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COST EFFECTIVENESS OF
RESEARCH AND DEVELOPMENT
RELATED TO RAILROAD ELECTRIFICATION
IN THE UNITED STATES

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16. Abstract The object of this report is to determine the impact of research and development on railroad electrification in the United States. It is presumed that electrification is economically viable and that a prior commitment has been made to electrifying the high density mainlines. Research and development topics are identified from a series of government/industry workshops. Those near-term and mid-term topics found to have major impact include substation and railroad/utility interface improvements to reduce energy costs, improvements in catenary design and construction techniques, improvement in locomotive power density and adhesion, and reduction in electromagnetic interference. Their impact on a postulated network is measured by the savings which could accrue if the research and development accomplishments were implemented when available. Additional non-hardware topics identified for the near term include system engineering, standards, and socio-economic and environmental impact. Far-term topics identified include linear motors and brakes, d-c electrification, and improvements for electrification of lighter density routes. The cost benefits of d-c electrification for the second increment of the postulated network are presented.					
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PREFACE

This report has been prepared by the Electric Power and Propulsion Branch at the Transportation Systems Center (TSC) for the Office of Passenger Systems, Federal Railroad Administration. The purpose of the document is to identify the research and development topics in railroad electrification which would be cost effective to complete and implement. This report is part of the support provided by TSC to the Office of Passenger Systems in electric traction research and development.

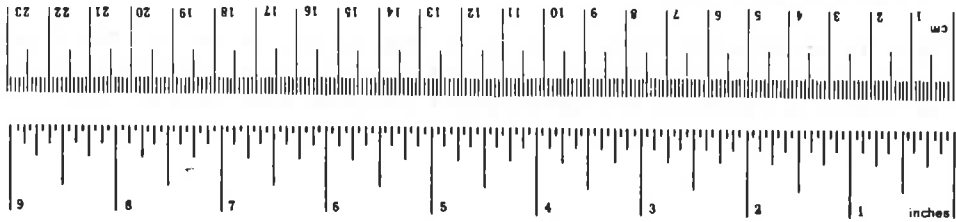
The source of the research and development topics identified by this report was a series of government/industry workshops. Individual contributors at the workshops are identified in Appendix A. The support of Alexander Kusko, Incorporated, is acknowledged in preparing cost estimates for the research topics and for the postulated electrification network. The support of Mr. Matthew Guarino, of the Office of Passenger Systems, in structuring the study, and the typing of the manuscript by Mrs. Ann Scott of FRA are also acknowledged.

This is an interim report. Work is continuing to refine the research and development cost estimates, to identify and price additional topics and to define a research and development program that defines the critical areas requiring government support.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	ac
MASS (weight)				
g	grams	0.036	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	st
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
	liters	1.06	quarts	qt
	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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ABBREVIATIONS AND SYMBOLS

A	Amperes
(A)	availability factor
AAR	Association of American Railroads
ac	alternating current
A&E	Architect and Engineer
AEG	Allgemeine Elektrizitaets-Gesellschaft (Germany)
AEP	American Electric Power
ANSI	American National Standards Institute
AREA	American Railway Engineering Association
ATO	automatic train operation
AT&T	American Telephone and Telegraph
B	Billion
BBC	Brown Boveri & Cie
BICC	British Insulated Calendar Cables
CCITT	International Telephone & Telegraph Consultative Committee
CL&P	Connecticut Light and Power
Conrail	Consolidated Rail Corporation
CTC	central train control
CTS	Cleveland Transit System
dc	direct current

ABBREVIATIONS AND SYMBOLS
(Continued)

dI/dt	rate of change of current
EI	Edison Electric Institute
EMI	Electromagnetic Interference
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FAA	Federal Aviation Administration
FCC	Federal Communications Commissions
FPC	Federal Power Commission
FRA/OR&D	Federal Railroad Administration/Office of Research and Development
FSK	Frequency Shift Key (modulation)
GE	General Electric
GM/EMD	General Motors/Electro Motive Division
GTM	Gross Ton Miles
hp	Horsepower
HVDC	High Voltage Direct Current
Hz	cycles/second
ICC	Interstate Commerce Commission
IEEE	Institute of Electrical & Electronics Engineers
kv	kilovolt (10^3 volts)
kVA	kilovolt amperes
kvar	kilovolt amperes reactive
kw	kilowatt
kwh	kilowatt hour
LIM	Linear Induction Motor

ABBREVIATIONS AND SYMBOLS
(Continued)

M	million
mi	mile
mi/h	miles per hour
m/y	miles per year
M/A	motor/alternator
M-G	motor generator
MTBF	mean time between failure
MTTR	mean time to repair
MU	multiple-unit
NEC	Northeast Corridor
NEMA	National Electrical Manufacturers Association
NRECA	National Rural Electrification Corporation Association
NFPA	National Fire Protection Association
NYMTA	New York Metropolitan Transit Authority
OSHA	Office of Safety and Health Administration
PC	printed circuit
PCB	polychlorinated biphenyl
PCM	Pulse Code Modulation
PCU	power conditioning unit
PF	Power Factor
R&D	Research and Development
REA	Rural Electrification Administration
RFI	Radio Frequency Interference
rms	root mean square
RR	Railroad
R/W	right-of-way
(S)	Seasonal Peak Load Factor
sec	second
SEC	Securities Exchange Commission
SNCF	French National Railways

ABBREVIATIONS AND SYMBOLS
(Continued)

SOAC	State of the Art Car
S.P.	Southern Pacific Railroad
TGT	Trailing Gross Tonnage
TIF	Telephone Interference
(U)	Regional Unbalance Factor
U.P.	Union Pacific Railroad
V	Volt
VV/VF	variable voltage/variable frequency
WABCO	Westinghouse Air Brake Company
Y	year
μ s	microsecond
ϕ	locomotive weight factor

EXECUTIVE SUMMARY

Electrification of U.S. railroads could begin immediately by adapting existing technology from foreign rail systems and from past electrification experience in the U.S. However, the long term implications of this decision deserve further consideration, particularly if a commitment is to be made to large scale electrification in the U.S. This report documents a TSC study which identifies and evaluates the cost effectiveness of selected research and development (R&D) in railroad electrification. It is presumed in the study that a commitment will be made to electrification of high density routes and that an R&D program will accompany this commitment to assure development of a modern and efficient system.

The source of R&D topics was a series of industry/government workshops conducted early in the study. In order to provide a quantitative measure of the impact of individual R&D topics, a scenario was established for implementing an electrified network in the U.S. Costs were estimated with and without implementation of the proposed R&D topics to determine their cost effectiveness.

The study concludes that the successful completion of selected R&D can result in reductions in costs, both capital and operating, and that the savings are sufficient to justify the R&D. However, no technological breakthroughs are forecast which would render an electrification system that used present technology obsolete. Those topics found to have major impact include substation and railroad/utility interface improvements to reduce energy costs, improvements in catenary design and construction techniques, improvement in locomotive power density and adhesion, and reduction in electromagnetic interference. The magnitude of the benefits depends on the cost and size of the network and the installation rate as well as the degree of success in completing the individual R&D efforts.

It is recommended that the R&D topics and the related cost estimates of this report be periodically reviewed and updated, recognizing that this is a time of rapid development in electrification technology and this can significantly influence R&D emphasis.

1. INTRODUCTION AND BACKGROUND

The 1974 DOT-Industry Task Force on Electrification (1)* concluded that railroad electrification is the only available alternative to diesel-electric operation and that it offers the only feasible means to utilize 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 with the present state of railroad finances. This is contrasted to the enormous savings to be gained at the turn of the century in converting from steam to electric motive power and the even greater savings in the forties in converting from steam to diesel-electric motive power (2).

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

Specific conditions make electrification more attractive. For example, the availability of low cost hydroelectric power, the short term-high power demands of mountainous routes and of schedules with frequent acceleration requirements, and the requirement to eliminate emissions in tunnels and urban areas are characteristics which were influential in making the decision to electrify specific routes in the U. S. 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 nonavailability to the railroads of the United States. Their consumption is a small percentage of the total oil consumption and could always be accommodated. Rather, the agitating effect is the uncertainty in the cost

* Numbers in parentheses refer to references listed in Section 7.

of fuel which crimps the capability of the railroads to develop long range growth plans. The upper limit on diesel locomotive power density appears to have been reached, analagous to that of the steam locomotive. Railroads now use up to 12 unit consists for the very long trains. Attempts to increase engine horsepower have resulted in losses in reliability, and in increased maintenance. 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 (3) 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 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 guarantee obligations for the purpose of electrifying high density mainline freight routes. Other railroads have informally notified the FRA of their desire to apply for electrification funding under other provisions of the Act.

A sector of the Conrail track which has been given consideration for electrification is the route from Pittsburgh to Harrisburg, which has the highest traffic density in the U.S. Because the Conrail route from Harrisburg east to the Northeast Corridor (Amtrak) is presently electrified, the new wiring represents an extension of electrification. Upgrading the Northeast Corridor will force Conrail to decide between upgrading the present electrification equipment, or 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.

To determine if there are other routes which are better served by electric traction, site specific studies are required. 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, 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 design parameters on the result. Such items as traffic forecasts, fleet size, energy costs, and civil reconstruction to provide clearance can have a major effect on the investment decision.

1.1 NEED FOR R&D IN RAILROAD ELECTRIFICATION

Electrification of U. S. railroads could begin immediately by adapting existing technology from the European, Russian, and Japanese rail systems. Implicit in this statement is the assumption 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 restrain electrification until a major evaluation of technology requirements is completed. No technological breakthroughs are on the horizon which would render an electrification system which used present technology obsolete. If feasibility studies determine that electrification of a sector is justified with present technology, it should be implemented and then modified as technology evolves to achieve maximum return on investment.

This report presumes that the U.S. will make a commitment to electrification of its high density route system and that a comprehensive R&D program will be structured to accompany this commitment. Major R&D topics are identified by this report which must be addressed to assure the development of a system which satisfies the requirements of the railroads, the users, and the overall objectives of the nation.

1.2 CLASSIFICATION OF ELECTRIFICATION R&D

R&D is divided into topical areas in three time frames, near-term, mid-term, and far-term. Near-term and mid-term R&D consist primarily of technology development and assessment, and impact studies performed to define, evaluate, and improve equipment that could be used in current and planned electrification programs in the U.S. Near-term R&D can be implemented in five years; mid-term R&D would require ten. Far-term R&D consists of the assessment of new concepts and the establishment of policy directives to provide a smooth transition where technology might otherwise dictate major changes in capital equipment for the existing network and/or its extension. The near mid-and far-term topics are described in detail in Sections 2 and 3.*

* The primary source of R&D topics discussed in this report are the three industry/government workshops held on electrification. These workshops and the resulting R&D topics are summarized in Appendices A and B, respectively.

The purpose of classifying R&D initially by topical areas, rather than hardware, is to establish the qualitative gains that can be expected. In order to quantify the benefits, it was necessary to postulate an electrification model. Appendix C describes a two-part network model in which an 8,500 route mile increment is electrified in the 10-year period from 1980 to 1990 and 10,000 route miles are electrified between 1990 and 2000. The near-term and mid-term R&D benefits are measured by the savings accrued relative to diesel operation for electrification capital investment and operating costs in the first increment. Far-term R&D benefits are measured by the savings accrued relative to operation with first generation electrification in the second increment. These savings are described in Chapter 4. Savings have not been estimated for near-term R&D topics related to systems engineering, standards, and socioeconomic and environmental impact.

The magnitude of the savings is highly dependent on the magnitude of the electrification program. It should be emphasized that the program defined herein is assumed only for the purposes of this report and is not a predicted or proposed electrification program for the U.S. If the amount of electrification or the implementation rate differs, the R&D gains will change accordingly. However, the gains of the individual R&D topics can be expected to retain their relative importance.

In Section 5, the goals of electrification R&D are established and a sampling of studies and projects is tabulated to show their relationship to the major R&D areas defined in the previous sections.

2. MAJOR NEAR-TERM AND MID-TERM R&D AREAS

Historically, electrification has been considered primarily for the investment gain. Studies indicate that implementation on routes with high traffic density offers an attractive return on investment. It is presumed in this report that adequate feasibility studies have been completed to make a commitment to electrify such routes based upon existing technology.

Conversion requires a significant capital investment which must be recovered through savings in operating costs and improvements in service. Because electrification impacts the heart of the railroads, the risk of failure must be virtually eliminated. The near-term and mid-term R&D topics of this section are directed toward reduction of the risk and offer increased return on investment.

The R&D consists of system studies, and development and test of prototype equipment. Some of the near-term R&D can and must be accomplished prior to commitment to electrification of a mainline. Other R&D must of necessity accompany electrification of the first mainline sectors.

2.1 SYSTEMS ANALYSIS AND ENGINEERING

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

- 1) Review and adaption to the United States application of foreign technology.

Because railroad electrification has progressed so far in Asia, Europe, and Japan, as compared to the United States, studies must be carried out on foreign technology to determine its applicability to railroad operations of the United States. At the analysis level, this should include delineation of the similarities and differences of equipment, construction, and operation and assessment of alternatives including the adaptation of foreign technology to meet present United States railroad operational requirements, and adaptation of U.S. operational requirements to make use of foreign technology as is. At the equipment level this can include test and evaluation of foreign locomotives and fixed plant equipment on United States properties and

test facilities and evaluation of locomotives designed to United States requirements on foreign properties.

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 of service speed and reliability in conversion to electric operation. Operational changes to optimize the benefits of electrification should be evaluated. Complications such as the management and maintenance of a dual fleet (presuming partial electrification of any one railroad), the limitation of the electric fleet to mainlines which are wired, the extra change requirements, and the reduced diesel utilization should be evaluated. Reliability of the two alternatives as it effects service to the shipper should be quantified including the above factors as well as railroad and utility equipment reliability.

More detailed computer models must be formulated for electrified railroad operation to answer such questions as schedules, size of trains to be operated, numbers of locomotives required, designs of yards, and other factors necessary to proceed with an extensive electrification program.

Transportation models have been used for studying operation of trucks, personal vehicles, and rapid transit car systems. Similar computer models should be prepared before actual designs are carried out for electrification.

3) Interfacing between Railroads and Electric Utilities

The supply of thousands of miles of electrified railroads from adjacent electric utilities raises many problems which require study and resolution at an early stage. These problems include whether or not to build dedicated transmission lines paralleling railroad, whether to reinforce weak utility systems or employ artificial phase balancing methods, and how to handle phase breaks between adjacent utility companies. Who will retain ownership of capital equipment must be established. Rate structure must be developed, accordingly, to reflect the capital investment required by the utility to meet the energy and demand requirements.

