not as attractive as it once was. And, until we find out about the many unknowns mentioned above, we do not know how attractive the rate of return would be in the future.

SUMMARY

Let us review some of the advantages, disadvantages, and uncertainties that we are concerned with when we consider electrification. There are a number of advantages.

1. Electrification would reduce the dependence of transportation on petroleum. Assuming about 10 percent of the nation's railroads were electrified, savings could be in excess of 7 billion L (2 billion gal) of diesel fuel a year.
2. Electrified lines would have lower fuel costs. However, there are enough uncertainties in the area of future costs that the tendency in making electrification studies is to use a conservative approach, i.e., to project escalation of electric power rates at approximately the same rate as petroleum fuel costs. This conservative approach reduces the estimated return on investment to a marginal level. The calculation of return on investment is more sensitive to fluctuation in electric power rates and diesel fuel costs than any other single item.
3. The railroads would reduce their air pollution problem, returning it to the power plant, where control can be more readily accomplished.
4. The maintenance cost for electric locomotives is two-thirds that for diesels.
5. Electric locomotives have higher adhesion and the ability to furnish short bursts of additional power for climbing grades.
6. Fewer electric locomotives are required, since they have higher availability and less maintenance.
7. There is a decreased need for an inventory of material, including petroleum fuel, lubricating oil, and replacement parts for the internal-combustion engine.

The disadvantages are primarily the high capital cost, low estimated return on investment, and the fact that there are pressing needs for the money elsewhere. There are other disadvantages among the many uncertainties that still exist, specifically:

1. We are not sure the electric locomotive has been developed as thoroughly as it can be.
2. We do not know what it will cost to deal with the problem of signals and communications because we really do not know what kinds of problems a 25 or 50-kV system will create.
3. We do not know where the money for electrification is coming from. Some railroads may be able to afford the substantial investment, assuming that the return on investment were attractive, but for marginally profitable railroads federal assistance, in the form of tax incentives or some other kind of assistance, will probably be required.
4. We do not have any confidence in our ability to predict the cost of electric power over the next few years, much less over the 30-year expected life of an electrified system. Without some reassurance on this point we will not see electrification to any degree in the immediate future without government sponsorship.

I personally believe that electrification of heavy-density rail lines in this country will come, but I do not know when. Many of the uncertainties mentioned above might be clarified as a result of the Railroad Revitalization and Regulatory Reform Act. Specifically, the Secretary of Transportation guaranteed obligations of the Consolidated Rail Corporation up to $200 million for the purpose of electrifying high-density main-line routes. Certainly an expenditure of this magnitude and the upgrading of existing electrified rail lines should produce answers to some of our questions. The sooner we deal with the issues and uncertainty that exist, the sooner we can move forward.

An Economic View of Railroad Electrification

Scott B. Harvey, Association of American Railroads, Washington, D.C.

There are many proponents of railroad electrification and very few vocal opponents. Arguments based on economics and energy policy have been marshalled in favor of substantial investment in electrification. But despite these arguments, no major investment in electrifying rail freight lines has occurred in recent years. It is my position that, even if the major arguments advanced in favor of electrification are correct, many issues need to be resolved before substantial public or private investment in electrification is made. I will here assume that the conclusions reached by general studies are valid and suggest other considerations that have prevented electrification and are likely to continue to do so.

To briefly state the issue, there are two competing motive-power technologies—the diesel electric and the electric. U.S. railroads overwhelmingly use diesel-electric power. Proponents of conversion to full electrification contend that, for certain high-density lines, electrified systems are superior economically and operationally. The findings of several studies (1, 2, 3, 4) are summarized below.

1. Electrification is technologically and operationally feasible.

2. Economic justification requires arraying and comparing the economic variables over time and at assumed volume levels.

3. The motive-power characteristics of electric systems are such that fewer, more powerful locomotives are needed. Electric locomotives have a longer economic life—perhaps 30 years compared with 15 to 18 for diesels (3). The cost/unit power may be lower for electric locomotives. The net result is that a smaller investment in locomotives is required for an electrified system than for a dieselized system.

4. Electric locomotives require less maintenance per locomotive-kilometer. If the experience of foreign countries and on electrified portions of the former Penn Central Transportation Company is representative, maintenance costs might be 25 to 50 percent those of diesel maintenance costs (4). Fewer locomotives and less maintenance per kilometer will result in savings in operating expense.

5. An electrified system, however, requires substantial investment in fixed facilities that are not required for diesel operations. Catenaries, substations, and signaling and communication systems may cost from \$75 000 to \$300 000 or more/route km (\$120 000 to \$500 000/route mile) (1). Reconstruction of facilities to maintain clearances and permit electric operations might cost up to \$100 000/route km (\$160 000/route mile) (1).

6. Electrified systems rely on power generated by electric utilities, which may in turn use a variety of energy sources—coal, atomic power, hydroelectric power, oil, and so on. Diesel operations rely on diesel fuel and are, therefore, subject to the vagaries of oil prices and supply. Energy efficiency and energy costs are about even now (4, 5), but diesel oil prices are likely to rise more than electric power rates over the life of the investment, thus generating operating expense savings from electrification.

7. The size of the required fixed-facility investment and the characteristics of electric motive power mean that high-density operations over a minimum route length are required for economic feasibility. Estimates of minimum route density run from 18 to 36 gross Tg (20 to 40 million gross tons) annually. The minimum route length appears to be 400 km (250 miles). Therefore, the entire rail system cannot be economically electrified. Most studies propose electrification for about 10 percent of the current trackage, which carries about 50 percent of the volume (3).

