# Cost/Benefit Evaluation of Electrification of a U.S. Rail Network

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**A model was used to analyze the economics of an electrified U.S. freight-hauling network consisting of 96 route segments for 16 railroads and totaling nearly 29,000 route-miles. For the base case analyzed the rate of return for the network was substantially greater than predicted by previous FRA studies. Considerable variation of rate of return between route segments was found depending on the combination of critical site-specific factors that exist. The factors found to have major influence on the rate of return were traffic density, type of diesel locomotive being replaced, type of electric locomotive, dispatch policy, catenary cost, and differential cost of fuel compared with electricity. The best single surrogate for these factors was found to be annual fuel consumption per route-mile. However, dependency on variables uncorrelated with fuel consumption is still sufficient to require computation of the rate of return.**

Railroad electrification has proven to be economically feasible in many countries. Excluding the United States, nearly 20 percent of all track in the world is currently electrified (1). Less than one percent of the track in the United States is electrified, and the only electrification installed in the last 40 years is limited to a few hundred miles of private coal-hauling and commuter operations.

Before the energy crisis, reduced locomotive maintenance and improved traction capability were considered to be the major advantages of electrification when compared with diesel motive power. In recent years instability in the price of diesel fuel relative to electric energy and uncertainty regarding the availability of diesel fuel have made energy a significant consideration. Traction advantages have become less significant with the introduction of diesel locomotives that have higher adhesion.

Numerous studies have been made of main line electrification in the United States. Most have concluded that the rate of return is positive, but the capital cost of conversion is too great to justify the risk. A government-industry task force concluded in 1974 that electrification was the only feasible alternative to liquid petroleum fuel for intercity movement of goods and people (2). A 1977 study mandated by the Railroad Revitalization and Regulatory Reform Act of 1976 concluded that, although electrification of certain routes would be beneficial to the owning railroad, the national benefits were not sufficient to warrant government assistance beyond the commitment of the Reform Act of 1976 (3). FRA and 16 major railroads initiated a joint study in 1980 to examine, in more detail, the effect of route-specific factors (4). The model developed in conjunction with this study and the cost/benefit results for a U.S. rail network are described elsewhere (5). The results of that study are summarized in this paper.

## ROUTE DEFINITION AND CONSTRUCTION SCHEDULE

Route selection began by identifying line segments based on their traffic density in 1978. As a rule, 30 million gross ton-miles per route mile (MGTM/M) was used as the minimum for segment inclusion in the study. This selection criterion was modified to provide a limited number of necessary connecting links and to make each railroad's electrified segments cohesive from an operating standpoint. Figure 1 depicts the final network analyzed for electrification. It is a national network of 29,000 route-miles, consisting of 96 route segments that belong to 16 railroads. Route segments range in size from 36 to 1,035 miles long and typically connect major operating centers. Within this network a smaller, more heavily used, core of about 10,000 route-miles was also identified, primarily on the basis of each link carrying at least 40 MGTM/M.

A significant percentage of the route-miles in the network actually consists of more than one track, and all routes include some amount of yard trackage and sidings that for operating purposes would need to be electrified. Track mileage is given in Table 1 by number of tracks and the average curvature--factors that affect the cost of construction. The percentage of total traffic on a route segment that would actually be hauled by electric locomotives varies from virtually 100 percent down to slightly more than 50 percent, depending on factors such as the amount of local switching service and the presence of traffic moving to and from non-electrified lines at intermediate points. The table below defines how the potential volume of electrically hauled traffic is distributed over the mileage of the network.

| Traffic Density Range (MGTM/M) | Route Mileage (%) |
|---|---|
| > 40 | 41.0 |
| 30-40 | 28.6 |
| 20-30 | 27.0 |
| < 20 | 3.4 |

The study demonstrated that a conversion program of this magnitude could be carried out in a reasonable period of time under a set of assumptions that included limiting construction to 1,000 route-miles in any year [by comparison the Soviet Union achieved nearly 1,200 miles annually between 1955 and 1976 (6)]. The use of arbitrarily assigned starting times for the electrification of individual links resulted in distortions in the economic analysis because of the effect of traffic growth on those links begun later in the program. Therefore, the date on which design engineering was initiated for the first link of each railroad was set to January 1, 1982. Each individual link still required the same length of time for design and construction as estimated earlier, and those railroads that have fewer miles to be electrified would complete their program sooner.

## OPERATING PARAMETERS AND TRAFFIC ASSUMPTIONS

Both published and railroad-supplied data were used in the analyses. Figure 2 shows the railroad questionnaire form used to obtain data on each route segment. For consistency of traffic projections on a national basis, items 1 and 2 of the questionnaire were completed by FRA based on traffic projections (7). The participating railroads were asked to comment on the reasonableness of this traffic data and supply items 3 through 10. Table 2 identifies the characteristics obtained from published data and the specific source for each.

Traffic for each route segment is input with sufficient detail and accuracy to achieve the de-

Figure 1. Hypothetical 29,000-mile network studied.