2.2 STANDARDS

Standards must be prepared for electrification facilities to insure that they are safe, compatible with other services, and utilize reasonably uniform equipment. It is recommended that a standards committee be established and begin immediately with the task of establishing recommended practices based on best available knowledge. The committee shall be responsible for evolving the recommended practices into a set of standards as use and review establishes their validity. A start must be made in the preparation of standards long before designs for equipment are frozen for major production as time is required for standards to be reviewed by public agencies and by industry groups before their acceptance. Areas for standards are the following:

1) Telecommunications 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 FRA's Transportation Test Center, and at already operating electrified facilities. Until these standards are written and approved, designers of electric locomotives and wayside facilities cannot guarantee 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 the maximum voltage unbalance at the supply bus. Standards for negative sequence current have already been set by the IEEE, but standards are still required for voltage unbalance. The maximum voltage unbalance is generally limited by the overheating of induction motors operating from the unbalanced voltage source. In addition to the preparation of standards, extensive testing is required to insure that the standards are not overly conservative.

3) Current harmonics at the locomotive.

Locomotives employing phase-controlled rectifiers will produce harmonics in the catenaries and result in potential telecommunications interference. The harmonics can be controlled within the locomotive by filters, and by other design measures, which generally add to the cost of the locomotive. Standards are required for the percent harmonic current at the locomotive as a guide to the locomotive manufacturer and as an insurance to all railroads buying such locomotives that the potential interference is at a controlled level. Extensive testing will be

required of sample locomotives under controlled facilities and in in-service electrified systems to insure that reasonable standards have been set.

4) Current harmonics at the electric-utility interface.

Maximum allowable harmonics have been set at utility interfaces in European countries, but not in the United States. Standards must be set that are peculiar to railroad service, as compared to normal industrial rectifier service. These standards must be confirmed by calculations and tests to insure that they are reasonable. Current harmonics in a utility can produce resonances within ac capacitor banks and high voltage cables, resulting in possible failure.

5) Catenary nominal voltage levels.

At the present time ac voltages of 25 kV and 50 kV are being considered as standards. These levels should be formalized in a standard. DC levels, such as 3 kV, 6 kV, and higher voltages, should also be established. Setting standards early in the electrification program will avoid selection of inappropriate voltages, assure interchangeability of equipment between railroads and provide cost savings of scale based on higher production levels.

These voltage levels should be researched to insure that they are reasonable and are adequate to handle future growth in United States electrification.

6) Substation and catenary voltage limits.

To insure the compatibility of electric locomotives and multiple unit cars with operation on any electrified railroads in the United States, standards must be set for the maximum and minimum limits of voltages that such rolling stock will encounter from catenary operation. Manufacturers of electric locomotives and multiple unit cars presently set such limits for 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 which provide insulation, and for electrical equipment installed within rolling stock. These clearance standards are fundamental to the development of the whole electric railroad industry. Standards must be set which will 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 at all other points where they may be exposed to high voltage. These standards must also include grounding methods, fault detection and 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, OSHA, NFPA, IEEE, and other organizations who work in the safety field.

9) Reliability of subsystem and system equipment.

Standards are required for specifying, testing, and applying reliability parameters, such as MTBF, and MTTR, for electrification equipment. In addition, preliminary standards should be generated for electric locomotives, and for 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 reliability parameters with railroad service demands and to obtain reliability numbers for use in the standards.

10) Test methods.

As in the industrial electrical engineering field, standard test methods must be developed for all types of electric railroad subsystem and system equipment, to insure a uniformity from manufacturer to manufacturer in quoting and delivering equipment to railroad customers. Development of such standards for testing is a massive effort which will require the cooperation of industry and railroad representatives over a several year period. In some cases, ANSI and NEMA test methods can be adapted to railroad purposes. However, testing will be required by committee members, as well as neutral agencies, to confirm the validity of proposed standard test methods.

11) Methods for energy measurement.

Energy measurement 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 employed as a basis for measuring the energy for which the railroad pays. In cases where energy charges are based upon metering at multiple points, 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 as railroad service prevail.

2.3 SOCIOECONOMIC AND ENVIRONMENTAL IMPACT

The impact of railroad electrification on the social, economic, and environmental conditions along the routes, and in the nation generally must be studied early in the electrification program. By so doing, decisions regarding equipment design, standards, manpower requirements and industrial facilities, will be structured to bring the maximum benefit to the country for the investment in electrification. Topics to be studied include the following:

1) Impact of electrification on the environment.

Electrification will transfer the source of propulsion energy from the diesel oil on the locomotive to the coal, oil, and nuclear fuel in power plants located in the supply utilities. The first impact will be a reduction in pollution and noise along the railroad routes. The second impact will be a reduction in the dependence on oil for operating railroad locomotives. Studies should be made of the reduction in social costs brought about by electrification, and the increased value of the land along railroad rights-of-way as a result of reduced pollution and noise.

2) Economic growth along electrified corridors.

Electrification of existing railroad routes and improvement of passenger service will most likely create growth of industrial and residential communities along the routes. Studies made in advance of electrification will help in determining the locations for passenger stations, for freight facilities, and for railroad yards, so as to best serve the types of industries that will benefit from the improved transportation and passenger travel flexibility. These studies should include the development of transportation models for the electrified routes, and econometric models for the interrelated industries that will develop along those routes. The impact of market capture from other transportation modes should be evaluated.

3) Shifts in railroad equipment industry product mix.

Electrification will require the existence of a large production shift to provide electric locomotives, catenary equipment, communications and control systems, and other products to serve a new industry for the United States. Plants presently manufacturing diesel electric locomotives will be required to shift design and production for the new market. Studies must be made for the market growth, adequate time for development of new products, availability of subcontractors to supply the main contractors building final equipment and electrifying the routes. New industries, or new divisions of existing companies, may have to be formed to meet the requirements of the market.

4) Electric utility long-range planning for system expansion.

Electric utilities plan their expansion programs for generating plants and transmission lines on a 10 and 20 year-ahead basis. Utilities must include in these plans the power and energy requirements for electrification along routes in their territories. Studies must be made by the utilities well in advance on reinforcement of their transmission systems to supply the load requirement of an electrified railroad and any associated industrial growth and to insure that adequate generating capacity will be available at the suitable dates.

5) Retraining of railroad industry employees.

Electrification will require that railroads train their personnel to carry out the functions of locomotive operation, repair of the electric power equipment, repair of electronic control and communications equipment, maintenance of catenary and other tasks of an electric railroad. Studies must be made of personnel availability, requirements for training programs, numbers of personnel for electrified railroad operation, and other employee-related items.

6) Public-agency regulations for railroads.

Regulations must be adapted to large scale electrified railroad operations. These regulations include operating safety, electrical safety, electrical interference, and various other design, inspection, and operating regulations. Such proposed regulations must be prepared well in advance, allowing time for hearings, railroad acceptance, and changes to electric equipment before it is introduced into mass manufacturing and use.

7) Public-agency regulations for utilities serving railroad load.

State public utility commissions, or the Federal Power Commission, must study the bases for rate structures particularly suited to electrified railroads, which are served at multiple points along their routes. Studies should be made to establish equitable rate structures, that do not change from company to company, or state to state, along the electrified route. The public agency regulation should also include requirements on the railroads for the character of the loads that they impose on the utilities.

2.4 SUBSTATION AND RAILROAD/UTILITY INTERFACE IMPROVEMENT

The nature of the railroad electric load is unique and will require connection to the electric utility at a power 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 passed on to the railroad either as connection or reinforcement costs rolled into the rate structure. It is recommended that R&D be initiated to reduce the impact of utility capital cost on the energy costs of the railroads as follows:

1) Peak Demand Reduction.

During the past several years, industrial users and commercial users of electricity have been able to make reductions in peak demand and in total energy used by application of digital computing equipment to control the time and amount of power usage. It seems probable that similar techniques applied to an electrified railroad might reduce peak demands either at individual substations or the peak demands on a single utility by all substations connected to that utility. There may be substantial reductions if the responsibility of the power dispatcher is increased. Better control of fleet, both real time limiting of power demand and fleet management can result in better load factor and reduced demand charges if improved computer and CTC techniques are developed.

2) Phase Balance Improvement.

Traction power on the catenary is a single-phase electric load. Traditional electrification practice in the United States has been to operate the railroad load from 3-phase to 1-phase frequency converters such that the railroad load, when reflected back into the electric utility, represented a balanced load. However, this conversion equipment represents a significant cost penalty to electrification, and 3-phase to 1-phase converters should be used only where the utility grid cannot accept direct connection of the single-phase load.

Operation of the railroad load directly from the commercial frequency system has been extensively used for the past quarter century in such countries as the United Kingdom, France, Japan, and Russia.

Operation of the railroad 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, the following conditions must be considered: the unbalance current flowing through the system alternator stators causes rotor heating; unbalanced currents cause unbalanced voltages in transmission voltages resulting in similar heating of motors on the line. These impacts generally require the power system to have power available significantly in excess of the railroad power requirements.

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 unbalance currents safely.

Various circuits using static inductors, capacitors and transformers can connect a single-phase load to a three-phase source in such a way that the three-phase load to a three-phase source sees a balanced load. For single frequency conversion, this has generally been done at low power levels. There have been a limited number of solid state converters built which operate from three-phase power and deliver three-phase power at the same nominal frequency. However, no examples of three-phase to one-phase converters operating at one frequency exist, at the application stage. If it can be verified that these types of equipment will be economically attractive, and will meet the conditions of variable loading and variable power factor, it may be practical to have three-phase/single-phase conversion without rotary equipment or active components.

3) Reactive Power Reduction.

The propulsion circuits of locomotives operating from a 60 Hz 25-kV or 50-kV 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 conditioners produce complex current wave forms having many harmonics. The lagging reactive current produces voltage drops in the catenary which limit distances between feeders. The harmonic currents flowing in the catenary can produce interference in

communication and signaling circuits near the railroad. The ampacity of the catenary must be adequate for the rms total current, i.e., the rms sum of the fundamental active current, fundamental reactive current and all of the harmonic currents.

Capacitors and/or filters on the locomotives can reduce interference, reduce lagging reactive currents, and reduce harmonic currents. This may permit greater spacing between feeders for the catenary, and may permit smaller conductors in the catenary. However, the amount of correction which can be accomplished with capacitor control is limited.

It is common practice for utilities in the United States to use capacitors to correct power factor on transmission and distribution lines. The leading reactive current needed to correct power factor varies with the load. 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. R&D is 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 for conserving energy and assisting in braking. Although technically feasible, regeneration entails many problems that have prevented its widespread use. 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 that regenerated energy to the utility will be credited against the railroads energy consumption. The problems of relaying, safety, voltage swing, and waveform must be addressed as well as development of catenary phase breaks, feeders, and substation equipment to handle regeneration to other locomotives and back to the utility.

2.5 CATENARY IMPROVEMENTS

2.5.1 Automated Catenary Installation

The amount of catenary installed in the United States in the last forty years has not been sufficient to preserve and update the installation techniques and skills developed in the first quarter of the century. Further, the procedures used in recent projects have not been concerned with track blockage because installation was not over mainline tracks where interference with revenue operation is critical.

Choice of installation procedure, like most engineering decisions, must ultimately be based upon schedule and cost considerations. Some reduction in cost of hardware and labor can be expected as electrification experience accrues, regardless of the choice of installation procedure, and no R&D is required to achieve this gain. However, significant savings can be achieved if labor costs, which represent more than 50% of the catenary capital investment, can be reduced by using automated equipment that is track mounted. This will permit significant reduction in installation time.

Although catenary installation can be performed in a variety of ways, four basic tasks can be defined:

- 1) Drilling holes, driving casements or piles, or pouring foundations.
- 2) Pole setting.
- 3) Wire stringing.
- 4) Final adjustment.

Recent procedures developed in Russia have emphasized the use of work trains for each of these tasks. This philosophy reflects commitment to large scale electrification where maximum use is made of the track for transporting materials and personnel and for ease of placement of work machinery (all work being within 10 feet of the rail)(4).

Elsewhere, installation procedures reflect a less intensive electrification commitment; there is generally less mechanization, the tasks are subdivided and completed in steps, and much of the work is completed with off-track equipment in an attempt to minimize track blockage. It is anticipated that in the absence of government sponsored development, such a procedure, as typified by the Edison Electric Institute (EEI) recommendations (5) for electrification of the Penn Central from New York to Cleveland, would develop in the United States, since less capital investment is required and risk to the railroad's revenue operation is minimized. The purpose of this R&D is to determine the degree of automation that would be the most cost effective for large scale catenary installation in the United States, and to develop the necessary equipment to demonstrate the capability.

Installation of foundations, whatever they may be, and pole setting, tasks 1 and 2 in the above list, are particularly labor intensive tasks where mechanization can significantly reduce cost. When this work is performed from a work train with augers, backhoes, and mechanized pole setting equipment, the installation rate can be increased. As an example, Russian equipment, in good soil conditions, accomplishes tasks 1 and 2 with a single train pass and achieves installation rates as high as 8 poles per hour. This approach is reasonable when "work windows" of 2-to-3 hours are available. When soil conditions are poor, blasting and pile and casement driving operations and pouring of concrete for gravity foundations drop the installation rate significantly. It is then more reasonable to separate the drilling and pole setting tasks and/or perform the work with road/rail vehicles which create less track blockage or with off-track

equipment only. The British approach (6) is a 3-step operation using gravity foundation: (1) road/rail vehicles are used to drill, dig and drive piles; (2) a work train with multiple, drum concrete mixers pours foundations; and (3) a work train then sets and grouts the poles and caps the grouting, all in one pass. The use of several drum mixers rather than one large machine has improved reliability. The use of polystyrene for core holes has speeded the pole setting operation. A shrink-proof grout was developed to permit pole setting to be completed in one pass.

The EEI study concluded that a side bearing foundation (tubular piles) would be most economical wherever drilling was possible. Gravity foundations were recommended for rocky locales. Foundation work, including pouring, was to be done by road/rail equipment, a work train would be used to set poles, and a plumbing and grouting crew would follow using road/rail equipment to complete the pole setting.

Support arms and insulators can be mounted prior to setting the poles (as was done on the Muskingham RR) or after setting the poles using a train (Russia), road/rail vehicles (EEI recommendation) or from trackside (Lackawanna RR). When installed prior to pole setting, error in alignment of the messenger is greater, necessitating more adjustment later.

Messenger and contact wires are generally strung from trains, although British requirements have necessitated the development of trackside stringing techniques for areas where traffic is heavy. The Russian procedure (4) is to drop the messenger to the ground from a train, to attach droppers and jumpers in preparation for attachment of the contact wire and lift and to attach the messenger with a mounting train. An alignment crew then makes adjustments from a road/rail vehicle so that the contact wire could then be installed by a crew of four operating from a small rail car. Variations to this approach are:

- 1) On the Muskingham RR temporary hangers were used to attach the contact wire to the messenger, followed by an adjusting crew which installed the permanent hangers.
- 2) The EEI recommended installation of permanent hangers after the messenger was installed using a road/rail vehicle.
- 3) On the Lackawanna RR (7) electrification, the auxiliary and two contact wires were installed simultaneously with temporary hangers, followed by a crew which attached permanent clips and tensioned during shorter "work windows."