8. Electrification of high-density lines requires substantial initial investment; the returns come in the form of reductions in operating expenses in future years. These expense reductions can produce a return on investment. How great that return would be is subject to some doubt, but returns of 15 to 20 percent before taxes for electrification of particular lines have been estimated in some studies (1, 2).

9. The economics of electrification will vary considerably for lines of like density according to grade, traffic characteristics, terrain, access to electric power, and so on. Electrification must be studied on a line-by-line basis. Rates of return can vary significantly, and no overall formula to predict which rail lines should be electrified (if any) has yet been developed.

There is considerable debate on some of the points this summary makes, e.g., the magnitude of the maintenance savings that can be predicted. The arguments have been sufficiently persuasive, however, to prompt several individual railroads and the federal government to invest in detailed studies of the electrification alternative. These studies should permit more precise calculations of the values of the variables involved. In spite of these studies, there has not yet been a major conversion from diesel to electric operation in the United States, although interest continues. Since economists give great weight to the presumptive validity of the decisions of economic institutions, an initial hypothesis can be drawn that electrification is viewed as a marginal investment by railroads. The benefits of electrification apparently do not now justify conversion, but they may do so in the future.

OTHER ECONOMIC ISSUES

Continuing study should narrow the range of estimated investment requirements and operation and cost savings, but there are many other economic issues that must be addressed before meaningful conclusions concerning electrification can be reached. These issues relate primarily to the ability of industry to finance electrification and the desirability of such investment, given the current uncertainties about government policy.

1. There is a basic methodological question. The economic comparisons that have been made are between electrified and dieselized systems. Since the comparisons must be made over the life of the investment—30 years is assumed in most studies—many technological assumptions are necessary. For instance, a major source of savings from electrification is in maintenance. Should diesel locomotives become more efficient in the future, projections must assume either the same rate of improvement for electric systems or a reduction in the benefits of electrification.

More fundamentally, there may be other alternatives than electrification and dieselization. A recent review by the U.S. Department of Transportation (DOT) discussed electrification briefly and concluded that "it is not clear whether turning coal into electricity is preferable to developing a locomotive that burns coal or a coal derivative to power a locomotive directly" (6). Clearly, the methodology employed assumes the selection of optimum alternatives, and the importance of considering alternatives increases when the advantages at the margin are apparently as slim as they are in comparing dieselization and electrification.

2. Some proponents of electrification have contended that service reliability and speed would be improved and, therefore, additional traffic generated as a result of electrification. Most general studies have not taken this factor into account. The procedure has been to compare electric and diesel systems at the same projected volume levels. Since the speed and reliability characteristics of diesel locomotives have not been the primary limitations on improving rail service, this procedure is probably correct.

There are several other rail industry problems that affect service quality, including track and yard conditions, time spent in yards and interchange, and so on. These conditions need to be resolved before major service gains can be made. Nevertheless, electrification, along with other changes, could increase revenue generation. Potential increased revenue should be considered carefully, in particular in terms of possible diversion from other modes, since traffic growth would be a potential benefit and would also increase density and improve the economics of electrification.

3. Even under the most optimistic projections of electrification, the entire rail system would not be electrified. Since diesel operations would still be used on lower density lines and in yards, a number of operational

questions concerning a dual system would be raised. From an economic point of view, there is the real possibility of generating costs that should be charged to electrification. For instance, the ability to interchange locomotives throughout the system and to respond to changes in demand would be reduced in the case of a mixed fleet. Certain economies of scale would be eliminated and the remaining diesels might be less efficiently used. The cost of reduced utilization should be charged to electrification.

4. The economics of electrification raise important structural issues for the industry. A 1973 study (3) concluded that 9929 route km (6171 route miles) were economical to electrify but did not attempt to identify which lines should be electrified when a route had more than one rail carrier (3). The ability to translate the potential into actual investment would be limited by the need to resolve complex issues of intraindustry competition.

For instance, DOT's recent line classification study identified certain corridors of excess rail capacity in the nation. In many of these corridors, the density is more than sufficient to meet the minimum requirements for electrification, but only one, or none, of the carriers operating lines in the corridor generates a density on its own lines sufficient to justify electrification. The line from Dallas-Fort Worth to Houston is an example. The corridor has a density of 73 gross Tg (81 million gross tons), but none of the five carriers operating in the corridor generates more than 24 gross Tg (27 million gross tons) (7). Restructuring and the elimination of excess and duplicate capacity have been major goals in recent rail legislation. Accomplishing these goals would increase electrification possibilities and, should electrification prove economic, the arguments for further restructuring would be strengthened.

5. Although economic studies indicate that electrification of certain high-density lines would produce a rate of return sufficient to cover interest and amortization, this is not enough to warrant investment, despite the principles of marginal economic analysis. The railroad industry has been suffering from capital shortages. As a result, many alternative investments that promise a return equal to or greater than electrification have not been made. In the railroad industry, capital budgets are the product of the availability of funds rather than the rate of return on potential investments. Further, a substantial proportion of most railroad's capital budgets is dictated by the requirements of staying in business and by legal requirements (8). In this environment, electrification must find its place among a number of capital alternatives, some of which do not really involve discretion, others of which are desirable but have been deferred in the past, and some of which may promise a higher return on investment.

6. Probably the single most important point, even if all these issues were resolved in favor of electrification, is that it is highly questionable whether the industry could support the substantial investment required. By one estimate, electrification of 10 percent of the total trackage would cost more than $7 billion (9). In comparison, current capital spending amounts to $1.5 billion/year, and most agree the industry should be spending at a much higher level to meet deferrals and growth requirements. Even at current levels of capital spending, the industry is burdened by relatively high debt-equity ratios and rising fixed charges. Prospective lenders would question the ability of the industry to support spending on electrification. Even if funds were guaranteed by the government, the fixed charges and debt-equity impact would make investment questionable for railroads for financial reasons.