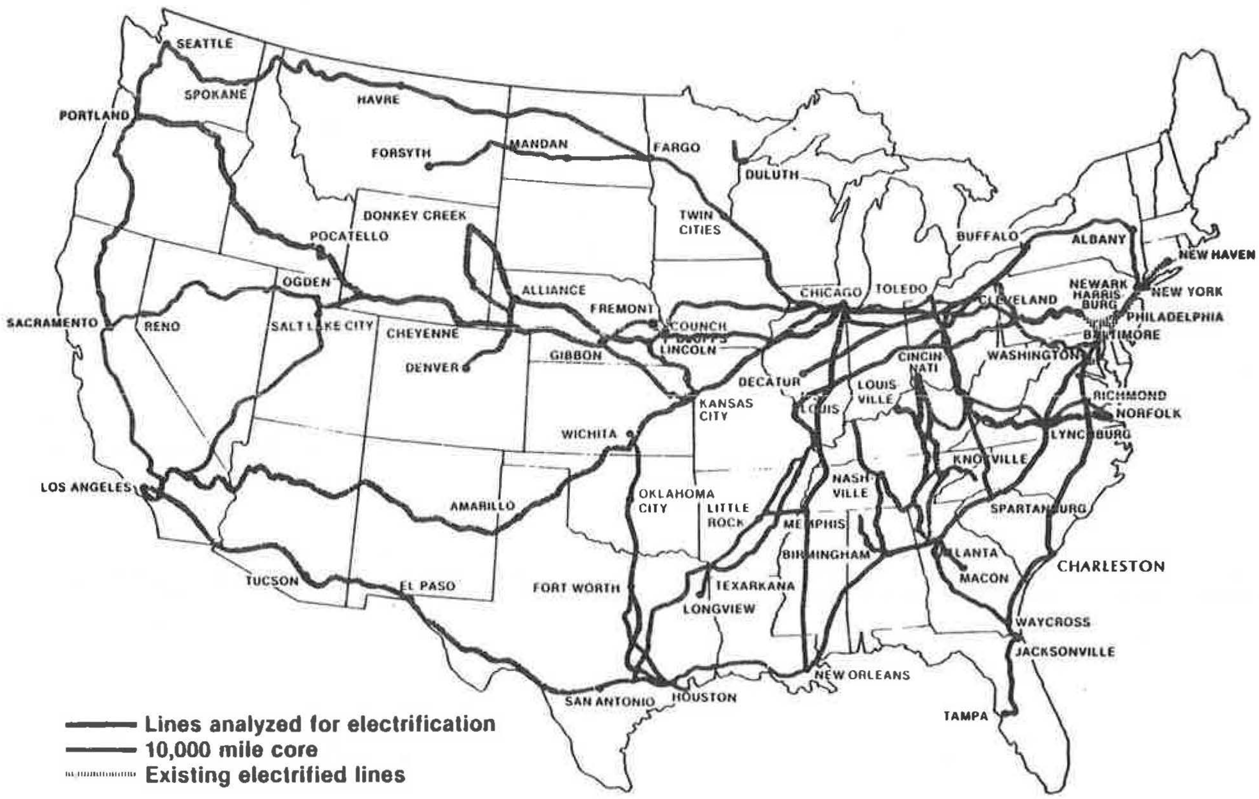



Table 1. Track characteristics.

| Curvature Category | Route-Miles 1-Track | 2-Track | 3-Track | 4-Track | Total |
|---|---|---|---|---|---|
| Tangent-to-light curvature, 0 to 1 degree avg. | 14,930 | 9,473 | 289 | 82 | 24,774 |
| Medium curvature, 1 to 3 degree avg. | 2,172 | 1,162 | 85 | 41 | 3,460 |
| Heavy curvature, >3 degree avg. | 287 | 154 | 6 | 1 | 448 |
| Total | 17,389 | 10,789 | 380 | 124 | 28,682 |
| Track-miles | 17,389 | 21,578 | 1,140 | 496 | 40,603 |
| Sidings and yards | | | | | 9,575 |
| Total track-miles | | | | | 50,178 |

Table 2. Route characteristics obtained from published sources.

| Characteristics | Source: 10,000 Route-Mile Core | Remainder of 29,000 Route-Mile Network |
|---|---|---|
| Route and track mileage | | |
| By no. of tracks | Railroad timetables | Railroad timetables |
| By avg. curvature category | FRA data base[a] | Estimated |
| No. of bridges | FRA data base[a] | FRA data base[a] |
| Avg. grade category | FRA data base[a] | Estimated |
| New transmission line | A.D. Little[b] | A.D. Little[b] |
| Substation spacing | Electrack[c] | Electrack[c] |

[a]Assimilated by the Policy Office during studies under the 4-R Act.
[b]From Schwarm (8).
[c]From Kneschke (9).

sired discrimination in economics of one segment versus another. The four aspects of traffic contained in input data are as follows.

1. Traffic is specified by direction in order to include the impact of imbalanced traffic on locomotive fleet size and maintenance.
2. Traffic between two points is specified by up to four types of service that have been defined as bulk (e.g., coal, ore, or grain unit trains), normal (mixed freight), expedited [e.g., trailer on flatcar (TOFC) and perishable trains], and passenger to accommodate major distinctions that may exist in locomotive type, ratio of locomotive horsepower to weight of train (dispatch level), run time, energy consumption, and maintenance.
3. When more than one distinct pair of operating end points exist for the motive power on a route segment, then the fleet, energy, and maintenance requirements are calculated for the traffic moved over each operating sector by the separate fleets. Multiple operating sectors may result from (a) traffic that originates, enters, leaves, or terminates at intermediate points on a route segment, assuming it is desired to haul this traffic with an electric fleet; otherwise intermediate traffic is ignored; (b) route segments that contain branches; or (c) helper locomotives added to main-line motive power at major grades for part of the segment.
4. Annual traffic growth on a route segment is specified for each direction, type of service, and traffic pattern. This growth rate is applied from the traffic base year through 1990, after which no growth is assumed for the remainder of the study period.

## MOTIVE POWER REQUIREMENTS

The basic performance requirements of a freight locomotive consist are (a) sufficient traction to

Figure 2. Completed railroad questionnaire for sample segment.

Railroad: URAIL & Company

Route Sector: UTown yard (Forward (FWD) ----►) To: UCity, USA (Reverse (REV) ◄----)

| QUESTIONNAIRE ITEM | DIREC-TION | 1 COAL | 2 GRAIN | 3 CHEM-ICALS | 4 IRON ORE | 5 SAND, STONE, GRAVEL | 6 NONMET-ALLIC MIN. | 7 FOREST PRO-DUCTS | 8 CEMENT, CLAY & GLASS | 9 FOOD | 10 GRAIN MILL PROD. | 11 PULP, PAPER | 12 PRIM-ARY METALS | 13 TRANS. EQUIP-MENT | 14 LUMBER, WOOD | 15 FREIGHT FWDR., & LCL | 16 ALL OTHER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. FRA projected annual growth in revenue tonnage to 1990. | FWD | -9.3 | 4.8 | 2.8 | 0 | 1.7 | 2.4 | 0 | -0.8 | -0.2 | 1.4 | 2.3 | 1.6 | 2.9 | -0.5 | 3.0 | 3.0 |
| | REV | 0 | 0 | 1.4 | 0 | 5.8 | 2.2 | -2.1 | -0.3 | -1.0 | -0.3 | 3.0 | 1.2 | 1.7 | -2.1 | 2.3 | 2.3 |
| 2. Percent of actual 1980 revenue tonnage. | FWD | 0.4 | 15.9 | 2.3 | 0.1 | 0.1 | 0.3 | 1.0 | 1.7 | 1.2 | 1.1 | 1.5 | 1.9 | 0.6 | 0.9 | 7.1 | 3.7 |
| | REV | 0 | 3.8 | 0.5 | 0.9 | 0.1 | 1.4 | 0.3 | 0.6 | 4.9 | 0 | 5.7 | 4.5 | 1.1 | 32.7 | 2.7 | 1.0 |
| 3. Check those commodity groups where a measurable percentage moves in expedited service. | | | | | | | | | | X | | | | X | X | X | X |

| | | EXPEDITED | NORMAL | BULK | PASSENGER |
|---|---|---|---|---|---|
| 4. Diesel dispatch level in horsepower per ton. | FWD | 3.1 | 1.8 | - | - |
| | REV | 3.0 | 1.9 (+ 1.2)* | - | - |
| 5. Prevelent type of diesel locomotive used. | | SD-40-2 | SD-40-2 (SD-40-2) | - | - |
| 6. Typical running time. | FWD | 13 hr., 10 min. | 21 hr., 45 min. | - | - |
| | REV | 13 hr., 25 min. | 16 hr., 15 min. | - | - |