The use of a train for large scale stringing appears necessary even though track occupation requires long "work windows" because the wire must be strung in 1-to-2 mile lengths. Mechanization to increase stringing rates and to limit the stringing to one pass by simultaneous installation of the messenger, auxiliary, and contact wire are desirable.

Final adjustment can be made by a small crew operating from a road/rail vehicle. This is a labor intensive task for which little mechanization is possible. Experience in design and installation will reveal the improvements which can be made here.

2.5.2 Economical Catenary Design

The railroad electrification anticipated in the United States appears to be developing on two areas: 1) high-speed passenger service and 2) high-density mainline freight service. In the absence of recent electrification projects in this country, one looks to the wealth of experience accrued in Europe in electrified passenger and manifest freight service. This experience offers proven catenary designs that are particularly appropriate for upgrading the high-speed passenger service in the United States and for initiating electrified freight service in the United States. The minimal risk makes the use of this "conventional" equipment desirable on the initial electrification projects. However, the bulk of U.S. electrification will be freight service where 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 reduced expense. Potential savings can be achieved by 1) simplifying the design of components, 2) reducing material quantities, 3) reducing number of components, and 4) using alternative materials. Some of these changes will evolve naturally as electrification proceeds and can be integrated into the catenary design without undue risk. The purpose of the R&D described herein is to expose and evaluate unproven catenary designs which could provide significant reductions in equipment and labor costs but which must be refined to reduce the risk in revenue application.

The European catenary which appears to be most popular is the two-wire design, which is generally referred to as a simple catenary, and consists of contact wire suspended by droppers from a messenger wire. With varying degrees of sophistication such as stitching, sagging, and constant tension, the two-wire design can be used for any speed up to 180 miles/hr, although for high-speed applications, 3-wire (compound) designs are often used. The emphasis of recent catenary developments has been on raising the speed capability, with little effort directed toward improving the characteristics of low speed designs and reducing their cost.

Single-wire designs, often referred to as trolley wires based upon their application, offer the potential for significant reduction in the quantity of wire, hangers and poles, in installation costs, and for increases in installation rates. The maximum attainable speed using trolley wire is less than that of the two-wire system. With single-wire, British studies optimistically predict that speeds up to 150 miles per hour can be achieved. The limiting speed in revenue operation is governed by how much arcing can be accepted and how much wire wear can be tolerated due to pantograph inertia creating large contact forces in certain portions

of each span. Methods for improving single-wire performance need to be evaluated under controlled tests in order to develop a design which is suitable for revenue operation. Specific parameter variations which would reduce arcing and trolley wire wear need to be evaluated:

- 1) Reduction of sag by reducing span length.
- 2) Increasing wire tension.
- 3) Suspension of wire from springs and dampers.
- 4) Adjusting wire weight to offset zero slope change in wire as pantographs pass supports.
- 5) Pantograph improvements.

2.6 LOCOMOTIVE AND MULTIPLE UNIT MOTIVE POWER

2.6.1 Improved Adhesion

The wheels of a locomotive reach their adhesion limit on the rails and start to slip under two conditions: when the locomotive is exerting maximum tractive effort at speeds below the horsepower limit; and when the locomotive is braking at any speed at rates that exceed the horsepower-limited tractive effort. The adhesion limit is lowered by wet or icy rails, and by increased speed.

Most wheel-slip control systems are additions to the locomotives propulsion plant, which already has been designed. These systems are used on diesel-electric locomotives, electric locomotives, and on rapid transit cars. The wheel-slip control systems operate by monitoring changes in the speed of individual wheels compared to the average speed, sudden drops in traction motor current, or acceleration of individual wheels. The monitors initiate a reduction of current to one or more wheels. The current or braking effort is then restored in some prescribed way, either by ramping up, or by steps, to the level of sustained adhesion.

Manufacturers have described systems (9) (10) for phase-controlled-thyristor dc-traction motor locomotives that utilize well designed control loops for the slip control. However, once the wheel starts to slip, the control system has no a priori knowledge of how much power to remove from the wheel to restore adhesion. Sensors, such as toothed-wheel tachometers, are vulnerable to damage and clogging. The performance of the control system depends upon the sensitivity and accuracy of the sensors. Even the theory of adhesion is not well understood.

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 for reduction of reactive-power load. However, Brown Boveri has described an experimental electric locomotive (11) which employs individual adjustable frequency inverters and induction motors for propulsion. Wheel slip is monitored from the inverter frequencies, without use of wheel tachometers; power is reduced at selected slipping wheels by reducing the frequency of the appropriate inverters, in order to control wheel slip.

The average presently attainable adhesion is 25%, or a traction force equal to 0.25 x the axle weight. For a typical locomotive axle weight of 25 tons, the tractive force will be 12,500 lb/axle. For 1% rolling friction, the axle can pull on the level grade 12.5, 100-ton freight cars, corresponding to 1,000 hp at 30 mi/h. The objective of R&D in this area should be to raise the average adhesion limit by at least 25%. Below the horsepower limit, at low speed, the locomotive will be able to pull 25% more cars up a grade, and brake the cars down the grade.

The areas of R&D that must be addressed are:

- 1) Theory. Advancement of the theory of adhesion by analytical and experimental techniques for the conditions corresponding to railroad operation. Study of the theory of "micro" slip adhesion. Development of parameters for use in control-system design.
- 2) Sensors. Development of rugged, sensitive sensors for use on motor and wheel shafts. Development of the circuits for use with the sensors to obtain signals proportional to relative wheel velocities and accelerations.
- 3) Control Systems. Design of propulsion control systems with the raising of the adhesion limit as the primary objective.

Primary output of R&D in this area is the development of techniques and equipment for use on locomotives to raise the tractive effort and braking effort under all conditions. The consequence will be greater productivity by each locomotive because of increased acceleration, deceleration, and drag power on grades. The results should be applicable to both dc and ac traction motor locomotives.

2.6.2 Power Density Improvement

The productivity of a locomotive is limited by the maximum tractive force that it can exert at low speeds, and by the horsepower that the propulsion plant can deliver at high speeds. A fixed amount of horsepower 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.

Experimental/prototype locomotives using solid-state inverters and ac traction motors have been built by Brown Boveri, ASEA, and others. These have received their prime power from an on-board diesel generator or an ac catenary. WABCO built an inverter propulsion system for Cleveland rapid transit cars, operating from the wayside 600 V dc system (12). The inverter-ac motor drive field has undergone industrial development by the major electric-drive companies: General Electric, Westinghouse, Reliance, Borg Warner, etc., with drives of various types up to 18,000 hp. Garrett built a 6-MVA rectifier-inverter and LIM propulsion

system operating directly at 8.25-kV 3-phase power rail voltage for the DOT 300 mi/h air-cushion vehicle. Allis-Chalmers built a prototype solid-state synchronous-motor 1,500-hp drive system for off-highway vehicles (13). Considerable work has been done by the FAA and others on high-reliability inverters for uninterruptable power systems (14).

AC squirrel-cage traction motors up to 1,500 hp can be built for axle or truck mounting. AC synchronous motors can be built with stationary field windings in the Lundell construction, which is not particularly efficient in use of materials, or in the brushless-exciter form. The motor can also be built as a two-stage motor in a single frame, as developed at Massachusetts Institute of Technology and elsewhere, for operation at synchronous speed corresponding to the inverter frequency. 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. Both axle and truck-mounted motors are used in Europe and the United States.

Research and development is required in this area on other advanced types of propulsion systems including such candidate systems as inverter driven synchronous traction motors and inverter driven asynchronous traction motors.

Areas where R&D must be considered are:

- 1) Converter Development. Development of candidate converters from the input terminals at catenary voltage to the terminals of the ac motors.
- 2) Propulsion Controls. Development of control circuits and equipment which will accept as input signals the cab and automatic train controls, and will deliver as output signals the information to operate the converter.
- 3) Traction Motors. Development of asynchronous and synchronous traction motors to meet the power, life and voltage requirements of the locomotive and to accept the power delivered by the converters.

Some of the primary outputs of R&D in this area will be: increased horsepower and increased productivity of the locomotive without increasing its weight; improved truck dynamics by reduced motor weight for a given horsepower unit; reduced motor maintenance and reduced levels of harmonics and EMI through the use of brushless ac traction motors.

2.6.3 Regeneration in Electric Locomotives

Regeneration of electric power back into the catenary to decelerate an electric locomotive has been considered for conserving energy and assisting in braking. Although technically feasible, regeneration entails many problems that have impeded its widespread use.

Regeneration of power from a motor to the supply line has been used for many years with dc motors supplied from m-g sets or from rectifiers. When the dc motor must be decelerated rapidly or reversed, the field current is manipulated to make the dc motor act as a generator and the kinetic energy of the motor and its load is pumped back to the source. Typical applications include reversing machine-tool and rolling-mill drives, and elevators. The utility does not see the reversal of power flow because the regenerated power tends to serve the load in the same building or plant; the power flow from the utility dips during the regeneration period. The purpose for the regeneration is both to conserve energy and to dispose of the kinetic energy into a form other than heat.

In the past, railroads and rapid-transit systems have not seriously addressed the regeneration problem but it is now emerging as an energy-saving means. There are four problems with regeneration on railroad-type equipment. First, the actual energy savings are relatively low, compared to the total used, estimated as 10% to 20%. Second, the propulsion control system must be more complicated to 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. This is more complicated with rectifiers and dc catenaries than with ac catenaries. Fourth, the locomotive or rapid-transit 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 R&D that must be considered are:

- 1) Determination of the amount of energy that can be recovered by regeneration.
- 2) Development of equipment for the locomotive or multiple unit car to handle regeneration.
- 3) Development of braking systems that will incorporate all of the modes: friction, dynamic, and regenerative, to match all operating conditions.
- 4) Evaluation of the cost benefits of regeneration.

Primary outputs of R&D in this area will be the cost-benefit analysis of regeneration, and the equipment that must be installed on the locomotives and in the substations.

2.7 POWER HARMONIC AND ELECTROMAGNETIC INTERFERENCE (EMI) CONTROL

Electric locomotives, using thyristor control of the traction motors, 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 cause equipment and other problems in the utility supply system to the railroad.

The electric-utility and communications industries have historically carried out considerable individual and joint work on power harmonics and EMI. The design of power-harmonic filters, the use of 12-and-24-pulse rectifiers, and the techniques for calculating power-harmonic currents dates back to the 1920's with the introduction of the tank-type mercury-arc rectifiers. The calculation of telephone interference (TIF), and the use of special cable techniques for reduction of induction from 1-phase railroad 25-Hz catenaries and shared electric and telephone-utility poles also dates back to the first ac electrification in the United States.

New locomotives are using thyristor control of the traction motors, compared to multi-step tap-changing transformers on the previous ac locomotives. The consequence of thyristor control and 60-Hz catenaries will be more induction and over a higher frequency spectrum than the previous 25-Hz systems. Measurements, calculations, and correction steps have been taken in Europe for thyristor locomotives supplied from 16 2/3-Hz and 50-Hz catenaries.

The methods that have been attempted for control of interference include power filters on the locomotives, the burying all wayside signal and communications circuits, waveform shaping active filters on the locomotives, and power harmonic filters at the substations. Real measured data are lacking on the interference produced by a locomotive in service, and on the susceptibility of various wayside circuit configurations.

The areas of R&D that must be considered are:

- 1) Methods for reducing EMI with wayside railroad and the public communications facilities.
- 2) Techniques for minimizing the interference from power semiconductor circuits on controls and signal equipment on locomotives.
- 3) Methods for reducing radiated EMI and its effect on television and radio reception abutting the railroad.
- 4) Methods for reducing the generation of power harmonics on the locomotive and their transmission through the substations to the electric and communications utilities.

The primary outputs of R&D in this area will be the establishment of design guidelines for reducing 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.

3. MAJOR FAR-TERM R&D AREAS

During implementation of the "first generation" electrification network, there will be considerable design modification proposed. Many of the changes can be evaluated with little risk and require no R&D support. The R&D in this chapter is identified as evaluation of concepts and equipment that can offer significant gains over the "first generation" system but which require large expenditures, long development times, and perhaps significant risk of failure. Successful completion of the R&D topics would mark the emergence of a "second generation" electrification system which could offer increased service capabilities and cost savings for additional routes to be electrified and for electrified routes with first generation equipment that has reached the end of its economic lifetime.

3.1 LINEAR MOTOR STRUCTURE BRAKES AND THRUSTERS

The full utilization of the propulsion plant on electric locomotives and self-propelled cars is limited by the steel wheel on steel rail adhesion limits. This is particularly true in accelerating and braking on grades and on wet track. Linear induction motor (LIM) structures can provide additional tractive or braking force directly on the rail or on a supplementary reaction rail laid between the running rails.

The linear brake structures are relatively simple. The operating coils can be energized with direct current from the vehicle. The linear brakes can apply up to about 7 lb. of braking force per square inch of facing area either to the top of the running rail or to a supplementary rail. The linear thruster structure is built as a LIM. It requires an ac power source on the vehicle which can either be adjustable frequency or fixed frequency depending upon the magnitude and duration of the thrust required. Braking force can be developed with the same structure. Tractive forces of the same order of magnitude as the dc operated brake can be developed.

Considerable work has been done in the United States on LIM's for air-cushion vehicles under DOT sponsorship (15). The design is well understood and considerable test data is already available to guide the development of structures for the proposed applications. Additional work has been done throughout the world, as well. The

application of LIM's to actual vehicles has been paced by the progress in air-cushion and magnetically-levitated vehicles. LIM's have been used in Great Britain and France for linear propulsion of test vehicles, mine cars, and other loads.

The dc linear brake has been built in two forms: (1) with the magnetic force pulling the brake surface against the stationary rail to brake by friction forces; (2) by inducing eddy currents in the stationary rail to obtain electromagnetic forces. The friction type, now promoted by Knorr (16), has been installed on rapid-transit cars. The electromagnetic type is under development in Japan and France for vehicles normally under electric power, and for vehicles carrying special small generators dedicated to operate the brakes. The electromagnetic type is more critical than the friction type on spacing of the brake surface to the stationary rail; however, the electromagnetic type operates independently of stationary rail conditions.

The areas of R&D that must be considered are:

- 1) A systems analysis to determine:
 - a. Required levels of thrust and braking force for each type of vehicle and service;
 - b. Acceptable sources of operating power;
 - c. Integration with present train-line and individual vehicle control systems;
 - d. Physical size, mounting methods, cost;
 - e. Allowable levels of running rail heating.
- 2) Development, test and evaluation of LIM thrusters, linear friction type brakes, linear electromagnetic brakes, and the associated power sources for each of the above.
- 3) Evaluation of the cost-benefits of these braking systems.