7. There is the crucial issue of uncertainty. Calculating potential return on investment does not resolve this issue, and the use of sensitivity analysis, probabilities, and payback periods only serves to improve its definition. In general, as uncertainty and the size of the investment increase and the time stream of benefits lengthens, a given return is viewed less favorably. It is not an exaggeration to say that the failure of an electrification project could break a railroad.

Railroads apparently view the costs and benefits of electrification as being highly uncertain. They are uncertain about many of the key variables, including the economic life and maintenance requirements of locomotives, the feasibility and cost of diesel-electric interactions, the future price of electricity and diesel fuel, and so on. While experience from electrification demonstrations would help to reduce this uncertainty, current doubts are deep-seated.

8. Although there are convincing arguments in favor of lessening rail reliance on diesel fuels, there are also considerable uncertainties concerning the future of electric power in terms of supply and price. Electric utilities have had difficulty raising capital and have huge capital requirements. There are unresolved environmental issues concerning the use of coal and atomic power. Several changes in utility pricing schemes designed to increase rates to volume users are being considered as a means of conserving energy. The relative prices of diesel fuel and electric power have changed over time. From 1959 to 1972, oil and electric prices rose at about the same rate. In 1973 and 1974, the relative price of diesel fuel shot up, but since then electric power rates have been increasing more rapidly than diesel fuel prices (10).

In terms of energy conservation and public policy, most studies conclude that electrification, while it would reduce oil consumption, does not save energy. Since railroads are relatively small users of oil (less than 2 percent of domestic consumption) (4) and would be relatively small users of electric power, their fate under either fuel source would ultimately be tied to national energy policies and programs. For example, an oil policy that relied on price controls and rationing rather than price-based allocation might benefit the economics of the diesel alternative.

9. Finally, there is the question of the interest and possible role of the government. The thrust of this argument has been that private funding of large-scale electrification would be doubtful. The arguments for a major government role would follow a familiar logic: Railroads are important and are both energy efficient and environmentally efficient; electrification is the most apparent means of reducing the dependency of transportation on oil; and electrification could improve the industry's economic health. Therefore, government investment in electrification would accomplish two objectives—aiding the industry and reducing oil use—at once.

The most obvious question, from the point of view of public policy, is whether economic health for the industry and reduced oil use in transportation can be accomplished by more efficient, effective means, such as the alteration of promotional policies to encourage rail versus highway movement. Looking at the issue from an energy viewpoint, a $7 billion expenditure would reduce oil requirements by less than 1 percent—in an industry that is relatively efficient in its energy use—and would not reduce overall energy requirements.

Further, public investment in an alternative technology like electrification represents an approach that is different from current public policy directions. Congress has passed major rail legislation in recent years that assumes that the industry's problems are not technological but rather structural and regulatory. It is too early to predict the success or failure of the resulting policies. The impact of industry restructuring and regulatory reform has yet to be measured. Nor has the issue of current promotional policies and their impacts on transportation been addressed. The impact of restructuring, regulatory reform, and modification of current promotional policies would need to be assessed before electrification could be justified on the grounds of transportation policy.

SUMMARY

There are convincing arguments that electrification can have economic and energy benefits. These benefits are not, however, sufficiently large now to merit extensive private investment, particularly in an industry that has the economic characteristics of railroading. What might be interpreted as a failure of the industry to adopt the best possible technology is really the reflection of conditions in an industry that is already highly capital intensive, has difficulty raising capital, and cannot afford risky or marginal projects.

In these circumstances, major electrification has to await basic changes in the industry's financial condition, further research, and perhaps government-sponsored demonstrations to reduce uncertainty, as well as the resolution of the basic uncertainties surrounding national transportation and energy policies.

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A Financial View of Electrification

Henry H. Livingston, Kidder, Peabody and Company, Inc., New York

We talk earnestly about a national policy for energy, especially for a number of industries that are subject to substantial change. This certainly affects electrification of the railroad industry, but there may be even more changes in sight for the utilities.

The utilities are now large consumers of oil and thus add to the nation's burden in buying oil from abroad. But the utilities can pass the costs of that fuel through to the bills of their customers and can thereby comply conveniently and readily with environmental standards on stack emissions by burning higher cost low-sulfur oil. If, however, they were to convert to coal, they would have to make capital investments in new boilers or boiler conversions. These capital costs cannot be passed on to the customers on a current basis; only after increases in rates have been approved can they recover capital costs. Therefore the utilities' conversion to coal would present capital problems similar to those electrification presents for the railroads.

Long delays, often caused by regulatory agencies, inhibit the recovery of capital costs by the utilities, which in turn dilutes their return on investment over the life of the new plant. Although a 15 or 20 percent return on capital may be anticipated in several years, there is no return until well after the plant is put into operation unless adequate flows of funds are available at the outset. In fact, there is often a negative return because the cash flow that provides the initial capital investment, regardless of source, is diverted from the assets column of the balance sheet of the utility (or the railroad company) making the investment, especially if there is a long lead time until completion.

The present tax incentives for additional investment are an important part of this. They are being offered by the federal government as an aid to economic recovery. Currently, the railroad industry is generating about 8 percent of the total investment tax credit generated nationally. But because the resultant net rate of return on railroad investment is so low—and therefore taxable income is likewise so low—this investment tax credit has not been fully used. So the proposed increases in investment tax credit as an incentive to conversion may not necessarily stimulate future additions to capital investment for industries that already have a low rate of return.