*Helper at Big Mountain Pass where one-way operating mileage is 18.2 miles.
**Reverse ruling grade outside helper district is 1.0; inside, 1.8.

| | FORWARD | REVERSE |
|---|---|---|
| 7. Ruling Grade | 1.0 | 1.0 (1.8)** |
| 8. 1980 Actual Gross Ton Miles (average). Does/does not include locomotives. | 16.6 | 15.8 |
| 9. Approximate percentage of total tonnage moving in expedited service. | 40% | 50% |
| 10. Percentage of total tonnage expected to move with electric locomotives. | 100% | 100% |

Table 3. Design characteristics and cost in 1980 for diesel locomotive types used in network study.

| Item | Design Characteristics and Cost by Type | | | | | | |
|---|---|---|---|---|---|---|---|
| | Type 1 | Type 2 | Type 3 | Type 4 | Type 5 | Type 6 | Type 7 |
| Typical manufacturer's model no. | | | | | | | |
| General Motors | GP-38 | SD-38 | GP-40 | SD-40 | SD-45 | GP-50 | SD-50 |
| General Electric | U-23B | U-23C | U-30B | U-30C | | B-36-7 | C-36-7 |
| Rated horsepower | 2,000 | 2,000 | 3,000 | 3,000 | 3,600 | 3,500 | 3,500 |
| Rail horsepower[a] | 1,700 | 1,700 | 2,550 | 2,550 | 3,060 | 3,000 | 3,000 |
| No. of axles | 4 | 6 | 4 | 6 | 4 | 4 | 6 |
| Weight per axle | 64,000 | 59,300 | 64,000 | 61,300 | 61,300 | 65,000 | 65,000 |
| Adhesion capability | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.25 | 0.25 |
| Continuous tractive effort at adhesion limit | 46,000 | 64,100 | 46,000 | 66,200 | 66,200 | 65,000 | 97,500 |
| RHP/lb of tractive effort | 0.037 | 0.027 | 0.055 | 0.039 | 0.046 | 0.046 | 0.031 |
| Cost/unit ($000) | 630 | 730 | 660 | 760 | 830 | 700 | 820 |
| Cost/RHP ($) | 371 | 429 | 259 | 299 | 272 | 233 | 273 |
| Cost/lb of T.E. ($) | 13.75 | 11.50 | 14.25 | 11.75 | 12.50 | 10.75 | 8.50 |

[a]Rail horsepower (RHP) = 0.85 x rated horsepower (assumed).

start a train and climb the ruling grade on the route and (b) sufficient power to maintain the necessary speed to move the train over the route in a specified time. A consist is ideally matched to these basic requirements when it has just sufficient power and traction capability.

The range of power and traction capabilities of the diesel locomotive types now in service is diverse. Table 3 (10) identifies the characteristics of the diesel road locomotives currently in service on the network. In a fleet required for work where some line segments include significant grades and others have few or no gradients, the final choice is of necessity a compromise to avoid too great a number of locomotive types, and the result is full use of neither tractive effort nor power rating.

Similar compromises are required when considering the type of electric locomotive to be used. Three electric locomotive types were defined with the characteristics listed in Table 4. The selection procedure adopted was to replace diesel units on a segment with electric units that have precisely the traction capability required on the ruling grade and a minimum of power in excess of the current diesel dispatch level.

Table 5 gives the locomotive requirements of the 29,000-mile network. The 2,550 rail horsepower, six-axle diesel dominates the existing service and

**Table 4. Design characteristics and cost in 1980 for electric locomotive types used in network study.**

| Locomotive Type | Type 1 | Type 2 | Type 3 |
|---|---|---|---|
| Rail HP | 2,500 | 4,000 | 6,000 |
| No. of axles | 4 | 6 | 6 |
| Weight/axle (lb) | 65,000 | 65,000 | 65,000 |
| Adhesion capability | 0.25 | 0.25 | 0.25 |
| Continuous tractive effort at adhesion limit | 65,000 | 97,500 | 97,500 |
| RHP/lb of tractive effort | 0.038 | 0.041 | 0.062 |
| Cost/unit ($000 000) | 0.720 | 1.2 | 1.4 |
| Cost/RHP ($) | 360 | 300 | 233 |
| Cost/lb of T.E. ($) | 11.10 | 12.30 | 14.40 |

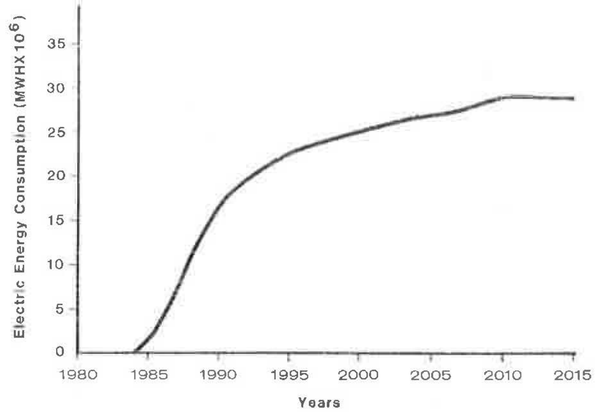
**Table 5. Calculated locomotive requirements for 29,000-mile network.**

| | Quantity Required by Type of Service | | | |
|---|---|---|---|---|
| Locomotive Type | Bulk | Normal | Expedited | Total |
| Diesel | | | | |
| Type 1: 4-axle 1,700 rail horsepower | 19 | 632 | 121 | 772 |
| Type 2: 6-axle 1,700 rail horsepower | 0 | 21 | 0 | 21 |
| Type 3: 4-axle 2,550 rail horsepower | 0 | 499 | 270 | 769 |
| Type 4: 6-axle 2,550 rail horsepower | 137 | 1,755 | 728 | 2,620 |
| Type 5: 6-axle 3,060 rail horsepower | 0 | 408 | 242 | 650 |
| Type 6: 4-axle 3,000 rail horsepower | 13 | 21 | 7 | 41 |
| Type 7: 6-axle 3,000 rail horsepower | 0 | 0 | 0 | 0 |
| Total | 169 | 3,336 | 1,368 | 4,873 |
| Electric | | | | |
| Type 1: 4-axle 2,500 rail horsepower | 0 | 30 | 0 | 30 |
| Type 2: 6-axle 4,000 rail horsepower | 100 | 247 | 26 | 373 |
| Type 3: 6-axle 6,000 rail horsepower | 0 | 1,245 | 502 | 1,747 |
| Total | 100 | 1,522 | 528 | 2,150 |

the 6,000 rail horsepower, six-axle electric dominates the electric service. The diesel and electric power requirement in each direction on each segment were calculated by using the actual dispatch level (rail horsepower per gross ton) and run time obtained via the railroad questionnaire. The power requirement on a route is typically established by a train performance calculator (TPC) when performing a feasibility study. The use of actual dispatch data obviated the use of a TPC and included the factor of safety that each railroad applies to contend with unpredictable events such as locomotive failure and weather-dependent variations in traction. Fleet size was established to account for variation in directional requirements and to account for turnaround time and nonuse.