The above R&D should result in braking systems that can provide significantly improved braking when compared to present systems. In addition, overall improved train braking performance should result, since the above concepts can be used on all types of rolling stock.

3.2 DC ELECTRIC TRACTION

At the present time electric locomotives use dc motors powered from a catenary that carries single-phase ac current. Near term R&D will examine the economy of ac induction and ac synchronous motors powered from ac catenaries. The use of high voltage (HVDC) catenary to power dc motors offers further potential cost savings resulting from simplified connection to the utility at distribution voltage levels and from increased substation spacing because of lower voltage drop associated with dc systems. The state-of-the-art does not permit implementation of HVDC catenary at this time at a power level required for the mainline freight hauling application. It is anticipated that electrification at HVDC will require a minimum of 10 to 15 years of concentrated R&D. The following R&D must be accomplished to make HVDC electrification feasible.

1) Distribution System Parameter Identification Effort*

All parameters necessary to specify a complete HVDC distribution system should be identified and their ranges determined where applicable. These would include but not be limited to:

- a. System voltage (maximum, nominal, minimum);
- b. System loads (maximum, short time, nominal);
- c. Substation spacing, substation electrical parameters, and line impedances including capacitance to ground;
- d. Vehicle parameters which affect the distribution system such as starting currents, line ripple, jerk rates, dI/dt and top speed;
- e. System transient behavior including system overvoltages, overcurrent, and other characteristics due to lightning, switching surges and faults;
- f. System configurations including two or four track, tie point requirements, methods used to decrease impedance and two or three wire distribution;
- g. Distribution system clearance requirements both through air to ground and over insulators to ground.

* Section 1 extracted from reference (17), with permission of author.

This study should be undertaken knowing the parameters of comparable ac distribution systems and always keeping them in the forefront. The system parameters would also be based on models of the operation of electrified systems including train consists, headways, speeds, etc., from which the electrical loadings can be established. System studies are required for topics unique to HVDC electrification including the following:

- i. Electrical transient analysis should be completed on the DC and AC distribution system configurations considered. This analysis will be necessary both to specify transient-type parameter ranges (for circuit breakers, insulators, etc.) as well as to understand the system parameters which are most significant in determining transient behavior.
- ii. An investigation should be carried out on DC arc behavior at these higher voltages. This investigation should be directed toward arc generation between a moving pantograph and a contact wire as well as arc damage to wire. Comparisons ought to be made with similar voltage AC arcs.
- iii. The question of insulator polarization (metal particles) should be investigated at these high voltages. Experiments should be carried out on this phenomena. Again comparisons ought to be made with AC case.

The output of studies ii and iii would be used to select line to ground separation over air and insulators. The smaller the separation, the less expensive the insulator.

2) DC Circuit Breakers for Traction Service

In the dc electrification system, circuit breakers will be required to protect the substations, catenary conductors and locomotives from the consequences of fault currents produced by severe overloads, short circuits, equipment failures and lightning. These circuit breakers will be placed in the following locations:

- a. Main breakers, located between the dc output terminals of the rectifiers and the dc buses at each substation.
- b. Feeder breakers, located between the dc busses and the catenary conductors at each substation.
- c. Gap breakers, located at sectionalizing points of the catenary conductors.
- d. Locomotive line breakers, located within the locomotive between the pantograph and the PCU equipment.

- e. Locomotive auxiliary breakers, located within the locomotive between the main dc bus and auxiliary equipment, such as a voltage-reducing chopper.

DC traction breakers have been successfully built and operated in traction service up to 3kV. These breakers are categorized into 600 to 750 V dc for urban systems, typically subways and rapid transit, and 1500 V and 3000 V dc for railroad service. The BART system uses 1000 V dc breakers. The Erie Lackawanna railroad uses 3000 V dc breakers built by General Electric. The same voltage ranges prevail in the rest of the world. The Russian railroads are planning to raise parts of their 3kV electrification to 6kV necessitating the development of a breaker for 6kV service. Their approach might be to use multiple lower-voltage gaps (contact pairs) in series; this technique is used even in the 3kV and below breakers.

The technical problem in dc circuit breakers is to quench the arc from the opening switch contacts by extracting its energy. All dc traction breakers to date quench the arc by magnetically "blowing" it up into arc chutes where it is lengthened and cooled by the side walls of the chute. Obviously, the "blow-out" approach is physically limited for the higher dc voltages and other methods must be developed and used.

The required voltage range for the breaker will be from 10kV to 25kV; dc continuous current will be about 2000 A. It is anticipated that several circuit breakers will be required to cover this voltage range. The maximum rate of current rise will be about 25 A/ μ s, and peak current about 200,000 A, under fault. Circuit breakers for these voltages and currents are standard for ac systems, but have not been developed for dc systems, primarily because of the technical problems, and secondarily because there is practically no market for them. The ac circuit breaker relies for current interruption on the current zeroes that occur each 1/120 s in the alternating wave. The dc circuit breaker must interrupt the current by forcing it to zero at a faster rate than it is rising into the fault.

Development work is proceeding in the U. S. and abroad on dc breakers for dc transmission lines. The voltage requirements are much higher than for traction service, typically 500kV to 1500kV. The work in the U.S. is partially supported by corporate money and by EPRI (Electric Power Research Institute). The results can be adapted to traction breaker requirements.

The approaches for dc traction breakers that should be subjects of R&D are the following:

- i. Extension of the present magnetic "blow out" technique to higher voltages.
- ii. The Hughes dc breaker using crossed-field interrupter tubes.
- iii. Vacuum interrupter with capacitor-type commutation circuit to force the current to zero.
- iv. SCR (thyristor) switch with capacitor-type commutation circuit to force the current to zero.
- v. Liquid or gas arc cooling to extinguish the arc, corresponding to techniques used in ac breakers.

The development of the dc circuit breaker requires the extension of known technology into a new area of application to arrive at a reliable, compact, economical package.

3) DC Locomotives

A series of electric locomotives must be developed for service on railroads to be electrified with dc voltage at about 25 kV. The largest locomotive will be rated from 10,000 to 15,000 hp for operation up to 120 mi/h.

Propulsion systems consisting of the power converter, traction motors, trucks, and braking system must be developed for the 25KV dc prototype locomotives. The requirements for the propulsion systems will be given in the specifications for the locomotive itself.

Electric locomotives for the horsepower and speed of the required dc locomotive have been built by ASEA and others. These locomotives are built to operate from 25kV ac catenaries supplied from the utilities at 50 or 60 Hz. They employ an on-board transformer with multiple secondary windings, sequential thyristor rectifiers, and dc traction motors. Harmonic power filters are provided on the locomotive to reduce the electromagnetic interference (EMI) that they cause.

DC locomotives have been built and are operating at a maximum dc voltage of 3kV on the Erie-Lackawanna, in Western Europe, and in Russia. These locomotives employ resistance and motor switching to control the tractive effort and speed. The traction motors are always connected so that at least two in series share the total voltage of 3kV. The maximum per motor voltage is limited to a nominal 1.5kV by the commutator. This limitation has prevented the use of higher catenary voltages than 3kV in the past. The Russians have reported on the development of a

6kV dc locomotive which uses semiconductor devices to operate on upgraded sections of their existing 3kV railroads.

The development of the high voltage power-type semiconductor thyristor and diode and their associated equipment has opened the way for dc locomotives operating at higher than 3kV. For example, the Garrett air-cushion levitated LIM vehicle employs a 6-MVA rectifier-inverter operating directly from an 8.25kV 3-phase power rail. Utility dc transmission-line terminals have been built with semiconductor rectifier-inverter bridges up to 200kV, 360 MVA. Single-motor semiconductor adjustable-speed drive systems have been built with ratings that exceed 10,000 hp. Practically all of the technology for the construction of the proposed dc locomotive is available today. However, the integration of the technology into a series of reliable, maintainable and manufacturable locomotives is a substantial task, and one that will require significant development, test, and evaluation effort.

Areas where R&D should be considered are:

- a. Systems Engineering. Establishment of the performance requirements and ratings for the locomotives. Establishment of the ratings for the major equipment groups. Establishment of standards for clearances, grounding, protection, quality, reliability, etc. Control overall problems of EMI, surge voltage, etc.
- b. High-Voltage Equipment Group. Development of all of the equipment that interfaces with the 25kV dc system including pantographs, switches, lightning arresters, fuses, main and auxiliary breakers.
- c. Propulsion System. Development of the propulsion system from the 25kV dc supply point within the locomotive to the rails including power converters, traction motors, trucks, and braking system. Explore the power converter options by building and testing prototypes.
- d. Controls. Development of the control system for the locomotives as an integrated package. Included shall be way-side control, control of speed and tractive effort, wheel slip, braking, and multiple unit operation.
- e. Reliability and Protection. Development of fault diagnostic systems and the design and test of electrical fault clearing systems. Included in this would be the carrying out of fault and failure analyses of the overall locomotive and equipment groups and the setting of reliability goals.

- f. Auxiliary Equipment. Development of the auxiliary electric power system to be supplied from the 25kV bus, of the cooling system for the propulsion plant, of communications and signaling systems, and of a brake system.

3.3 ELECTRIFICATION OF LIGHTER DENSITY ROUTES

The quantitative evaluation of R&D for the first increment was based on electrifying routes with a traffic density greater than 40 MGTM per mile per year. At present, 8,200 miles of U. S. mainline exceed this traffic density. At the time of implementation of a second increment of electrification, further mainlines will exceed 40 MGTM per year due to traffic growth. R&D and product improvement can be expected to reduce costs such that electrification can be justified for lines with less traffic density. The R&D defined in this section is directed to cost reductions that can make electrification justifiable at lighter traffic densities.

- 1) Hybrid Locomotive. A concept which requires no additional fixed plant investment is to use locomotives with dual propulsion systems, operating from the catenary in electrified territory and from stored energy in non-electrified territory. Hybrid operation should be considered for yard and branchline service and for run through of trains to intermediate yards. Power sources to be considered for non-electrified operation should include diesel engines, batteries and flywheels.
- 2) Transmission Line Extension. Cost of transmission line extensions will be greater for electrification of light density lines because the routes will, in general, be serving regions with less utility development. It is possible to reduce this cost by including electrification in the planning of utility expansion. Studies should be made to evaluate the possible savings resulting from joint planning including use of railroad right-of-way for transmission line extensions and improvement of railroad load demand by connection in combination with other utility loads with congruent characteristics.
- 3) Wayside Energy Storage. Where ruling grades are extreme or acceleration demands are large, it is possible to reduce the fleet size and the size of the fixed plant by locating supplementary power at the high load points. The concept of wayside energy storage for an electrified railroad using flywheels and/or batteries is currently being evaluated

from a technical and economic point of view. Results of the study are anticipated to show the feasibility of the concept. Further development and demonstration are required to bring the concept to the state where it can be integrated into a railroad's revenue operation.

4. IMPACT OF R&D ON THE ECONOMICS OF ELECTRIFICATION

The purpose of this section is to show the economic impact that research and development can have on electrification in the United States. This is accomplished by postulating an electrification scenario wherein cost structures are developed through the use of current technology. Revised costs are then established as a result of technological improvements obtained from research and development. It should be noted that this cost analysis is not an economic study in the sense that electric alternatives are evaluated over their lifetimes, nor is the time value of money considered. Such an analysis, which compares electric alternatives with the existing diesel-electric alternative, is not appropriate since the credits and cost differentials used in the analysis would distort the cost categories used to measure the impact of the proposed R&D topics. Further, the effort required for a discounted cash flow analysis would be excessive considering the accuracy to which it has been possible to estimate the value of R&D gains, R&D costs, and the cost of the projected electrification network. Cumulative costs over the 10-year construction period and operating costs of the completed network in year 10 adequately portray the impact of R&D on cost savings.

The analysis is based upon a plausible set of assumptions and indicates quantitatively, the impact of R&D under that scenario. For other scenarios, such as more or less intensive electrification, more or less R&D and for variations of cost projections, the impact is scaled with the R&D topics retaining their relative importance.

4.1 BASELINE ELECTRIFICATION SCENARIO

The baseline electrification scenario is given in Appendix C and establishes estimates of the capital investment and annual operating costs resulting when diesel-electric operation is supplanted by all-electric operation. The scenario consists of the 8,500 route miles of double track with a traffic density in excess of 40 million gross ton miles per year in 1980.* Table 4.1 defines the schedule for

*The mileage of the scenario is consistent with service level 1 of the proposed electrification network developed by the Mitre Corp. under contract to DOT/FRA (18). The mileage of service level 1 is 8,200 route miles and contains those sectors with greater than 40 MGTM per year in 1976 (see Figure 4-1).