The 1976 Railroad Revitalization and Regulatory Reform Act has helped greatly by raising the amount of usable credit to 100 percent of the tax bill, but this soon reverts to 50 percent under the new law. The investment tax credit device by itself cannot come near meeting the capital needs of conversion, not only for the railroad industry but for other industries with long-lived plants and insufficient or even no returns on the investment to be made to achieve a shift in energy sources.

Electrification studies appear to focus on two areas—an answer to the energy crisis and the possibility of achieving a more efficient railroad operation. But such studies may not deal adequately with the problems of accurately forecasting the probable rise in electricity rates in the future. In the last few years the price of electric power has lagged behind the increases in the prices of diesel fuel by as much as 2 or 3 years. I have not seen any serious studies of the relative advantages of switching to another source of liquid fuel, such as the conversion of coal to diesel fuel.

I recently checked with some organizations that are heavily involved in coal research and fuel conversion. Although not much work has been done yet on the liquefaction of coal, there has been research on coal gasification. Of course, there has long been available the inefficient Lurgi process (45 percent loss in processing) for conversion of coal to gasoline; it is now used in South Africa and was once used in Germany during World War II. Given a large-volume requirement and full implementation of today's technology, coal could be converted to diesel oil for a sale price of 21 cents/L (80 cents/gal). That is obviously more than twice its present price but, in view of both inflation and the large market for diesel fuel outside the railroad industry, economies of scale and economies of total capital employment might well bring that price down. This alternative should not be passed over lightly, since it would not make obsolete our oil and oil-products pipelines and tankers already in service that convey much of the production we live on today. Thus, the continued use of an in-place facility may further reduce the overall needs for new capital.

The solution of our energy problem is of overriding national significance because everybody in the country personally benefits if oil imports and the loss of our funds to foreign countries are reduced. To the extent that our nation as a whole will be relieved of these inflationary and diseconomic effects, some major contribution to solving this national problem should occur at the level of the federal government without invasion of the private sector. I mentioned briefly the investment tax credit and the fact that it has already reached its limits as a concrete, useful tool. One way to achieve this government involvement would be to provide a tax-exempt municipal or revenue-bond security to finance those long-lived assets that will have low depreciation rates and long payback periods. This would provide much cheaper funding; it is a route that the Treasury Department should seriously consider. Since the Treasury Department is naturally trying to protect all its sources of revenue, the necessity to finance very long-lived assets must become so much a part of national policy that it overrides the importance to the Treasury Department of its inflows of revenue.

Electrification has had a long and checkered history. When I was a boy the Pennsylvania Railroad electrified its line between Washington and Philadelphia. Even at that time, the drive of management to complete the job—in full recognition of the risk it was taking in possibly exceeding prudent capital limits—caused concern in the financial community. You may also remember that there were some indirect subsidies in the form of Public Works Administration (PWA) funds available to create jobs. Later, the Pennsylvania Railroad successfully refunded all of its PWA obligations to the government through the sale of two large bond issues (to mature in 1981 and in 1984). Today, of course, they are worth only a fraction of their face value. Investors who bought these bonds originally and planned to keep them to maturity, as is the basic policy of the life insurance industry, knew full well then that they were on their own. But they had sufficient conviction that the project and the management were worth that risk. Today, such confidence in 50-year credit is gone. The longest private-sector debt financing one can reasonably expect today is 25 years for a sound railroad investment and up to 30 years for the telephone company. Nevertheless, long-term credit is indeed available to railroad companies that can effectively manage their resources.

But we must further improve the industry's credit standing. Return on investment is still very low. The Southern Railway Company earns a bare 6 percent return on its investment. Its return on equity is higher but still not enough for an inflationary environment. Why? Return on investment and return on equity measure in two different ways the amount of net contribution before the payment of the principal due on debt and dividends. One has to look further; the amount of cash available after current debt service and dividends have been calculated is the important figure by which to measure the growing strength of credit. This finally permits the examination of the debt-equity ratio. The equity portion must be adequate to support present debt and must also grow if additional debt is to be raised. In this respect, even the best railroad companies have not had nearly enough growth in their retained earnings, although from now on there appears to be an opportunity for it to appreciate a little. But the target for such growth must be significantly higher than the rate of inflation. The 15 to 20 percent return on investment is therefore not really high after one discounts its future projections to the present value of cash flow and adjusts for inflation.

In the financing of electrification we are dealing with two types of investment—that in equipment and that in catenary, transformers, and other fixed facilities that can be financed only in the long-term bond or equity markets. Such financing is not rated as high as debt for equipment. Equipment financing has long enjoyed special privileges under the railroad bankruptcy laws that have been unavailable to the rest of railroad financing. In the case of bankruptcy, the trustee is specifically prohibited from holding equipment after there has been a default on equipment financing. As a result, for more than 100 years the equipment trust certificate has had a virtually perfect record of paying out. Bankruptcy trustees have had to "pick up pennies in the street" to pay the current amounts due on equipment bonds still outstanding in order to retain possession of locomotives and cars for day-to-day operations. But that is not so in the case of mortgage bond financing, for which the interest is tied into the estate until the end of reorganization, which is often prolonged through litigation or until a basically profitable corporation has been achieved.

If the operation itself has become basically unprofitable, then the bondholder ends up with practically nothing, as we have seen in the Final System Plan. It is to the credit of the private sector that two strong railroad companies have more recently been able to sell new issues of mortgage bonds very successfully. Southern Railway Company sold $75 million in first-mortgage bonds at 8.5 percent interest and Southern Pacific Transportation Company followed, in a slightly better bond market, selling $100 million at 8.2 percent; both were A-rated bonds. We can now say that the strong railroad companies have reestablished their ability to raise major capital in the nonequipment market in spite of the record of the last 6 years in the bankrupt Northeast.