Based on the distribution in Table 5, a locomotive in the 4,000-rail horsepower range would be needed for bulk haul where the prime criterion is adhesion; for normal and expedited service locomotives of higher horsepower would be more economical. The optimum single electric locomotive type capable of providing service equivalent to the present diesel fleet and also making fullest use of power and traction capability has a power rating in excess of 4,000 rail horsepower (possibly even greater than 6,000 hp), but this is conjecture because no greater horsepower unit was included in the evaluation.

**Figure 3. Electric energy consumption on 29,000-mile network.**




The factor of adhesion for all electric locomotives was assumed to be 25 percent. Type 6 and type 7 diesel locomotives have improved wheel-slip controls to give them an assumed 25 percent factor of adhesion. All other diesels are assumed to have an 18 percent factor of adhesion. Fewer than 1 percent of the diesel units in service have improved adhesion; therefore, in essence the study compared electric locomotives that have 25 percent adhesion factors to diesel locomotives that have 18 percent adhesion factors and, as such, estimated the benefits of conversion from the existing diesel fleet to electric traction. Any detailed financial evaluation for investment purposes should also compare the replacement of existing diesels with improved diesels. Such studies would help in deciding whether to electrify or to evolve to improved diesel traction at lower benefit but much lower capital investment.

## ENERGY

Figure 3 shows the consumption of electrical energy on the rail network through the 28-year period of construction. The change in slope in 1990 is the result of assuming that all traffic growth terminates in that year. Hence, when construction is completed in the year 2010 railroad energy consumption becomes constant at 30 million MW-h/year. The corresponding consumption of diesel fuel on the rail network in 2010, assuming electrification does not occur, is 2,200 million gal or 52 million barrels/year. This fuel consumption is less than 1 percent of the total petroleum products consumed in the United States in 1980 (11).

Table 6 gives the railroad energy consumption by Bureau of Census region and the percentage of 1980 regional electric utility energy production that consumption by electrified railroads would represent. The total electric energy consumed by the completed rail network based on 1980 traffic levels is approximately 1 percent of total 1980 electric utility energy production. The Bureau of Census region that has the largest railroad energy consumption in percentage of 1980 electric utility energy production is the Mountain region with 2.7 percent, followed by the West North Central region with 2.4 percent. Total electric utility energy production in the United States is projected to increase by 3.6 percent/year from 1980 to 1990 (12). By Bureau of Census region the projections are 4.7 percent/year for the Mountain region and 3.8 percent/year for the West North Central region.

Table 7 gives the power line required to connect

**Table 6. Railroad energy consumption and cost of electricity by region.**

| Bureau of Census Region | Railroad Energy Consumption[a] (000,000 MW·h) | 1980 Electric Utility Energy Production[b] (000,000 MW·h) | Railroad Energy Consumption per Electrical Utility Energy Production (%) | 1980 Cost of Electricity[c] (¢/kW·h) |
|---|---|---|---|---|
| 1. New England | 0 | 78 | 0 | 5.3 |
| 2. Middle Atlantic | 1.4 | 261 | 0.6 | 4.5 |
| 3. East North Central | 2.4 | 397 | 0.6 | 4.1 |
| 4. West North Central | 3.9 | 168 | 2.3 | 4.1 |
| 5. South Atlantic | 3.3 | 418 | 0.8 | 3.6 |
| 6. East South Central | 2.1 | 214 | 1.0 | 3.6 |
| 7. West South Central | 1.9 | 313 | 0.6 | 2.9 |
| 8. Mountain | 5.5 | 159 | 3.5 | 2.8 |
| 9. Pacific | 2.6 | 269 | 1.0 | 2.5 |
| Total | 23.2 | 2,277 | 1.0 | 3.4 |

[a] Based on 1980 traffic levels for a 29,000 route-mile electrified network.
[b] From Statistical Yearbook of the Electric Utility Industry/1980 (12).
[c] Industrial rates.

**Table 7. Miles of new power line required for railroad electrification.**

| Bureau of Census Region | New Power Line Required for Railroad Electrification (miles) |
|---|---|
| 1. New England | 0 |
| 2. Middle Atlantic | 74 |
| 3. East North Central | 297 |
| 4. West North Central | 375 |
| 5. South Atlantic | 374 |
| 6. East South Central | 244 |
| 7. West South Central | 320 |
| 8. Mountain | 425 |
| 9. Pacific | 277 |
| Total | 2,386 |

Note: Estimates are based on a 29,000 route-mile U.S. electrified network.

traction substations to the existing utility substations and power line. The new power line voltage is 115, 230, or 345 kV, depending on voltage level of the closest existing power line. The average number of circuit-miles installed annually by the utility industry is slightly more than 10,000 (12), so that, if the 2,400 miles required for the electrification network were installed during a 25-year period, the installation rate would be increased by less than one percent.

The costs of electric energy and diesel fuel were projected to increase at a faster rate than general inflation. For the base case the cost of electrical energy is assumed to increase by 2 percent/year and diesel fuel by 3 percent/year above general inflation until the year 2000. Beyond 2000 no relative escalation is assumed.

## COST/BENEFIT MODEL

Questions of apportioning cost reductions between shipper and consignee and the issue of acquiring new business at the expense of other railroads or other transportation modes should not be considered when measuring the overall effectiveness of electrification on a network. For this application the simplified model based on the differential costs of operation is the appropriate choice. The model used to produce the results in this study assumes identical traffic, freight rates, and quality of service for diesel and electric operation. Figure 4 is a block diagram representation of basic model functions.

The financial index used in the model to measure the time value of an investment is the internal rate of return (ROR). Internal ROR is the most frequently used index in the railroad industry for discretionary investment projects (13) and is stipulated by FRA in applications for Title 5 assistance under the reform act (14). ROR is computed by using conventional procedures of engineering economy to determine the time value of the differential cash flow that results when electrification replaces diesel operation (15).

Three basic assumptions are made in constructing the differential cash flow that is used to compute ROR:

1. The cost of electrification is considered in total, regardless of the sources of the funds, thereby producing an equity rate of return;
2. All capital equipment is straight-line depreciated over prescribed economic lifetimes, is replaced as necessary, and a residual value is calculated at the end of the study period; and
3. No taxes or tax credits are included.

### Network Investments

Table 8 compares the net investments and net annual savings for the 29,000-mile network and 10,000-mile core (C) with those of the previous FRA studies of 10,000- and 26,000-mile networks (A and B) (3,15). The net investment in the C network is 9 percent less than in the B network even though it is 3,000 route-miles longer. This study did not postulate any segments in operation in its base year (1980); however, the previous studies had assumed all routes in operation in their base years. For comparison of results the annual costs and credits in Table 8, C columns, are therefore shown for operation of all segments at the 1980 traffic level. The net annual savings of the C network is 6 percent less than that of the B network.