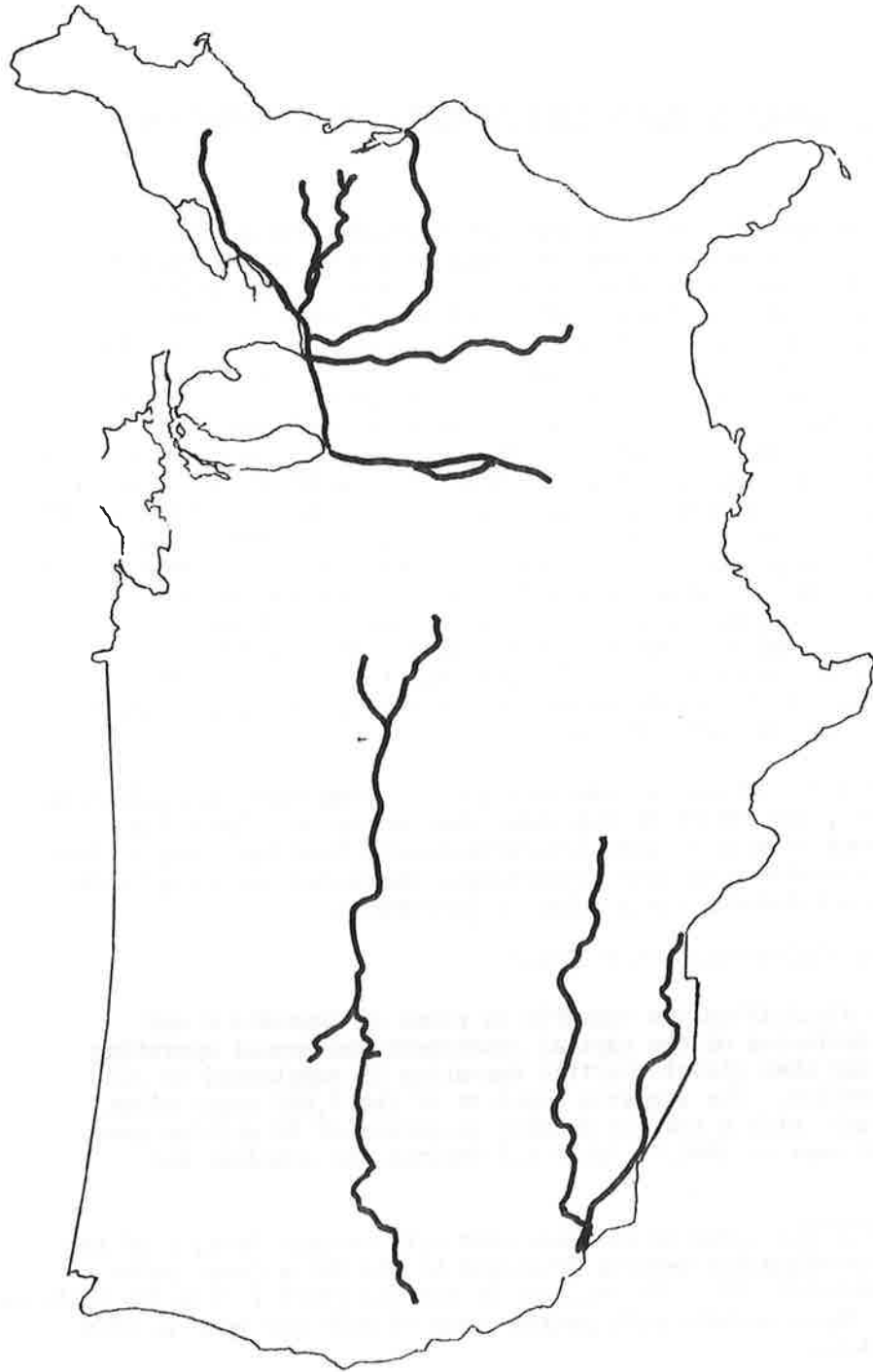


FIGURE 4-1 - SERVICE LEVEL I OF THE MITRE RAILROAD ELECTRIFICATION NETWORK

electrification and the projected traffic load over the installation period. The scenario is described in more detail in Appendix C including the associated costs.

Capital costs and operating costs are summarized in Tables 4-2 and 4-3. Cumulative capital costs over the 10-year construction period that can be impacted by R&D total \$8B. No credit has been given for diesel locomotive purchases that would have been required without electrification. The operating costs are itemized in the format used for ICC documentation. The cumulative operating cost of the mixed diesel-electric and electric operation over the 10-year period is \$39.3B. That portion that is related to electrification and, therefore, can be impacted by R&D is tabulated in a separate column. Electrification related operating costs over the construction period are \$6.6B. No credit is shown for diesel related operating costs that have been eliminated.

4.2 NEAR-TERM AND MID-TERM R&D BENEFITS

A summary of the estimated cost benefits for each hardware related topic in section 2 is given in tables 4-4 and 4-5. The R&D in table 4-4 can be achieved and brought to the implementation stage in 5 years with the funding indicated. The R&D in table 4-5 can be implemented in 10 years with the funding indicated. The negative numbers represent savings that can be achieved in the cumulative operating and capital costs of \$6.6B and \$8B, respectively. The capital cost for regenerative power management is a positive number indicating an equipment cost associated with implementation. Each topic produces a net savings over the 10-year period. R&D with capital cost savings should be completed prior to electrification so as to obtain maximum benefit from the R&D.

The data for tables 4-4 and 4-5 is based upon the estimates presented in Appendix D. The costs and savings result from implementing the R&D in the 8,500 mile network defined in section 4.1. The R&D topics of table 4-4 are implemented in the fifth year, thereby impacting the entire network. The R&D topics of table 4-5 are implemented in the tenth year. All benefits in table 4-4 and 4-5 have been rounded to the nearest \$50M to reflect the range which can result from variations in the intensity of electrification or the intensity of the related R&D.

The scenario costs with and without R&D in Appendix C are based upon electrification over the period 1980 to 1990. To make the results applicable for another period of time requires recalculation of the traffic load and updating of the cost data base. For start times from 1978 to 1984, the data base is not expected to change dramatically. Accordingly, a floating time frame of 10 years has been used in this section to summarize the cost models of Appendices C and D.

The benefits of tables 4-4 and 4-5 have not been totaled, purposely. It is not appropriate to assume that all the R&D benefits can be derived simultaneously. For example, a reduction in peak demand from the utility will reduce the benefits that can be achieved from R&D on reactive power reduction by reducing the energy requirement and, hence, the reactive power. Likewise, power density improvement can reduce the locomotive fleet and, thereby, alter reactive and regenerative power benefits by reducing the quantity of onboard equipment required. It is estimated that the total benefit, if all R&D of the tables were successfully completed, would be \$1.0B to \$1.2B through the tenth year. The savings would result primarily from reduced capital investment. Because the equipment has a remaining life at that time of greater than 20 years, the operating costs listed in the tables reflect only a part of the operating savings, sufficient to indicate the value of the related R&D. Additional modeling is required to project the total savings possible.

4.3 DC ELECTRIFICATION (FAR-TERM R&D BENEFIT)

The basic scenario of 8,500 route miles given in Appendix C is extended in a second increment where electrification is not at a constant rate of 1,000 route miles per year for 10 years. The purpose of this second increment is to develop the comparative costs of continuing the ac electrification or the implementation of high voltage dc electrification.

Tables 4-6 and 4-7 provide capital and operating cost comparisons for three alternative electrification systems: (1) 25 KV Alternating Current (AC); (2) 12 KV Direct Current; and, (3) 50 KV Direct Current. The substantial benefits are to be realized as savings in capital investment. Variations in cumulative operating costs are less than the variance due to accuracy of the estimates.

Tables 4-8 and 4-9 provide a breakdown of costs for an R&D program in DC electrification. Major R&D effort is required in locomotive development. The only significant fixed plant component requiring R&D effort is the DC circuit breaker. Cost of other fixed plant equipment development will be negligible by comparison. However, DC electrification is an area where the risk to successful implementation is great, and must be considered when placing priorities in R&D planning. The estimated benefits of R&D in DC electrification are summarized in table 4-10.

TABLE 4-1 - BASELINE ELECTRIFICATION SCENARIO

Y	ELECTRIFICATION						
	Miles Elect	Cum Elect. Miles Available E ₁	Traffic Growth Factor (1.0 for 1973) G	W/O Elec.	Traffic Load on 8,500 Mile Model Billions of GTM/yr		
					With Diesel	Elect.	Total
0	100	0	1,230	365.9	365.9	0	365.9
1	400	100	1,267	376.9	372.5	4.64	376.5
2	600	500	1,305	388.2	365.4	20.8	386.2
3	700	1,100	1,344	399.8	348.0	47.2	395.2
4	800	1,800	1,384	411.7	324.5	79.5	404.0
5	900	2,600	1,426	424.2	294.5	118.3	412.8
6	1,000	3,500	1,469	437.0	257.1	164.1	421.2
7	↓	4,500	1,513	450.1	211.8	217.3	429.1
8		5,500	1,558	463.5	163.6	273.5	437.1
9		6,500	1,605	477.5	112.4	333.0	445.4
10	↓	7,500	1,653	491.8	57.9	395.7	453.6
11	0	8,500	1,702	506.3	0	461.8	461.8
12	0	↓	1,754	521.5	↓	475.6	475.6

TABLE 4-2 - CUMULATIVE CAPITAL COSTS FOR ELECTRIFICATION OF
8500 ROUTE MILES OVER A TEN YEAR PERIOD

	\$M	\$M
Catenary Costs	1,700	
Utility and Substation Costs	2,210	
Interconnection - 510.5		
Utility Reinforcement - 1,275.2		
R.R. Substations - 424.3		
Signaling, Control, and Communications Costs	1,190	
Engineering & Design of Fixed Plant	794	
Other Fixed Capital Costs	<u>389</u>	
Grand Total Fixed Capital Costs		6,283
Locomotive Costs		<u>1,750</u>
Grand Total Project Capital Costs		<u><u>8,033</u></u>

TABLE 4-3 - CUMULATIVE OPERATING COSTS FOR ELECTRIFICATION OF
8500 ROUTE MILES OVER A TEN YEAR PERIOD

<u>ICC Accounting Item</u>	<u>Total \$M</u>	<u>Electrification Related Costs \$M</u>
I. Maintenance of Roadway and Structure	1,770	
II. Maintenance of Equipment	6,483	209
III. Transportation Expense Accounts	29,709	6,304
IV. Traffic, Miscellaneous, and General Expenses	<u>1,366</u>	<u> </u>
Totals	39,328	6,513

TABLE 4-4 - ESTIMATED COST BENEFITS FROM INDUSTRY/GOVERNMENT R&D
FIVE YEARS TO IMPLEMENTATION

	Operating \$M	Capital \$M	R&D Cost \$M
Cumulative Base Costs (1980-1990)	7,000	7,000*	
<u>R&D Area</u>			
Substations and Railroad/Utility Interface Improvement			
- Peak Demand Reduction	-400	-400	2
- Phase Balance Improvement		-500	5
- Reactive Power Reduction	-200	-100	6
Automated Catenary Installation		-100	15
Motive Power Wheel Slip Control Improvement	-50	-300	6
Harmonic and Electromagnetic Interference (EMI) Control		-100	4

*Cumulative Capital Cost of Table 4-2 Less Engineering and other Capital Costs

TABLE 4-5 - ESTIMATED COST BENEFITS FROM INDUSTRY/GOVERNMENT R&D
TEN YEARS TO IMPLEMENTATION

	Operating \$M	Capital \$M	R&D Cost \$M
Cumulative Base Costs (1980-1990)	7,000	7,000*	
<u>R&D Area</u>			
Regenerative Power Management	-300	+50	5
Economical Catenary Design		-100	5
Locomotive Power Density Improvement	-25	-100	10

*Cumulative Capital Cost of Table 4-2 Less Engineering and Other Capital Costs

TABLE 4-6 - CUMULATIVE CAPITAL COST SUMMARY: ELECTRIFICATION OF
10,000 ROUTE MILES (SECOND INCREMENT) IN A TEN YEAR
PERIOD

	25 KV AC \$M	12 KV DC \$M	50 KV DC \$M
Catenary Costs	2,000	2,000	1,720
Utility & Substation Costs	2,600	2,050	1,750
Interconnection	600	600	200
Utility Reinforcement	1,500	750	750
Railroad Substation	500	700	800
Signal Control, Communication Costs	1,400	2,050	1,050
Engineering & Design of Fixed Plant	922	788	700
Other Fixed Plant	<u>458</u>	<u>412</u>	<u>384</u>
Total Fixed Plant	7,380	6,300	5,604
Locomotive Costs	<u>2,963</u>	<u>1,896</u>	<u>2,133</u>
	10,343	8,196	7,737

TABLE 4-7 - CUMULATIVE OPERATING COST SUMMARY: ELECTRIFICATION OF
 10,000 ROUTE MILES (SECOND INCREMENT) IN A TEN YEAR
 PERIOD

	25 KV AC \$M	12 KV DC \$M	50 KV DC \$M
Maintenance of Roadway & Structures	2,102	2,102	2,102
Maintenance of Equipment	10,219	9,906	9,946
Transportation Expense Accounts	61,184	61,184	61,184
Traffic, Misc., & General Expenses	<u>1,168</u>	<u>1,168</u>	<u>1,168</u>
Total	74,673	74,360	74,400

TABLE 4-8 - MAJOR R&D NEEDS FOR DC ELECTRIFICATION

	\$M	R&D Cost \$M
DC Circuit Breakers for Traction Service		20
DC Electric Locomotive		60
Modify Electric Test Facility at TTC	5	
Subsystem Equipment Prototype Development	35 (See Table 4-7)	
Prototype Locomotive	6	
Prototype Locomotive Test & Evaluation Program	5	
Preproduction Locomotives (2)	8	
Demonstration Test Program	1	—
Total		80M

TABLE 4-9 - DC ELECTRIC LOCOMOTIVE

Subsystem Equipment Prototype Development	R&D Cost \$M
Systems Engineering	3.0
High Voltage Equipment Group	6.0
Propulsion System	20.0
Control & Protection Equipment Group	3.0
Auxiliaries	<u>3.0</u>
Total	35.0

TABLE 4-10 - ESTIMATED COST BENEFITS FROM INDUSTRY/GOVERNMENT R&D
 FAR TERM

	Operating \$M	Capital \$M	R&D Cost \$M
Cumulative Base Costs 25 KV AC (1990-2000)	13,000	2,000	
<u>R&D Area</u>			
Linear Motor Structure Brakes and Thrusters	(not estimated)		
DC Electric Traction			
- 12 KV DC	-300	-2,000	75
- 50 KV DC	-300	-2,500	
Electrification of Light Density Routes	(not estimated)		

5. IMPACT OF R&D ON ELECTRIFICATION TECHNOLOGY

In Sections 2 and 3, the intent was to categorize the R&D into sufficiently broad areas and with sufficient background material to permit quantitative estimates of the benefits to be made. In sub-sections 5.1 to 5.3 of this section, the goals are established for the R&D that achieves these benefits. In sub-section 5.4, a sampling of the studies, projects, and programs is tabulated to show their relationship to the major areas of the previous sections. The relationship is illustrated quantitatively for one R&D study.

5.1 WAYSIDE EQUIPMENT AND UTILITY INTERFACE

The wayside system is divided into three major subsystem categories as follows:

Utility Interface
Railroad Subsystems
Electromagnetic Interference.

A block diagram of R&D for wayside technology is shown in Figure 5-1.

1) Utility Interface

This category includes all of the topics concerned with the interface between the railroad substation and the electric utility supply system.