But now we are talking about installing today's electrification technology. This is something new—new transmission-line values, new kinds of locomotives, and an economic scene greatly changed from the 1930s. It is called project financing in the investment community rather than just routine underwriting. In other words, its financing would have to be put together and supported by technical expertise. The confidence and motivation of management would have to be behind it before a sufficiently large group of investors could be attracted.

On the brighter side, today's financial outlook for the railroad industry deals with a dozen strong railroad companies that are well managed and have improving finances. We look forward to the possibility that their equities may now grow faster on a net basis after the payment of dividends and repayment of debt, and we need more of this. But as of today, it is still premature to count on the private sector to finance electrification. The rest of my presentation will deal with questions.

QUESTION: How does the highway mode compare with rail for financial viability?

ANSWER: Highway construction and maintenance have a much broader base for sources of funds. The huge federal and state highway-user charges collected over the past several decades have virtually funded the whole highway system on a pay-as-you-go basis. As for the motor carriers, they are extremely efficient users of capital. A small amount invested in capital produces high revenues. The best example is Roadway Express, which has no debt. It meets all its capital needs from internally generated cash and, at the same time, has sustained a 20 percent growth rate in net income for the last 20 years.

The relative ease of highway financing is very difficult to duplicate. Where else is there such a broad base as the fuel tax and users as willing to pay for results? Since highway-user charges are called taxes and are collected by governments, the magnitude of those sources and the relatively light burden felt by the individual payer—the motorist—are nearly hidden. One must not overlook the significant decrease in cost entailed in financing on a pay-as-you-go basis—there is no interest expense.

QUESTION: Can you elaborate on your expectations that the railroad industry can improve its ability to finance expansion?

ANSWER: There are several strong companies today; others are coming along. A great deal of the weakness that remains is in pockets of underused or misused assets, particularly the freight-car fleet, which produces zero or less return on investment overall, and those segments of routes in weak carriers' hands that are underused because they are not in a high-density system. For instance, the current treatment of demurrage charges produces thousands of car-days a year that are not charged for because one kind of car receives fast unloading in order to offset it against another kind of car that has been ordered for outbound loading but is used in the interim to move the trash around the plant for a while before being loaded out. That kind of drain on railroad earnings is wasteful of railroad assets and perpetuates high freight rates. Demurrage charges themselves start too late and are too low. Two free business days per load is too much; demurrage rates should pay a sufficient return to the car owner to compensate not only for his investment but also for his potential loss in operating earnings from a loss of revenue days.

In attempting to segregate the return on investment in freight cars from that in locomotives and track, we found in one instance that the return on investment in the rest of the railroad, including the locomotives, was three or more times the return on investment of the railroad as a whole; there was virtually no return on the freight-car fleet. And yet the asset value of the freight-car fleet was by far the largest amount on the balance sheet. Better management of the fleet through the proper use of computer technology, such as the Missouri Pacific Lines are now doing, and giving the shippers no more than one 24-h period free of a realistically high demurrage rate will make a significant improvement in railroad earning power, help reduce the growth of equipment debt, and thus make room for more nonequipment financing capability. Equipment financing has been a relatively sure thing for more than a century, even without any known rate of return on the assets that secure it.

But we need to be able to look at the rate of return on invested capital in the railroad itself after the electrification is installed. We also need some way to finance the long lead times that greatly drain cash flow during the construction years and the early years of little or no return on that investment. Some form of a tax-exempt security or even a non-interest-bearing loan during the first 10 or more years would hasten the installation of electric systems. But we still have no separate financial information on the freight-car fleet and its return on investment versus the rest of the railroad system. More than half of the debt and half of the assets of the industry are now tied up in freight-car financing.

QUESTION: Could you discuss further the joint use of utility and railroad power sources?

ANSWER: We have not heard much discussion about the gain from optimal utility plants. There may well be a quantum improvement in the utilization of a power plant built to generate railway electric power with maximum efficiency in the demand area as long as there is the opportunity to sell the surplus power. I suggested this to some utility people, but they are cool at this time to the idea of "co-generation" for a number of reasons, including the complications caused by possible alteration of the jurisdiction between the 50 state regulatory bodies and the Federal Power Commission and the fact that the privately owned and operated electric utility has to look to its own rate-base growth for all of its rate relief. But these are problems worth studying and solving, if we can get a stable source of cheap power.

QUESTION: Would not simplification in the terminals cut the amount of no-return investment in an area like Chicago?

ANSWER: I do not know about consolidation in Chicago specifically, but I have heard that idea put forth generally in the last few years as a way to reduce the amount of capital investment by the railroad industry. The utility people, however, after the fuel crisis, the 1975 recession, and the credit crunch are no longer looking for any more new customers. They have scaled down their own forecasts. They now have major problems caused by regulatory delay in getting their own rate of return on investment to acceptable levels before adding the burdens of new construction. They have the same cash-flow problems railroads have; they also have a continuing financing problem with the same constraints of debt-equity ratios and continuing heavy demands for all forms of new capital. Unlike the railroads, the utilities do have mandatory debt standards in their indentures, one of which is that they do not have to build any more power plants if they cannot maintain earnings of twice the amount needed to cover their interest expense. But that is about the only protection they have from being forced to invest, a factor that may not be enough to prevent eventual disinvestment.

QUESTION: Do electric utilities have to add capacity?
ANSWER: Yes, the utilities have to build additional capacity if the demand is there. That is the quid pro quo for getting a rate level that pays an adequate return on both new and old investment.