The number of locomotives (diesel and electric) required was significantly less than previously estimated, thereby reducing the magnitude of these investments. The net locomotive investment now indicates a credit, whereas the previous studies showed an expense. This results from the difference in procedure for crediting diesel locomotives not required. The previous studies assumed that the locomotives displaced by electrification would have a life of 18 years and be uniformly distributed in age. Credit was taken against the initial investment for sale or use elsewhere at a price based on straight-line-depreciated value in the ninth year. Credit was also taken each year thereafter to avoid capital expenditure on replacing 1/18 of the diesel fleet that had been displaced by the electrification. The capital cost of new electric locomotives was included in the capital outlay, and the cost of replacement after a 30-year life was included in the cash-flow calculations.

For the larger railroads these assumptions represented the likely situation for electric locomotives but were not realistic in portraying the capital expenditure associated with the diesel locomotives displaced. This study assumed that the larger railroads would have diesel locomotive replacement programs based on acquiring each year new locomotives equal to 1/18 of their entire fleet. Further assumed was that, when the electric locomotives took over the work of a given number of diesels, the railroad would reduce their replacement program by an equivalent number of diesel locomotives and credit for this amount of capital expenditure would be avoided. The avoidance of a similar capital expenditure each 18 years was also credited. An estimate was made of the annual replacement need for line-haul diesel locomotives by the railroad concerned. Where this exceeded the annual building program for diesel

**Figure 4. Block diagram representation of railroad electrification assessment model.**

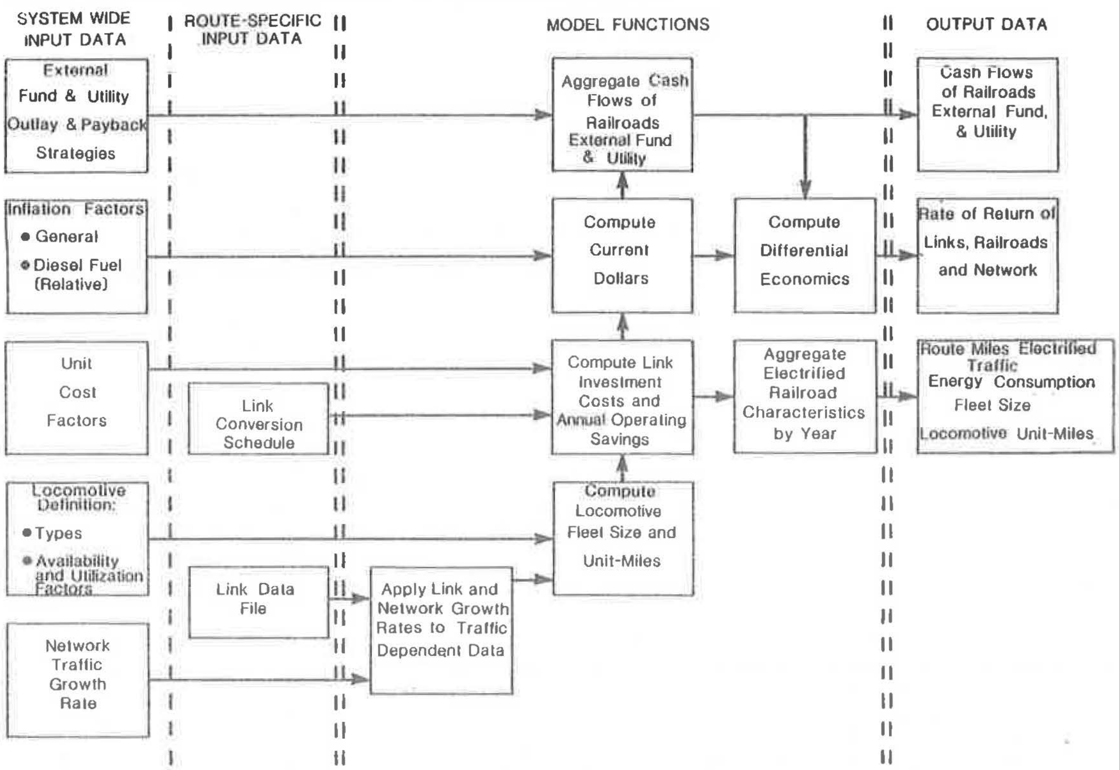



**Table 8. Net investments and net annual savings due to electrification.**

| | A ($000,000s in 1977)[a] | | B ($000,000s in 1980)[a] | | C ($000,000s in 1980) | |
|---|---|---|---|---|---|---|
| Category | 10,000-Mile Network | 26,000-Mile Network | 10,000-Mile Network | 26,000-Mile Network | 10,000-Mile Core | 29,000-Mile Network |
| Investments | | | | | | |
| Catenary | 1,660.6 | 3,595.8 | 2,646 | 6,040 | 2,605.2 | 7,592.3 |
| Substations | 516.4 | 1,175.2 | 1,320 | 3,000 | 522.9 | 1,534.3 |
| Utility connections | 100.0 | 260.0 | 150 | 390 | 167.7 | 513.6 |
| Signals and communications | 682.5 | 1,625.0 | 1,850 | 4,400 | 1,032.4 | 2,924.9 |
| Civil reconstruction | 361.6 | 858.0 | 696 | 1,660 | 216.5 | 909.4 |
| Design engineering | - | - | - | - | 454.5 | 1,347.4 |
| Construction engineering | - | - | - | - | 68.2 | 202.1 |
| Electric locomotives purchased | 1,800.0 | 3,400.0 | 2,770 | 5,240 | 1,835.8 | 3,604.1 |
| Diesel locomotive purchase avoided | - | - | - | - | -2,271.2 | -4,346.8 |
| Diesel locomotives released | -1,700.0 | -3,200.0 | -2,690 | -5,060 | 0 | -9.9 |
| Net | 3,421.1 | 7,714.0 | 6,742 | 15,670 | 4,632.0 | 14,271.4 |
| Annual costs and credits | | | | | | |
| Electric energy | 381.0 | 706.1 | 597 | 1,110 | 354.0 | 708.0 |
| Electric locomotive maintenance | 96.6 | 182.4 | 217 | 409 | 166.4 | 302.0 |
| Wayside maintenance | 20.0 | 52.0 | 44 | 114 | 43.6 | 122.8 |
| Diesel fuel | -398.8 | -739.2 | -807 | -1,500 | -760.9 | -1,500.0 |
| Diesel locomotive maintenance | -370.0 | -696.3 | -724 | -1,360 | -542.2 | -1,050.0 |
| Diesel locomotive purchases | -94.0 | -178.0 | -149 | -281 | -55.7 | -67.9 |
| Electric locomotive purchases | - | - | - | - | 51.3 | 60.7 |
| Net annual savings | 365.2 | 673.0 | 822 | 1,508 | 743.5 | 1,424.4 |

[a]From Spenny (15, Table C-2).