- a) Harmonics. Harmonic currents from rectifier type electric locomotives and multiple unit cars feeding into the utility system can cause resonant overvoltages and heating of certain components. Work is required on the setting of standards, the design of filter systems, and other measures to control harmonic currents.
- b) Single-phase loads. AC electric railroad operation will take place with single-phase power taken directly from the utility system. Studies, calculations, and field tests must be made of the impact of single-phase load on other customers of the utility system and on generators required to carry

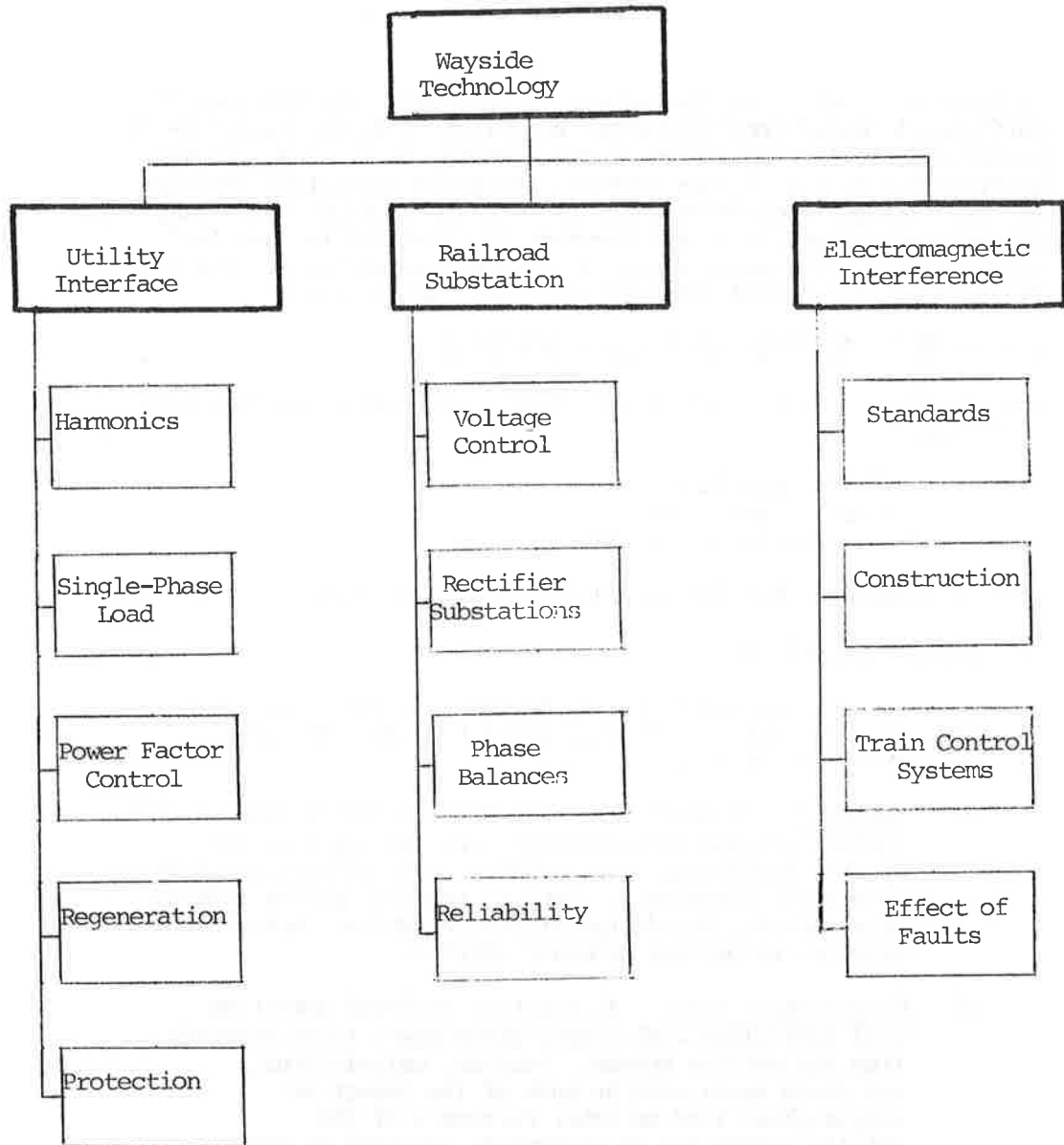


FIGURE 5-1 - BLOCK DIAGRAM OF R&D FOR WAYSIDE TECHNOLOGY

negative sequence currents. Voltage unbalance standards and methods for balancing voltages in case of weak system capability are required.

- c) Power Factor Control. Rectifier locomotives and multiple unit cars present power factor loads of 0.8 and lower to the utility system. Work is required on methods for control of reactive power not only at the locomotive, but at the railroad substation as well to minimize reactive power and negative sequence current. This work should include capacitor switching, continuous capacitor control with thyristors, and local gas turbine generators for providing reactive power locally.
- d) Regeneration. The problems of regeneration of energy from a railroad substation into a utility system must be addressed in terms of energy charges, voltage conditions, safety, reactive power flow, and all of the other problems attendant on energy return.
- e) Protection. The relay and circuit breaker systems for protection of railroad substations must be integrated with the utility protective system as well. The protective system must be designed to allow large train accelerating currents, yet be able to detect faults at the ends of the catenary sections which, if not cleared, could be destructive.

2) Railroad Substations

All types of ac and dc railroad substations are included in this category. The concept for direct supply of railroad electric power from a utility is new in the United States, but has had extensive development in Europe.

- a) Voltage Control. Work must be done to determine whether railroad substations should incorporate automatic voltage regulation to compensate for the voltage drop produced by heavy train current. This work can be done analytically, with computer models and by actual tests in the field. The consequences of such work can be a reduction in overall wayside system cost.
- b) Rectifier Substations. For future dc catenary and locomotive operation, rectifier substations must be developed which can supply the power and voltage levels anticipated. The technology is already available for the power and voltage levels, but dc circuit breakers are not available and must be developed for this service. DC traction breakers are available only up to 3 kV; dc traction systems in the far term will operate with considerably higher voltages.

- c) Reliability. Reliability studies are required to determine the optimum balance between extra capacity and redundant equipment in the substations with performance of the train on the electrified section. Various combinations of equipment in single substations, and in a number of substations, must be analyzed to determine the optimum combination.
- d) Phase balancers. R&D work is required on static phase balancers for reducing the impact of single-phase load on weak utility supply systems. Economic tradeoffs must be made between capital costs of phase balancers and capital costs of utility system reinforcements.

3) Electromagnetic Interference (EMI)

EMI from locomotive, multiple unit cars, and other sources impact on wayside railroad-owned signal and communications facilities, as well as publicly-owned telecommunications services.

- a) Standards. Testing and development work is required to set standards for interference produced in wayside telecommunications equipment by electric locomotives and multiple unit cars and to design equipment to reduce the impact of such interference. New types of telecommunication plants and new methods for signaling are required to operate in conjunction with the large horsepower locomotives anticipated in the future.
- b) Construction. Studies and tests must be carried out on the most economical form for telecommunications construction along railroad routes. This work includes underground construction, microwave construction, and other means for carrying signal information in parallel with railroad operation.
- c) Train Control Systems. Development is needed on train control systems which can operate reliably in the presence of the noise and potential fault currents generated by rolling stock and catenaries. This work requires that sample systems be built and tested under controlled conditions and followed up by installation on sample sections of electric railroads.
- d) Effect of Faults. Extensive study is required regarding the operation of wayside telecommunication systems when faults occur in the railroad electrification system. Both train control and wayside electric control systems must be operable during faults in order to insure equipment safety and passenger safety during those instances.

5.2 CATENARY EVOLUTION

In support of a national railroad electrification program, R&D work on catenaries should be carried out with the following objectives:

Speed and current. Catenary systems must be capable of supplying power to locomotives and multiple unit cars traveling at high rates of speed and taking currents in excess of that handled by known pantograph and catenary systems.

Cost. The catenary represents a sizeable portion of the capital investment per route mile. Reduction in unit cost is multiplied by all of the miles contemplated in a railroad electrification program.

Higher voltages. Catenaries operating up to 50 kV require electrical components and clearances beyond present practices.

A block diagram of R&D for catenary technology is shown in Figure 5-2. The catenary is divided into three major subsystem categories as follows:

Electrical
Mechanical
Construction.

1) Electrical

- a) Phase Breaks. Research is required on the necessity and location of phase breaks for utility supplied catenary systems including the optimum allocation of phase voltages. In addition, actual phase break equipment must be built and tested to insure that isolation across the phase break is accomplished, and smooth locomotive operation assured.
- b) Conductors. Catenary conductor design requires research to achieve the best compromise between catenary dynamics and electrical current carrying capacity. Various types of pantograph to catenary wear characteristics, and current transfer phenomena must be studied.
- c) Clearances. Clearances from catenaries to rolling stock and to fixed wayside structures must be established by tests for normal operating conditions and unusual fault and surge conditions to assure safety of equipment and personnel. Clearances normally used for industrial and electric utility applications are not suitable for railroad service with moving vehicles and current collection systems.

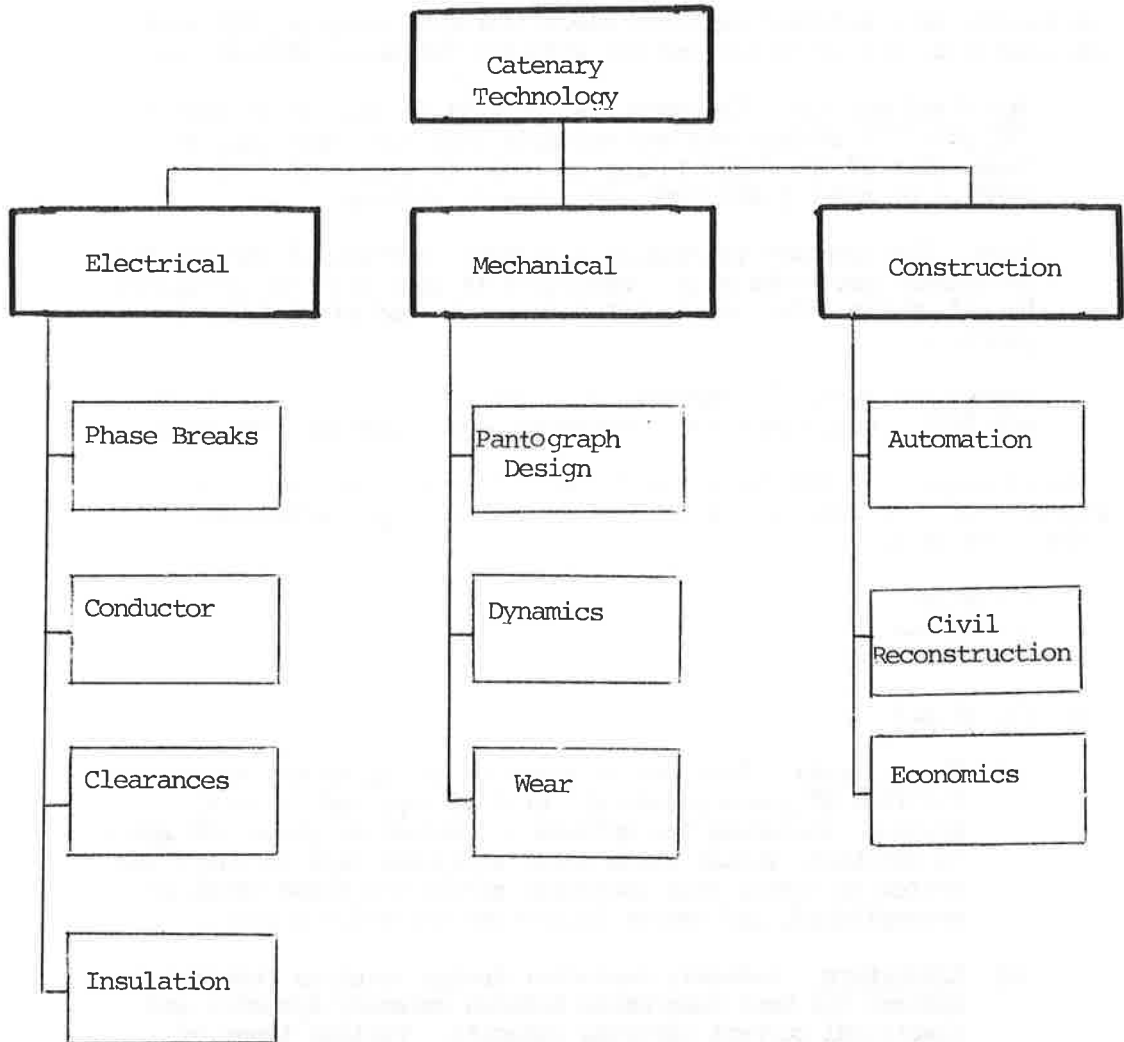


FIGURE 5-2 - BLOCK DIAGRAM OF R&D FOR CATENARY TECHNOLOGY

- d) Insulation. Insulators must be developed for maximum catenary voltages that can withstand the electrical and mechanical requirements of service. Other insulation must be developed for feeder cables, substation equipment, and even for wayside telecommunication equipment that might be exposed to direct contacts or induced voltages during special conditions.

2) Mechanical

- a) Dynamics. Analysis, design, and extensive testing must be carried out on sample pantograph and catenary systems. The design parameters must be worked out for the vehicle speeds and current collection conditions anticipated in future railroad electrification.
- b) Wear. Studies and testing are required on interfaces between pantograph shoes and catenary wires to insure extended life, minimum arcing, and minimum wear of the catenary wire.
- c) Pantograph design. Model and full-size pantographs must be built and tested for anticipated ac and dc voltage levels, and for standards for catenary wire, static and dynamic disposition.

3) Construction

- a) Automation. The cost of catenary construction can be reduced by automation techniques such as are used in the USSR and other countries. To achieve large scale electrification on a relatively extensive per year basis, machinery, techniques, and other measures must be taken to promote extensive automation of catenary construction.
- b) Economics. The whole cycle of catenary design, construction, and equipment costs must be studied to determine arrangements which assure minimum fixed costs and annual operating costs over the life of the catenary system. These studies can be done with economic models and with data obtained from European and early US experience.

5.3 LOCOMOTIVE AND MULTIPLE UNIT MOTIVE POWER

In support of a national railroad electrification program, R&D work on locomotives and multiple unit motive power should be carried out with the following objectives:

Increased performance. New locomotives and multiple units are required with capability for higher tractive force,

horsepower, and speed. These units must have high reliability, be compatible with anticipated train control systems, and be engineered for optimum operation with train loads and crews that will be trained for this duty.

Compatibility. New locomotives and multiple units must be compatible with future requirements on railroad-utility interfaces, railroad-telecommunication interfaces, and with environmental requirements for noise, pollution, and other factors.

Cost. Motive power designs must be achieved which permit a maximum use of standardization and modularization to reduce overall electric railroad costs. This may require the standardization of subsystem components such as traction motors among all manufacturers serving the US railroads.

Hardware development. Components, subsystems, and complete electric locomotives must be built on a developmental basis to test new ideas and the scaling of previous sizes of equipment.

A block diagram of R&D for locomotive technology is shown in Figure 5-3. The locomotive or multiple unit car is divided into four major subsystem categories as follows:

Pantograph-catenary interface.
Power conditioning.
Propulsion.
Wheel-rail interface.

1) Pantograph-Catenary Interface

- a) Power harmonics. Power harmonics in the current drawn from the catenary present one of the most serious problems for large electric locomotive operation. The power harmonics cause EMI in adjacent telecommunication facilities and cause problems within the electric utility systems supplying the railroad electric load. Work is required on filters located within the locomotive for suppressing power harmonics with minimum size and weight; work is also required on special rectifier power conditioning circuits and on auxiliary switching circuits to reduce the amplitude of power harmonics.
- b) Power factor. The reactive power drawn by the locomotive from the catenary because of the on-board load and the phase control rectifier causes voltage drop between the substation and the locomotive, which limits the length of the catenary sections supplied from each substation. On-board controllable capacitors, special rectifier configurations, and other equipment must be developed to better control the power factor of rectifier type electric locomotives.