QUESTION: How have the utilities been able to do so well in the past?
ANSWER: There are several factors. The overall growth in demand for additional electric power has been constantly heavy for several decades, which has inspired confidence in the long-term financial outlook. Improvements in efficiency in generation and transmission of power have also helped, especially through economies of scale. There has been much less overall pressure at the level of the user; consumers have enjoyed their larger disposable incomes, and their relatively low electric bills have reflected cheap and abundant fuel, until the fuel crisis. The costs of financing were relatively low before the period of runaway inflation. Much of the difference between individual electric utility companies in financing costs ultimately reflects the unevenness and myopia of the many different regulatory bodies. Until recently, the utilities have enjoyed a physical growth in the demand for power that has continually enlarged the cash flows over the historical life of the assets as a whole. But now that future growth rates are flattening to well below earlier projections, the incremental cash flow is no longer there. That puts another light on the subject.

QUESTION: How about using peak capacity for railroads as utility customers?
ANSWER: Although the rails do operate around the clock, the pressure at the grass-roots level now is to give preferential treatment to the residential consumer; the industrial consumer is to become the incremental user and pay the higher rates. This is in part due to rising political pressures on public service commission regulators because of inflation and taxes that further erode the individual's take-home pay and disposable income.

QUESTION: What implications are there in the way the case of the Penn Central Transportation Company has evolved?
ANSWER: The large creditors of the bankrupt railroads are quite disturbed by the very low values placed on the properties in the Final System Plan (FSP). They feel that railroad credit has been badly treated. This is particularly true of the life insurance companies that, after investing for the long pull, have been squeezed unnecessarily as a result of a crisis that is well short of the maturity date on much of the debt. The result of the FSP was enough to warn them that this was no longer debt suitable for a fiduciary. Their posture was made public in a letter of October 17, 1975, from James H. Torrey, the chief investment officer of Connecticut General Life Insurance Company, to several railroad presidents and investment bankers. A year later, as I mentioned, two prosperous railroad companies came successfully to the bond market. Obviously, these placements would not have been successful without broad participation and a consensus of acceptability, based largely on the remoteness of the likelihood of a repeat of the Penn Central debacle. There are also a great many more pension funds today that are more interested in debt than in stock or real estate as a result of the passage of the Employee Retirement Income Security Act (ERISA) in 1974.

Indeed the world of responsible financial management is moving toward more professionalism and financial prudence and away from faith and higher risk. So I cannot therefore be more specific in my answer because I do not know the specific kinds of institutions that bought the Southern Railway Company or the Southern Pacific Transportation Company bonds. This is private information, except for life insurance companies. But because the issues were successful—and I know they quickly sold out and were oversubscribed—the railroad industry has made a significant recovery in its long-term credit.

QUESTION: How do the utilities compare with the railroads in their financial needs?
ANSWER: Since I am a railroad analyst, I cannot speak too much about the utility industry; others follow it more closely than I do. However, I gather the experience with nuclear plants has been disappointing—cost overruns and unreliability of performance. Second, the external financial requirements of the utility industry are generally far larger each year than even the highest estimates for the railroad industry. Third, the often-asked question about the current size of the capital market is most honestly answered by saying that it is constantly changing in response to rates of savings by the U.S. population. When this is eroded by high taxation, inflation, or both, the sources of capital are seriously impaired. It is also related to prevailing monetary and fiscal policies and to the competition for funds. If the rate of inflation stays down, the capital market, even if it does not expand, can become more willing to take longer term risks, which puts money to work over a longer period and hence makes more efficient use of capital.

The long life of the assets is one of the inherent advantages of the railroad industry and of its electrification, especially when it is financed with fixed-rate long-term debt. Fortunately, railroads have not been heavy users of shorter term debt (10 years or less) and thus have not felt the changes in the prime rate as it reflects changes in monetary policy. The improving cash reserves in recent years have permitted railroads to increase their earnings from short-term investments. As you may remember, not long ago business in general had borrowed heavily from the banks. Then it got caught when the prime rate started to climb as monetary policy was aimed toward forestalling the beginnings of the 1974-1975 recession. Then another change occurred gradually as a by-product of the 1974 passage of ERISA, which directed the management of employee pension funds to assume more responsibility and inevitably procure better grade securities.

As to the competition for funds, the stronger railroad companies are improving their ability to participate in the private capital market, up to a point. But eventually both they and the industry will have to improve their rate of return. The core problem hinges on how much new equity will be generated, especially internally, so that there is a base for more debt. But if this trend goes the other way, so that the market substantially reduces the book value, the whole capital structure of the company is eventually threatened.

QUESTION: Can you elaborate on the cost of 21 cents/L (80 cents/gal) for diesel fuel made from coal?
ANSWER: This is a ballpark figure that needs to be explored more thoroughly as an alternative to electrifi-

cation. The total market for middle distillates, of which the railroads are a relatively small user, should have a bearing on this. The total middle-distillate market includes household heating fuel as well as the fuel for many utility boilers that meet pollution requirements (the added cost of which is passed through to the customer). Maybe there could be another trust fund established on the basis of user charges to fund energy conversion. If there is a broad base of sources of funds collected in small quantities (as there is in the Highway Trust Fund), there is a large amount of money to work with. This would spread the cost of developing a feasible system of converting coal to diesel fuel over all the potential users, not just the transportation industry.

QUESTION: Could you explain further the debt-equity ratio?

ANSWER: The debt on the books should not have more than a one-to-one ratio to the book equity. Unfortunately many railroad companies have aggregate market values of their equities that are much lower than their book values. For some companies it has been that way for a long time. This further inhibits increasing the debt. It is a simple exercise to look at the price of the stock and multiply it by the number of shares to calculate the market value of such an equity. When you sell new equity at a market price per share that is lower than the book value per share of the old equity, you are in effect diluting the book value of it all on a per-share basis and thus eroding the value of the present holdings. This then has to be made up out of earnings. The debt-equity ratio does not deal permanently with a certain amount of debt. If the equity grows, debt can also grow.