Note: The 10,000-mile network has 10,000 route-miles and traffic of 502,470. The 26,000-mile network has 26,000 route-miles and traffic of 945,800. The 10,000-mile core has 9,860 route-miles and traffic of 484,035. The 29,000-mile network has 28,681 route-miles and traffic of 1,044,751.

locomotives, the credit was spread over as much as 3 years, starting with the first year of electric operation.

## ROR Calculations

The network ROR results are compared with previous FRA results in Table 9. The ROR is substantially greater for several reasons:

1. Previous studies did not consider that conversion of the network would require a finite number of years, thereby allowing traffic to build to higher levels on many of the routes before conversion;
2. Traffic forecasts and dispatch levels have been examined in more detail and the unit costs have been refined to push the ROR higher; and
3. Avoidance of new diesel purchases during the investment period produces more credit than does selling of the excess used diesels at their market value.

Table 9. ROR for three network scenarios.

| Network | Scenario | RoR for 10,000-Route-Mile Network (%) | RoR for 26,000-Route-Mile Network (%) |
|---|---|---|---|
| A, 1977 | Without fuel differential | 12 | 10 |
| | With fuel differential | 15 | 12 |
| B, 1980 | Without fuel differential | 14 | 11 |
| | With fuel differential | 17 | 14 |
| C, 1980 | Without fuel differential | 18.9[a] | 14.4[a,b] |
| | With fuel differential | 25.5[a] | 19.4[b] |

[a]Constructed from other computer model runs.
[b]C analysis has 29,000 route-miles.

Of more significance than the magnitude of ROR is the wide variation among the 96 segments as summarized by the table inset in Figure 5. Analyses were made to determine the operational or performance factor most influential in establishing ROR. The graph in Figure 5 is a linear regression plot of ROR versus traffic density, the traditional figure of merit used to identify routes suitable for electrification. The numbers scattered about the straight line locate ROR and traffic density for individual route segments. The numbers (0-10) are weighting factors that indicate the relative influence of each point in establishing the regression line. The weighting factor accounts for variation in annual traffic on each route.

Figure 6 is a linear regression plot of ROR versus diesel fuel consumption per route-mile per year. This was the best single variable correlation found, the R-squared value being 0.74 (16). Fuel consumption implicitly includes traffic density but also brings in the effects of dispatching policy and gradient. Thus, a route that is heavily graded with a high horsepower per ton dispatch level will benefit more from the fuel differential and locomotive maintenance savings between diesel and electric motive power at any given traffic density.

## Sensitivity Tests

An accurate forecast of economic growth (or recession), the rate of inflation, or the price and availability of fuel oil, for example, over a 56-

Figure 5. Plot of ROR versus total gross traffic density for links of network base case.

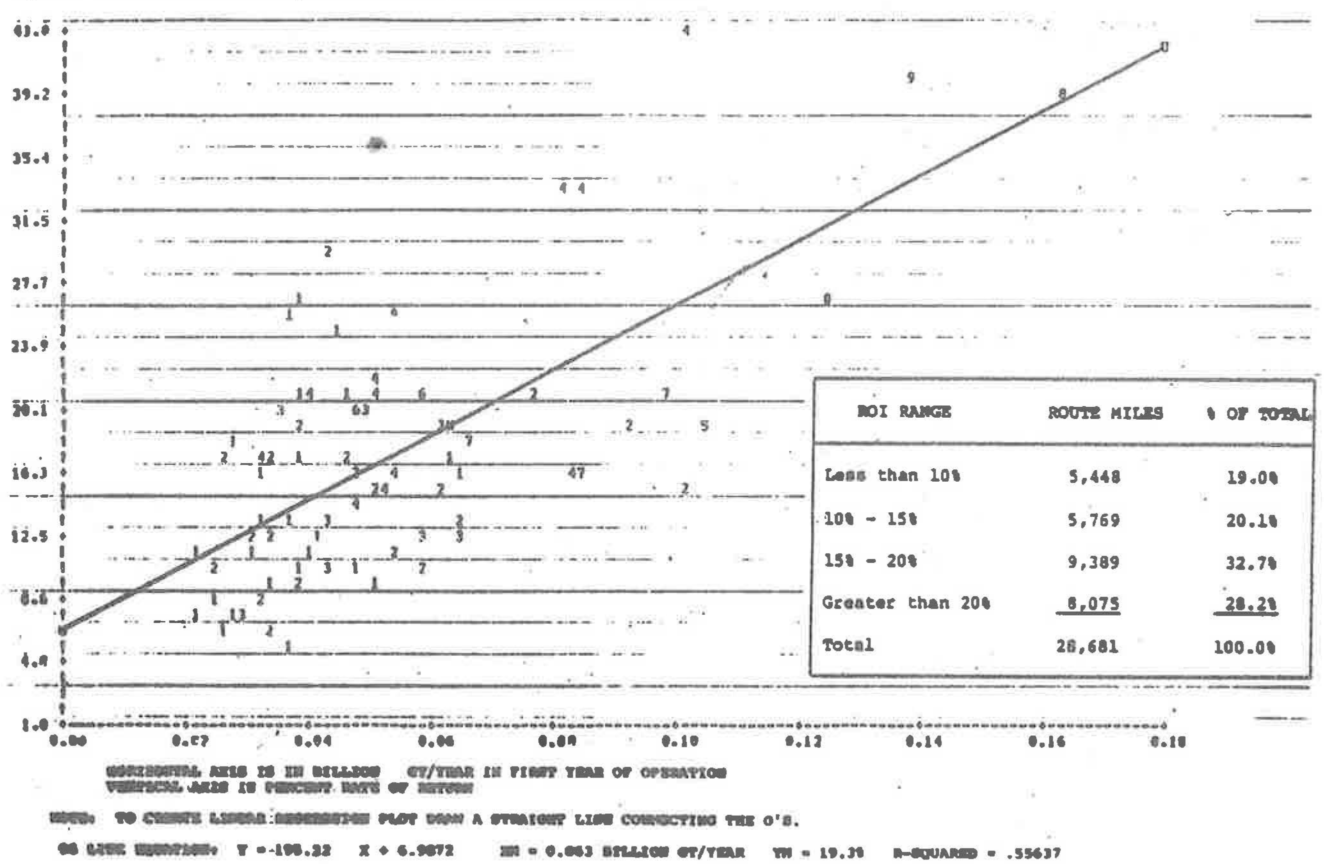
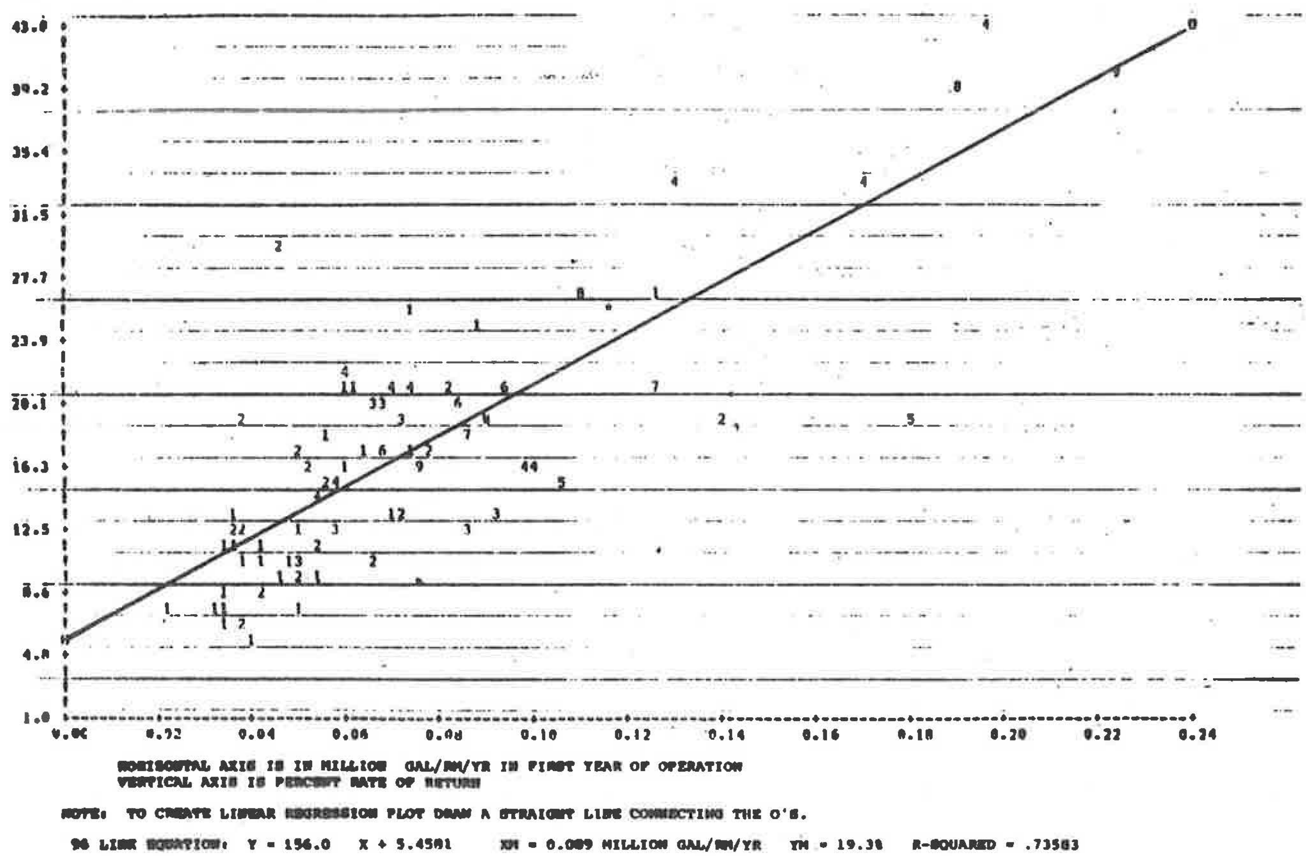