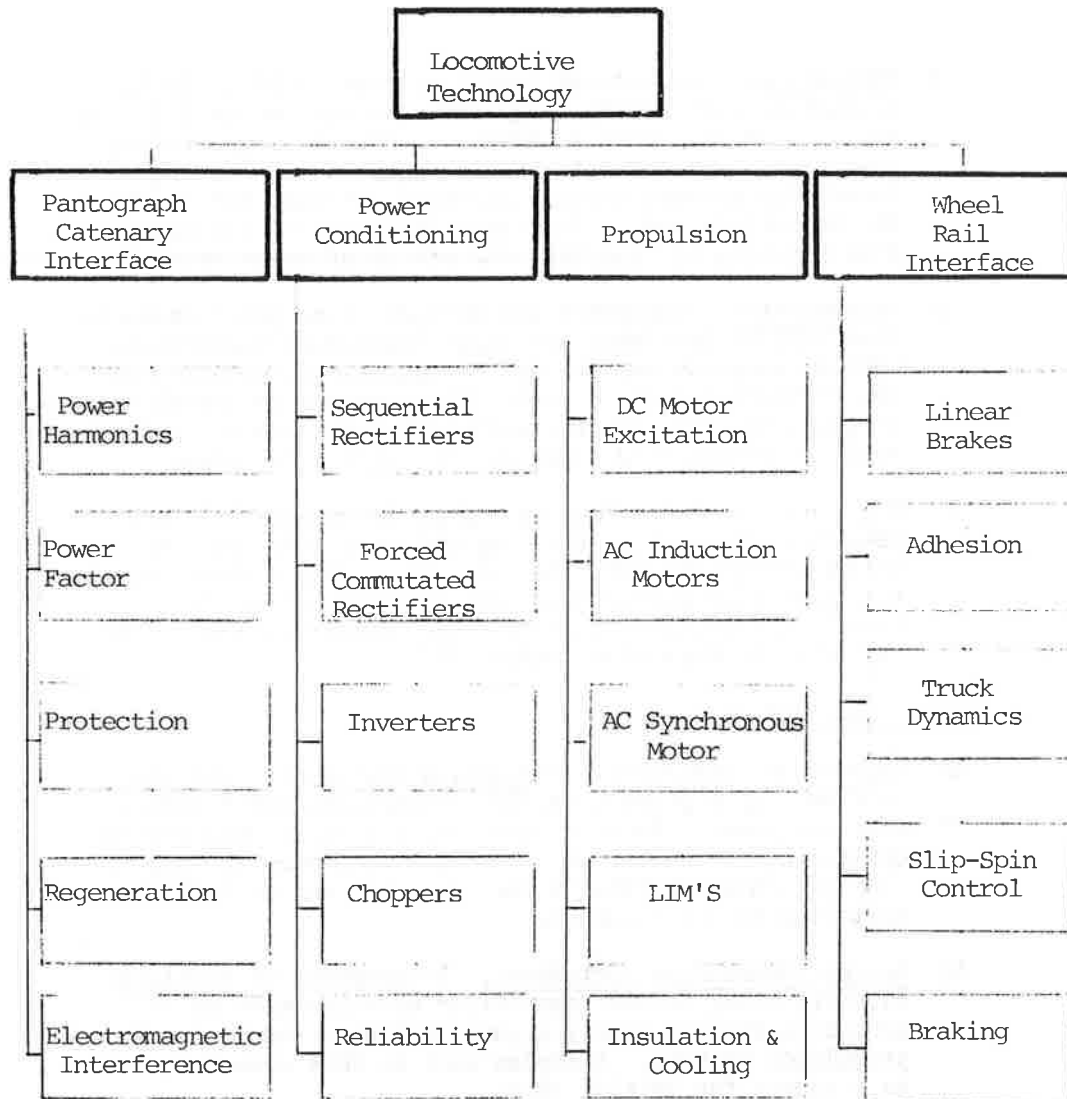


FIGURE 5-3 - BLOCK DIAGRAM OF R&D FOR LOCOMOTIVE TECHNOLOGY

- c) Protection. Locomotives operating from 25 kV or 50 kV catenaries can sustain large currents for internal faults and will be subjected to severe lightning surges during operation. Development work is required both on high-speed high-current circuit breakers suitable for mounting on locomotives and on lightning arresters with surge protection networks for limiting the effect of surge voltages.
 - d) Regeneration. Equipment and methods of ac power regeneration must be developed for large horsepower locomotives both to conserve energy and to conserve dissipation in the on-board braking system. The regeneration problem includes reactive power availability and problems of handling regenerated power at the utility interface.
 - e) EMI. Equipment development and production methods are required for limiting the propagation of EMI from the locomotive itself and from the catenary currents which supply it. Extensive development work is required on filters, circuit design, shielding methods, grounding, and all of the other factors that control EMI.
- 2) Power Conditioning
- a) Sequential rectifiers. Sequential rectifiers have been used on single phase rectifier locomotives for limiting reactive power. Further development work is required on optimizing the number of steps in a sequence, the allocation of semiconductors to the sequence, and methods for switching in the sequence.
 - b) Forced commutation rectifiers. Development of rectifier circuits using forced commutation or other methods is needed to control reactive power and power harmonics in propulsion systems. European work in this area can serve as a source for initial ideas.
 - c) Inverters. Long range development of both ac powered and dc powered electric locomotives will require inverters for ac induction and synchronous motor propulsion. Development work must be carried out on all aspects of inverters, including protection, reliability, use of most modern components, so that they will be available for future traction service.
 - d) Choppers. Chopper development at both high and low power levels is required for dc operated locomotives and other rolling stock, and for auxiliary equipment on such vehicles. Chopper development work must encompass the same objectives as inverter work.

- e) Reliability. Electronic equipment for power conditioning and train control on locomotives and multiple unit cars has not met the anticipated reliability performance. Extensive development work is required on setting design standards, methods for predicting reliability, concepts for redundancy and standby equipment, and all of the other factors to improve the reliability of such equipment.

3) Propulsion

- a) DC motor excitation. Research and development work is required for rectifier locomotives on the performance of dc motors with series excitation, as compared with independent field excitation. Certain advantages accrue, which must be tested, during braking and regeneration with independent excitation.
- b) AC induction motors. Development work is required on ac induction traction motors for developing larger tractive forces and horsepowers per axle than is presently available with dc traction motors. These ac motors must be compatible with inverter power conditioning equipment.
- c) AC synchronous motors. Development work on both wound field and Lundell-type synchronous motors is required to match inverter power conditioners. Synchronous motors are capable of higher peak torques and better material utilization than induction motor counterparts.
- d) Linear induction motors. Investigation is required on the use of linear induction motors to provide supplementary tractive methods on locomotives on grades and for other purposes. The design, sizing, and power supply for such linear motors must be investigated.
- e) Insulation and cooling. Common to all propulsion motors is the problem of improved insulation and cooling methods to increase the horsepower per lb and to increase the life of such machinery. Development work in the industrial sector is helpful, but is not always fully pertinent to transportation requirements.

4) Wheel-Rail Interface

- a) Adhesion. Development and testing of propulsion control circuits and equipment must be carried out continuously to improve the adhesion of steel wheels on steel rails under all weather and operating conditions. The adhesion parameter determines the requirements for locomotive tractive force and horsepower and is responsible for major cost increments in equipment procurement.

- b) Truck dynamics. Development work of locomotive trucks and traction motor suspension is required for the large electric locomotives to be built in the future. This work should include analysis, simulation, model studies, and the construction and testing of full size equipment.
- c) Slip-spin control. Development work is needed on control systems to insure maximum adhesion during acceleration and braking of the locomotives. Modern computer techniques can be incorporated into these control systems to optimize their performance.
- d) Braking. The whole spectrum of locomotive braking requires constant development work. Improved braking for long trains can be achieved by the use of electrical braking controls, linear electromagnetic brake, regenerative braking, and other techniques.
- e) Linear brakes. Linear electromagnetic brakes are being developed in France and in Germany on locomotives, rapid transit cars, and other non-powered vehicles. Linear brakes must be developed to supplement conventional braking systems operating at the limits of steel wheel on steel rail adhesion.

5.4 R&D PLANNING

Major areas of R&D have been identified for which significant cost savings benefits could be obtained. Tables 5-1, 5-2 and 5-3 show the impact of specific R&D projects, hardware improvements, and studies on these major areas. Since the areas described encompass all R&D which offers significant benefits, the distribution of specific R&D projects shown in the tables is desirable to adequately cover all of the near-term and mid-term areas, and should reflect a balanced R&D program. Priority of candidate projects should be reflected from the number of areas impacted by an individual project. For example, the electric traction test facility and traction motor developments do impact most of the R&D areas and represent logical high priority candidate projects.

On-going R&D has been footnoted in Tables 5-1, 5-2 and 5-3 to reflect the degree of industry and government involvement. While a significant portion of the R&D listed is ongoing, there has been no focus to this work to date. It is essential that an overall electrification R&D program be developed that defines the roles of industry and government and which will focus present and future R&D to achieve the most benefits from electrification. The Federal Railroad Administration's Office of Research and Development (FRA/OR&D) has been assigned the responsibility for railroad electrification R&D, and should be looked to as the organization to provide such focus.

The cost benefits realizable in completing individual R&D topics of this chapter can be estimated. As noted before, individual benefits are not additive and, therefore, do not measure the degree of completion of the R&D areas of Tables 4-3, 4-4 and 4-9. However, the estimates, while admittedly crude, do provide a qualitative measure for placing priority on R&D plans. An example is given below in Table 5-4 to illustrate the method for estimating project benefits.

The primary source of the individual R&D topics identified in this report have been obtained from a series of government/industry workshops which are summarized in Appendix A. These workshops, sponsored by the FRA/OR&D, have had as their objective the identification of those candidate R&D projects which could significantly benefit railroad electrification in the U.S. The topics have been screened to eliminate those which are high risk or which produce insignificant benefits. These high risk or which produce insignificant benefits. These topics presented in the tables are only a partial listing, and continued updating and extension of these tables is required to reflect the changing state-of-the-art.

TABLE 5-1 - R&D AREAS IMPACTED BY PROJECTS AND STUDIES IN
WAYSIDE TECHNOLOGY

Potential R&D Studies, Projects, and Programs	R&D AREA													
	Near Term							Mid Term				Far Term		
	Peak Demand Reduction	Phase Bal. Improve.	Reactive Pwr. Reduction	Automated Catenary Install.	Wheel Slip Improve.	EMI	Other	Regen. Pwr. Mgmt.	Econ. Cat. Design	Pwr. Density Improve.	Other	Linear Motor Structures	DC Electric Traction	Electrification of Light Density Routes
1). Development of sub- station equipment for power factor control #	x	x	x				x				x			
2). Improved Transformer Design#	x					x	x							
3). Wayside Energy Storage*	x	x	x			x		x			x	x	x	x
4). Load & Fault Discrimina- tion							x				x	x		
5). Improved AC Switchgear#							x				x	x		
6). Improved Voltage Regula- tion			x				x				x	x	x	
7). Modular Substation Design#											x	x	x	
8). Reduction of substation EMI						x	x				x	x		
9). Speed upgrading of Sig- nal and Communication Equipment*#							x				x			
10). Signal and Communication Interference Limits#						x	x				x	x		
11). Application of Fiber Optics in Signalling and Communication#											x	x	x	x

* Currently Government Funded R&D
Currently Industry Funded R&D

TABLE 5-2 - R&D AREAS IMPACTED BY PROJECTS AND STUDIES IN CATENARY TECHNOLOGY

Potential R&D Studies, Projects, and Programs	R&D AREA													
	Near Term					Mid Term				Far Term				
	Peak Demand Reduction	Phase Bal. Improve.	Reactive Pwr. Reduction	Automated Catenary Install.	Wheel Slip Improve.	EMI	Other	Regen. Pwr. Mgmt.	Econ. Cat. Design	Pwr. Density Improve.	Other	Linear Motor Structures	DC Electric Traction	Electrification of Light Density Routes
1.) Phase Break Design#		x				x				x		x	x	
2.) Catenary Design Standards#				x		x		x		x		x		
3.) Breakaway Catenary Suspension Design								x		x		x		
4.) Evaluation of the Trolley wire con- figuration				x		x		x		x		x		
5.) Corrosion Effects of Diesel Electric Exhaust							x	x		x			x	
6.) Evaluation of Alterna- tive Conductor Mate- rials#						x		x		x		x		
7.) Evaluation of Improved Pantograph Wear Strip Materials#						x		x		x		x		
8.) Pantograph Shoe Stan- dards						x		x		x				
9.) Evaluation of servo- operated and two- tier pantographs#						x		x		x		x		
10.) Development of vandal proof insulators#						x				x				
11.) Reduction of rail bond impedance#						x				x				
12.) Development of Emer- gency Safety Standards*#						x				x				

* Currently Government Funded R&D

Currently Industry Funded R&D

TABLE 5-3 - R&D AREAS IMPACTED BY PROJECTS AND STUDIES IN LOCOMOTIVE TECHNOLOGY

Potential R&D Studies, Projects, and Programs	R&D AREA													
	Near Term						Mid Term				Far Term			
	Peak Demand Reduction	Phase Bal. Improve.	Reactive Pwr. Reduction	Automated Catenary Install.	Wheel Slip Improve.	EMI	Other	Regen. Pwr. Mgmt.	Econ. Cat. Design	Pwr. Density Improve.	Other	Linear Motor and Brakes	DC Electric Traction	Electrification of Light Density Routes
1.) Diesel Electric to Electric Conversion							x							x
2.) Hybrid Locomotives							x			x				x
3.) On-board Battery Power														x
4.) AC Traction Motor Development*#	x	x	x		x	x	x	x		x	x		x	
5.) Electric Traction Test Facility*	x	x	x	x	x	x	x	x	x	x	x	x	x	x
6.) Evaluation of Traction Motor Suspension Concepts*#					x		x			x	x	x		
7.) Improved Performance and Reliability of the DC Traction Motor Systems#	x		x		x	x	x			x	x			
8.) Linear Motor Development*												x		x
9.) Development of Harmonic Filter Systems			x				x	x			x			
10.) Development of Variable Frequency Power Control*#	x	x	x		x	x	x	x		x	x		x	
11.) Transformer Coolant Alternatives*#								x						
12.) Wheel Slip Sensors#					x		x			x	x		x	
13.) Skid Bar Insulation and Rooftop Safety Standards								x			x			
14.) M.U. and Multiple Loco. Connections and Controls#								x			x		x	
15.) Modular Controls								x			x			
16.) Development of Auxiliary Power*#								x			x		x	

* Currently Government Funded R&D
Currently Industry Funded R&D

TABLE 5-4 - DEVELOPMENT OF A VARIABLE VOLTAGE/VARIABLE FREQUENCY POWER CONDITIONER

Proposal - To provide large starting torques with ac motors, variable frequency power as required. The equipment for converting wayside power on-board at the level required for freight service requires considerable development. Further incentive for developing a VV/VFPCU include the increased capability for controlling wheel slip and the capability for producing regenerated power of a quality that can be returned to the utility grid.*

*[Note that development of suitable ac traction motor, not included in this program, must also be completed in order to realize these gains.]