For example, a brief financial history of the Missouri Pacific Lines' present unique debt structure, a product of the bankruptcy period, may be of some help in understanding how things work. It has a high face amount of mortgage debt. The background is that the old New York State insurance law, enacted after the turn of the century, until recently restricted New York-based life insurance companies from owning equities; they could only own bonds. In 1933 the Missouri Pacific went bankrupt when two sizable noncallable bond issues came due that year in the middle of the depression. A short time later it began to make money again. After World War II it became increasingly profitable. This had the effect of perpetuating the reorganization process because of the inability to get agreement on a plan of reorganization to last long enough to get through the approval process. In fact, it is the only railroad I know of that began paying interest during its reorganization period on its senior debt (this was in 1948). The more junior creditors kept seeing chances to expand their participation.

When the capitalization was again restructured in final form in a desperate effort to get it out, a small equity was set out in the totally unrealistic form of two classes of stock, while a sizable amount of the old junior debt was set up as new debt rather than preferred stock. This created a greatly unbalanced debt-equity ratio. Fortunately, this junior debt is in the form of income bonds rather than fixed-interest bonds. As an analyst, I feel it would be legitimate to adjust the income-bond debt into a preferred stock and hence equity. Incidentally, the Missouri Pacific and its territory as a whole have been growing fast in many respects, including new chemical plants, forest products, and generally most kinds of traffic. Thus, with a strong, aggressive management and a well-maintained property, it ought to keep right on growing and becoming more prosperous.

QUESTION: What about proxy fights?

ANSWER: More often than not these occur when equity has already deteriorated in market value well below its book value. Then the financial raider, who often has an imperfect knowledge of the railroad industry, figures there are assets that are not earning their keep and, if culled out, would enhance earnings. While some may not like this attempt at a takeover—especially management—the raider performs an unpleasant but financially responsive role for an already sick situation. But in the railroad industry such cannibalization usually does not work and the frustration engendered makes it all the more difficult to manage the situation properly.

A Government View of Electrification

Thomas G. Allison, U.S. Senate Committee on Commerce, Science, and Transportation

The subject of railroad electrification in the United States presents something of a dilemma for those working in policy-making positions in the government. On the one hand, it is relatively easy to find statements supporting electrification made by both members of Congress and the executive branch. On the other hand, these various pronouncements do not seem to contain a great deal of weight when measured against the progress made since the 1930s in electrifying heavy-density main lines in this country.

One reason for the lack of progress could be that the benefits of electrification have been somewhat overstated at times. In an article in Trains in 1946 (1), an electrification engineer was asked whether the electrification of the Pennsylvania Railroad had been successful:

> "The answer is yes," he finally said, "but I am wondering just how to make the point clear. Perhaps this does it: It was the Pennsylvania Railroad electrification which, more than anything else, kept the government from taking over the railroads in this war as it did in the last. One might even say that if the Pennsylvania's eastern lines had not been electrified, we might have lost the war."
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> Asked to amplify, he continued, "The traffic to the central eastern

seaboard was the key to our wartime success, and the Pennsylvania is the key to this traffic. In the last war, it was the congestion backed up as far as the Pittsburgh area which necessitated rerouting of traffic to other roads with less capacity, and when they in turn became overloaded the government had to take over. In this war, the tremendous capacity of the electrified lines absorbed everything thrown into the central seaboard area and the traffic did not back up. All the way back across the country this capacity had its effect. The railroads were able to do the job, they stayed in the hands of their own management, and we won the war."

If one were to believe the statements made in this article, it would seem that the least that the government could have done since World War II is to sponsor further electrification of heavy-density railroad lines as a combination war memorial and defense precaution for any future conflicts that might occur.

The Executive Committee of the Transportation Research Board has identified the 10 most critical issues in transportation (2). At least seven of these ten issues pertain directly to main-line railroad electrification. The 1974 report of the government-industry task force on railroad electrification (3) specifically recommended that the government take an active role to help plan and fund railroad electrification when substantial improvements in national transportation efficiency can be achieved. The task force also recommended that legislation dealing with railroad improvement should permit assistance for railroad electrification projects in appropriate circumstances.

Partly in response to this report, Congress did enact legislation that allows railroads to apply for financial assistance for electrification projects—Title V of the Railroad Revitalization and Regulatory Reform Act of 1976. Unfortunately, since the enactment of that legislation no railroad has applied for assistance to electrify a heavy-density main line. Other parts of the Railroad Revitalization and Regulatory Reform Act of 1976 provide for a modernization of the electrification of the Northeast Corridor, including an extension of the electrified system from New Haven to Boston, and for electrification of the heavy-density freight main line of the Consolidated Rail Corporation (Conrail) from Pittsburgh to Harrisburg in a manner that will facilitate compatible operations with the Northeast Corridor. At the moment, Conrail is actively assessing this project, which may well become the first heavy-density freight main-line electrification project in the United States in almost 40 years.

But implementation of these electrification projects does not provide an adequate answer to the question of why, in light of its claimed benefits, electrification has not moved forward more rapidly in the United States. It has often been observed that, on almost every continent except North America, railroads are increasingly turning to electrification for a wide variety of reasons, and many of those reasons should be equally applicable here. The question seems all the more perplexing in view of the fact that the relatively capital-intensive United States is not engaging in electrification projects when such countries as Taiwan, Yugoslavia, and India are actively pursuing main-line electrification.