Figure 6. Plot of ROR versus diesel fuel consumed per route-mile for links of network base case.




year future period is virtually impossible. Many of the costs of electrification were, of necessity, theoretical estimates based on experience elsewhere and largely unrelated to U.S. conditions. Major assumptions had to be made regarding the types of electric locomotive to be used, availability, and maintenance cost. A sensitivity study was performed to establish the sensitivity of ROR to prescribed changes in the basic assumptions of the study.

The first variables considered were those concerned with physical performance:

1. Rate of traffic growth,
2. The difference in escalation rates of the cost of diesel fuel and electricity, and
3. Locomotive maintenance costs.

The next variables were related to the cost of the electric locomotives:

1. Capital cost of locomotives,
2. Dispatch level, and
3. Replacement ratio of electric to diesel.

The third group of variables were those related to the cost of fixed installations:

1. Signal and communication compatibility,
2. Civil reconstruction, and
3. Catenary.

Initially each variable was considered independently. Then the variables were grouped to establish their significance in total. In a simplified way this established the main areas of risk associated with the calculations, although no attempt was made to provide a detailed risk analysis.

Figure 7 shows the effect of percentage changes of selected variables on ROR on investment established in the base case. For example, a 10-percent increase in the capital cost of catenary reduces ROR by about 1 percent; a 10 percent negative variation in traffic growth would reduce ROR by a lesser amount, about 0.5 percent.

To establish the relative effect on ROR the expected deviation of each variable from the nominal value must be specified. Figure 8 is a bar chart depicting the results of sensitivity tests based on subjective opinions of the degree of risk associated with each parameter. For each variable a bar indicates the percentage change from the base case return on investment caused by the chosen variation. The size of each bar indicates the degree of significance of the effect of changing a particular variable by the amounts shown at the top of the chart. ROR is relatively stable even with wide changes in the basic assumptions. The largest element of change from any one factor (+4 percent and -5 percent) results from altering the escalation rates of diesel fuel and electric energy relative to general inflation from their base case values of 3 percent and 2 percent, to 4 percent and 0 percent, and to 0 percent and 0 percent, respectively. The effect is of about the same magnitude as the effect of a 5 percent inflation rate shown by the dotted lines. Most of the other sensitivities were below 2 percent; however, the group concerned with physical achievement (traffic growth, fuel cost differential, and difference in locomotive maintenance costs) was seen to be much more important than the other two groups. The total effect of cumulative variations of the parameters of all variables in each group is also depicted. Finally, the extreme range of all favorable-unfavorable variations is shown. This is a highly unlikely situation and is given only to show the robustness of the results.

## SUMMARY

The initial capital investment in the fixed plant and locomotives to electrify 29,000 miles of high-density main line, in constant 1980 dollars, is $18 billion, offset by a credit of $4 billion for diesel locomotives that would otherwise have been required, which leaves a net investment of $14 billion. For the base case analyzed the pretax ROR for the network is 19 percent, a substantial increase over the previously reported FRA results; the estimated annual diesel oil saving is 51 million barrels, 10 percent less than previously reported.

Sufficient study was performed to conclude that the economic advantage of electrification over diesel operation is real and on many routes substantial. Considerable variation of ROR between route segments was found depending on the combinations of critical site-specific factors that exist. The factors found to have major influence on ROR were traffic density, type of diesel locomotive being replaced, type of electric locomotive, dispatch policy, catenary cost, and differential cost of fuel

Figure 7. Generalized sensitivity results.

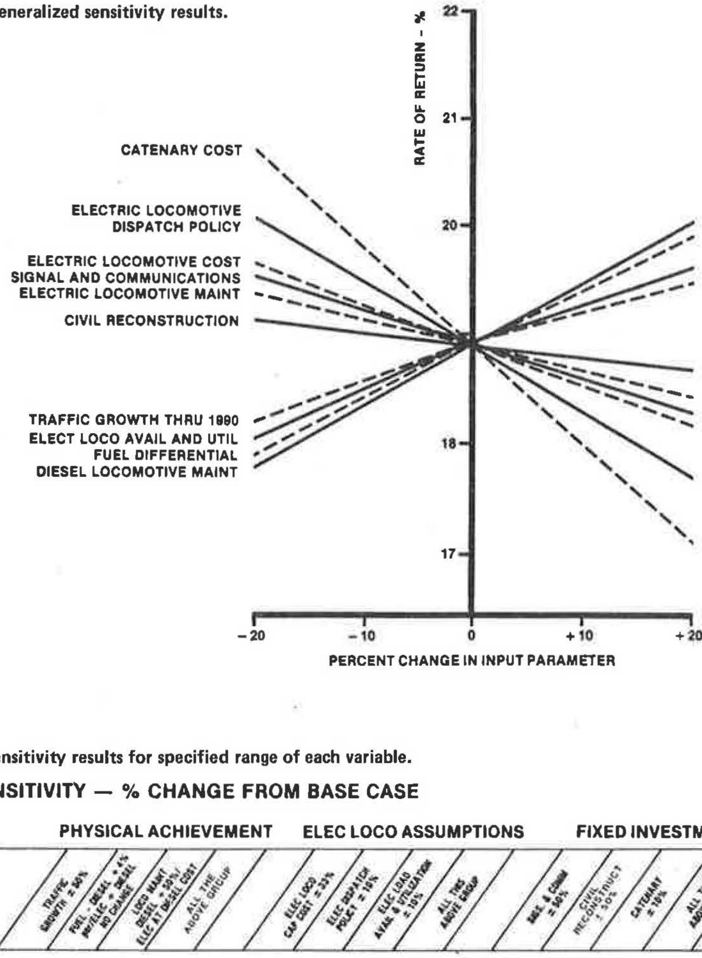
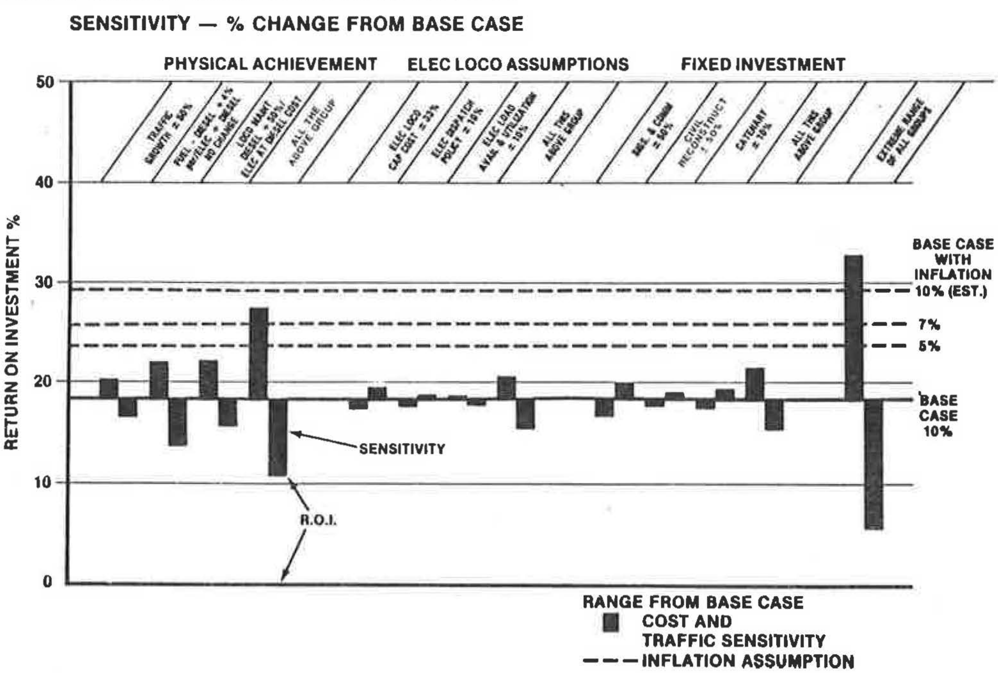



Figure 8. Sensitivity results for specified range of each variable.



compared with electricity. The best single surrogate to these factors was found to be annual fuel consumption per route-mile. However, dependency on variables uncorrelated with fuel consumption (e.g., bridge clearance and signal and communication compatibility) is still sufficient to require computation of ROR.

ACKNOWLEDGMENT

In October 1980, a joint FRA-railroad study was initiated to evaluate large-scale electrification in the United States under the direction of Louis S. Thompson, Associate Administrator of the FRA Office of Intercity Programs. The research presented in this paper is a result of that study. The project manager was G.B. Mott, then with the FRA. The assessment model was developed by C.H. Spenny, of the Transportation Systems Center.

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*Publication of this paper sponsored by Committee on Rail Electrification Systems.*

# Comparative Catenary Costs—European and U.S. Main Line Railroad Electrification

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**Recent comparisons of railroad electrification costs have reported costs of overhead contact systems (catenaries) for overseas electrification much lower than those of U.S. installations. Such direct comparison may not be valid for several reasons—the smaller load gauges, shorter trains, and lower labor costs on overseas railroads. To demonstrate a recent catenary installation on British Rail cost $112,000 per single-track-mile (STM) (1982 prices), but this value would increase to $201,100 per STM at U.S. cost levels on similar complex routes. Also, the U.S. projects compared (e.g., Northeast Corridor Rehabilitation and Pueblo Test Track) are not representative of main line railroads. More representative examples are the 78-mile Black Mesa and Lake Powell Railroad catenary ($180,000 per STM at 1982 prices), and the 370-mile Mexico City-Queretaro Railroad catenary (bid at $165,000 per STM at 1982 prices). An independent estimate was made for a hypothetical 300-mile U.S. main line catenary by using a typical 25-kV design, to be installed in 2 years. The resulting cost ($162,200 per STM) is considered representative for the United States. This cost could double should track access be difficult and work periods short. But, with good planning and improved equipment and experience, catenary costs on large-scale electrification could be reduced to approximately $150,000 per STM at 1982 prices. In conclusion, main line catenary cost in the United States is expected to be higher than that overseas but will reduce with large-scale programs and improved equipment and techniques.**

In an effort to approximate costs of U.S. main line electrification numerous comparisons have been made between costs of electrification in other countries and those experienced so far in the United States or estimated for prospective projects. These comparisons have generally concluded that costs in the United States [particularly costs for overhead contact system (catenary)] are considerably higher than