The government-industry task force on railroad electrification identified a number of issues that have influenced decisions by the railroad industry not to electrify, and many of these issues still have obvious validity. For instance, it is certainly true that diesel-electric locomotives have become standardized throughout the railroad industry. It is also true that they are relatively easy to purchase, even for the more marginal carriers. The operating familiarity of railroads in the United States with the relatively reliable diesel units typically manufactured here undoubtedly reinforces the familiarity of financing their purchase. It is also probably true that construction and successful operation of a major electrification project would go a long way toward breaking the ice. While there may not be a great rush to be second, the existence of an operationally and financially successful main-line electrification project would undoubtedly make even the most operationally conservative of domestic railroad managements consider seriously the benefits of electric traction.

After considering all the reasons for not electrifying—and assuming a rational and open mind on the part of railroad managements—one set of issues stands out. It is obvious that the issues surrounding financing of such a major capital investment must rank as the most important of all reasons that railroad electrification has not moved forward more rapidly. Not only do the economic benefits of electrification occur gradually over a long period of time, compared with the large investments necessary to initiate that flow of benefits, but many carriers can show a much higher short-term improvement in their operations through investments in other parts of their permanent way, such as rehabilitation of main lines and improved yard facilities.

Financing is available to purchase relatively reliable and proven diesel-electric locomotives, but financing is generally not available in any conventional manner for most carriers to engage in major electrification projects. Even carriers that could arrange for such financing may be unwilling to do so because of the massive increase in their debt that would result and the possible resultant inability to obtain capital in the future for other necessary improvements to their fixed plants. After numerous informal discussions with representatives of different railroads and the supply industry, I also believe that most railroads in the United States simply do not possess a clear and strong belief in the benefits of electrification compared with the benefits that could flow from government assistance in other areas, such as rehabilitation of track or reform of regulation. The railroad industry has never actively advocated that Congress should create any program to help electrify heavy-density main lines in the United States.

It seems to me that the reasons for the failure of the railroad industry to more aggressively advocate government financial assistance for railroad electrification probably combine inbred practices and familiarity with the existing fleet of diesel-electric power that has performed reasonably well, a lack of conviction regarding the benefits of electrification on the part of individual carriers, and perhaps a realization that major electrification projects should not be carried out in a vacuum. For instance, electrification could disrupt existing arrangements with other carriers, such as run-through trains, and perhaps should be looked at in a more comprehensive way, along with other improvements to the nation's rail system involving such issues as consolidation, mergers, elimination of excess trackage, and improvement of terminal and yard facilities.

When electrification is looked at in the context of all the improvements that would be desirable for the nation's railroad system, I do not believe that the government has treated electrification differently from many of the other important issues currently facing rail transportation in the United States. While financial assistance in the form of loans to railroads is available to a limited extent under the provisions of Title V of the Railroad Revitalization and Regulatory Reform Act, the implementation of that statute has not yet led to any applications from carriers for electrification projects. The recent change of administrations, particularly with respect to the U.S. Department of Transportation (DOT), may reverse this trend by promoting the use of these funds for improvement projects on a much wider scale, but I still would tend to doubt whether railroad electrification will be significantly advanced by the existing railroad assistance programs, except in the case of Conrail and the Northeast Corridor.

In enacting Title V of the Railroad Revitalization and Regulatory Reform Act, Congress realized that the financing provisions contained in it—$600 million of essentially low-interest loans and $1 billion in loan guarantees—were inadequate to deal with the capital needs of the railroad industry. Because the Senate Commerce Committee was faced with varying estimates of the capital needs of the railroad industry, ranging from $2 billion to $12 billion, it was felt it was appropriate to enact an interim financing measure while a better determination of the long-range capital needs of the industry was made. Section 504 of that act required DOT to submit to Congress in August 1977 a complete study and estimate of the capital needs of the industry. Obviously, this is a very complicated subject that involves the competitive relationships of the various modes of transportation, which are in turn influenced by such decisions as whether to impose user charges on the nation's inland waterway system and whether to revise the amount of user charges for certain kinds of truck traffic. In fact, some have even suggested that, if appropriate regulatory and funding changes are made for other modes of transportation, the railroad industry would have no capital shortfall at all.

Whatever DOT and Congress ultimately recommend as the most appropriate form of capital assistance for the nation's railroad system, consideration may have to be given to treating assistance for major electrification projects in a slightly different manner from rehabilitation of permanent way. Because of the existing debt structure of many carriers, it may simply be impossible for them to finance railroad electrification projects, even with government assistance, if this financing results in additional debt. Furthermore, railroad electrification efforts should probably be carried out in conjunction with a national planning effort to maximize the benefits that could flow from electrification. It may be necessary to finance electrification projects in a relatively unorthodox manner, such as direct government funding and ownership of electrification facilities with a lease to the applicable railroad in order to allow carriers to finance the improvement as an operating expense rather than as debt. Several other possible arrangements for financial assistance are conceivable; these involve concepts similar to leveraged leasing or a relatively conventional loan program that, when combined with coordinated improvements in the regulatory and competitive structure for the railroad industry, would allow the industry to carry the additional debt.

Although Congress and DOT seem quite favorable to moving ahead with some program to stimulate railroad electrification of heavy-density main lines in the United States, it is extremely unlikely that any major new government program will be enacted without the active support of America's railroad industry. It is unlikely that Congress will force the railroads to accept government money to engage in projects that the industry itself is not convinced will provide operating and financial benefits. In this sense, the government appears to be well ahead of the railroad industry with respect to advocacy of railroad electrification, and it would appear that this gap will have to be closed before any major new program specifically designed to promote electrification is enacted. Given the fact that Conrail may soon embark on the first major freight electrification project, it is possible that this gap will be closed in the near future.

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