R&D Cost - The development, test, and prototype testing is estimated to cost \$1.5 M.

Savings in Cost - The successful development of a VV/VFPCU is estimated to provide the following benefits for the R&D areas affected in Table 5-1.

	Estimated Benefit of this R&D (\$M)	Total Area Benefit (\$M)
Wheel Slip Improvement	20	350
EMI (Variable Frequency will increase interference)	(3)	(100)
Regenerative Power Management	5	250
Power Density Improvement	1	125

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Electrification can be implemented in the U.S. immediately by the application of existing technology - i.e. R&D is not required for successful implementation. No technological breakthroughs are foreseen which would render an electrification system based on existing technology obsolete. The question is therefore asked, "Do we really need further R&D?" This report has concluded that the successful completion of selected R&D can result in significant savings in costs, both capital and operating, and that the savings is sufficient to justify the R&D. For the 8500 mile scenario analyzed in this report, a savings in excess of \$1B is accrued during the ten year installation period by the implementation of the near-term and mid-term R&D described herein. During the installation period of the scenario analyzed, electrification related costs are \$7B capital costs and \$7B operating costs. Additional savings would accrue over the lifetime of the equipment through reduced operating costs.

Far-term R&D is identified that addresses potential limitations to expansion of service using existing electrification technology. For lines where traffic density grows substantially, adhesion limitations and utility unbalance limitations may be sufficient to make competitive the technology that results from far-term R&D. Likewise, extension of electrification to lighter density lines will be possible if far-term R&D is successful.

The decision to implement these far-term solutions or other solutions will occur before the technological limitations demand it, just as conversion from diesel to electric operation will occur before diesel fuel becomes unavailable. The decision, as with near- and mid-term R&D results, becomes an economic tradeoff in which the transition from existing equipment to new equipment is made with minimal retirement and retrofit of existing equipment. Such is the case with the changes identified by the far-term R&D of this report.

6.2 RECOMMENDATIONS

The state-of-the-art in electrification is continually changing and advancing in those countries where railroad electrification is a national commitment. As electrification planning and implementation is just beginning in the U.S., the changes can be expected to be even more rapid. It is recommended that this report be periodically reviewed and updated based on technological improvements being implemented.

This report is intended to be a planning document for formulating R&D plans and determining the value of specific R&D studies; it does not formulate R&D programs. FRA should proceed with formulation of electrification R&D programs in those areas identified by this report.

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APPENDIX A - WORKSHOP SUMMARIES

A series of workshops were held by the Office of Research and Development, FRA with representatives from the railroads and the architectural/engineering firms and manufacturers with experience or interest in railroad electrification. These meetings were held to assess the state-of-the-art and necessity for research and development prior to and during conversion from diesel to electric operation. Included in this appendix are the minutes of three such meetings. The first, held October 29, 1975, was attended by interested manufacturing firms. The second, held November 4, 1975, was attended by interested A&E firms. The third, held March 30, 1976, was attended by interested railroad officials. A list of attendees for each is presented prior to the minutes of the respective meetings. The agenda for each was equipment oriented, covering sequentially the items listed in Table A-1. Bracketed numbers indicate statements of individual attendees. Names have purposely been deleted.

TABLE A-1 - WORKSHOP AGENDA

1. Utility Plant
2. Substations
3. Catenary
4. Signal & Communication
5. Shops
6. Yards
7. Locomotives
8. Multiple Unit (MU) Cars
9. Civil Engineering Changes
10. Design

TABLE A-2

ATTENDEES - R&D ELECTRIFICATION MEETING AT FRA, OCTOBER 29, 1975

Matthew Guarino, Jr. (Chairman)	DOT/FRA
A. N. Addie	General Motors
Charles Beeley	General Motors
Jack Cunningham	General Railway Signal Company
K. H. Fraelich	Westinghouse
S. G. Hamilton	General Electric
Neubar Kamalian	FRA
R. M. Korow	United States Steel
A. Kusko	Alexander Kusko, Inc.
R. R. Lewis	Westinghouse
J. F. Mullervy	Westinghouse
Vilas Nene	Mitre
Richard Novotny	FRA
Eric Olson	ASEA
Frank L. Raposa	DOT/TSC
Clement Skalski	Mitre
Curt Spenny	DOT/TSC
Donald E. Stark	United States Steel
Carl Swanson	Mitre

MINUTES - OCTOBER 29, 1975 MEETING

Utility Plant and Substations (No. 1 and 2 on list in Table A-1)

- (1) Availability of electric power in United States is not a national problem, but may be a local problem in some regions.
- (2) From experience in Sweden, there should be no risk for lack of electric power in United States. With 90% electrification, railroads represent only 2-3% of the total load in Sweden.
- (3) Utilities are concerned about single-phase load. Limits are set by voltage unbalance and negative-sequence generator current.
- (4) Sweden and parts of Europe use dedicated 1-phase systems fed by special generation and converter stations. Converters: 3-phase to 1-phase; 12 pole motor to 4 pole generator; 50 to 16 2/3 Hz. France uses dc power; 50 Hz power fed from network with Scott T transformers. U. S. should look into what others have done, such as in France on network supply.
- (5) AEG in Germany has looked at electronic switching from 1-phase to 3-phase to balance the phases.
- (6) Maximum negative sequence tolerance from single-phase load set by generating plants in utility systems.
- (7) In Russia, transmission lines are sometimes built along railroads to serve electrification and to provide power to other industrial loads that build up along the route. Tends to aid balancing.
- (8) For the 44 substations in the NEC, the average utility connection cost is \$600,000 for 115kV, and more for 230kV. It may be more economical to extend service circuits parallel to the R/W, and reduce the number of connections.
- (9) Catenary per-mile resistance at 60 Hz is considerable, typically three times the resistance. Studies may show that there is an optimum frequency. In any case, 60 Hz will be used because of availability.

- (10) Problems as the frequency is raised include reactance, voltage drop, inductive coupling to wayside.
- (11) There is not much value in R&D on selection of alternative frequencies. Frequencies other than 60 Hz offer no significant advantages.

Locomotives (No. 7 on list in Table A-1)

- (1) Reasonable to assume that locomotives will be used primarily for freight traffic. Passengers will be carried in MU cars, and some locomotive drawn trains.
- (2) Swedish experience with electric motors is that the designs should be new. Use experience, but not designs, from diesel-electric locomotives. Important for U. S. to look at European and other experience on electric locomotives. Higher hp/T with electrics. With catenary on the power source, the electric locomotive can be built with heavier, higher-hp traction motors than the diesel. All European railroads use fully suspended, not axle hung motors. Traction motors rated up to 100kW cont. are built in Europe. Largest electric locomotive in continuous service, German & Swiss builders, is the B0-B0-B0-8000 hp. On motor mounting, optimization is required between maintenance cost of track and both capital and maintenance cost of locomotives. British Rail studies 15 years ago concluded that fully suspended traction motors were required to accommodate to the track.
- (3) How does the space available on the truck limit the rating of the traction motor with ASEA designs? With special insulation and cooling, the present 1000kW rating can rise to 1500 kW, and higher. ASEA is promoting dc motors as the optimum for traction.
- (4) Status of ac traction motors. All locomotive manufacturers support the use of dc motors. Locomotives with squirrel cage motors are few. No railroad is using them yet on a permanent basis. There are theoretical plus and minus factors. The ac motor provides more iron and copper active material between wheels than the dc motor.
- (5) Compared to Europe, U.S. railroads employ drag operation on the ruling grade. The locomotive effort is limited by traction force, set by adhesion, weight, grade, rather than hp rating. Speed is typically 11-13 mi/h on steep grades. For example, Cajon is a 1.7% grade for 31 miles. Space between the wheels and the size of the wheels limits motor size. Unless the railroads decide to increase the freight speed, they do not need sprung motors. European railroads operate with lighter trains and shorter grades.

The locomotives depend upon adhesion for acceleration. If U.S. locomotive loses adhesion, the train stops on the grade. If a European locomotive loses adhesion, it only reduces acceleration. European railroads operate mixed traffic, passenger and freight trains. The speed of freight is increased to match passenger trains.

- (6) Data from Russia: adhesion limits of 0.2 to 0.6 at various points along the track. Railroads there use the lower limit of adhesion with the older traction motors. New motors provide better torque-speed characteristics so that the adhesion level can be raised. Major effort in Russia on 3-phase ac traction motors to achieve higher adhesion limits.
- (7) ASEA feels that the size (rating) of the traction motor has many aspects. ASEA agrees with EMD that all requirements must be considered and that the largest motor may not be the most suitable. As a result of upgrading the Northeast Corridor, the track will be better. The trains must go faster in the Corridor to compete with vehicle traffic. Individual wheel-adhesion control is needed for high speed.
- (8) In an ac traction motor (induction or synchronous), the commutation process is transferred from the commutator on a dc-motor electric locomotive, to a black box. Thyristor voltage control plus separately-excited operation can provide better adhesion control. No argument to achieve better adhesion on the technical, but on economical grounds.
- (9) Ac traction motors can perform as well as dc traction motors. No changes will occur for at least 5 years.
- (10) Russians claim that 30 locomotives with ac motors are being built. Russia has government financed system, inferring that the locomotives may not be the economic solution. EMD studies ac motors in detail. They perform almost as well in lab as dc motors. No great advantage is seen. Enormous cost is required to change to ac motors. Must retool an industry already set up for dc motor production. No impetus from the market for ac motors. The inverter-ac motor system is a more complex animal and less reliable.
- (11) The separately excited motor is an economic problem. Wire and cabling is expensive for six sets of field windings and field supplies compared to that for series motors. Three or six thyristor converters (rectifiers) are needed for the field supplies. EMD is building a 10,000 hp electric locomotive with separately excited ASEA motors. The 6000 hp locomotive was built with EMD motors wound for separate excitation. It is obvious now that it costs more to use separate excitation. EMD has not tested the advantages.

- (12) ASEA introduced separately-excited motors 15 years ago. Swedish Railway tested them in the RC type locomotive. Since then 200 locomotives have been delivered with separately excited motors. ASEA concludes that based on their good experience, this is the right way to go. ASEA is waiting for the results of EMD comparison tests.
- (13) R&D should be addressed to series and separately excited motors to define the differences. EMD does not have evaluations of the two at the same axle loadings. EMD has data on one type and ASEA on the other. The characteristics of the series motor can be duplicated from the separately excited.
- (14) To make comparisons, the Russians built locomotives which used different-type motors on different axles of the same locomotive.
- (15) In discussing MU cars, one must distinguish between ac catenary and dc third-rail propelled cars. On MU cars equipped with choppers, ASEA uses separately excited motors.
- (16) The Helsinki subways operate with separate excitation. They are now experimenting with 3-phase motors.
- (17) The propulsion equipment by ASEA for the Stockholm commuter line is the same as the RC type locomotive with separately suspended, separately excited motors on every other axle. Stockholm subway uses choppers and separately excited motors for 650 V dc operation. ASEA only builds series dc motors for spare parts. All new projects for MU cars and subways use dc choppers.
- (18) ASEA customers generally have had good experience on adhesion with separately excited motors.
- (19) MU cars are not adhesion limited on acceleration but may be limited on braking with series motors. Might not have the same problem with locomotives.
- (20) The choppers in U.S. use series motors for their total advantage. In a few years there will be experience with both types of motors.
- (21) A formal report was prepared on the induction-motor inverter system built by Reliance and WABCO for Cleveland.
- (22) Westinghouse has an ac drive system, but there is much work yet to be done. Inverter-ac motor propulsion systems are 10 years in the future.

- (23) MU cars operate on railroads under ac catenaries vs. MU cars operate from third-rail 600 V dc power. Confine our discussion to MU cars on ac catenary systems. Cleveland CTS operates from a 600 V dc catenary. We will not consider subways today.
- (24) Much R&D is required on the overall inverter-ac motor system.
- (25) Much R&D is required on the overall system including the wayside, e.g., on the signaling, etc.
- (26) R&D required on the motor suspension vs. the track construction.
- (27) On MU cars, R&D is needed on the failures and problems of the auxiliaries, not the traction motors. This includes development of solid state inverters to supply hotel services. Also, R&D is needed on annunciators to tell whether the car has failed. Auxiliary power inverters of about 20kW to replace M/A sets will provide a development start on the ac propulsion system. A lumpy third rail will produce effects on an ac system. The revamped Metroliner will have an advanced monitoring system. Modern systems will fail; they must be annunciated.
- (28) If Europeans can build a price attractive ac locomotive, they can sell it in the United States. Diesel-hydraulic locomotive episode is an example of sale in the U. S. of a European locomotive.
- (29) U.S. railroad will require very high tractive effort; the dc motor will outshine the ac motor.
- (30) ASEA has carried out studies on ac systems. Minuses exceed the pluses. From a marketing aspect, ASEA sees the ac system in maybe 10 to 15 years, because of tooling and environmental problems.
- (31) Thyristors cannot do the ac propulsion job yet, of the state-of-the-art as applied to the railroads. There are 800 car sets of choppers throughout the world. Work is still needed on protection and application of thyristors in a tough environment.
- (32) After diodes of sufficient current and voltage characteristics became available, it took 5 years to apply them to the locomotive ac generator. There were many failures.
- (33) The rectifier interface at locomotive causes harmonic interference and EMI. It can also cause circulating currents in rails due to residual unbalance. How much filter you provide on the locomotive is an economic question. R&D is needed on EMI and filters.

- (34) Depending upon whether the propulsion system uses ac or dc motors, regeneration capability requires a different interface with the 1-phase catenary and the utility system. AC and dc motors feed different waveforms back to utility.
- (35) Work is required on high speed passenger locomotive and MU cars on auxiliaries and monitoring. Can always work on the motors; insulation not yet all Class H. Power conditioning work is required. AC systems still a cost problem.
- (36) Thyristors now make possible the use of ac traction motors. With continuing improvement of power conditioners, the ac system may come along.
- (37) Work should be done on the power conditioners (inverters). Up to 200 kVA of inverter capability for auxiliaries can be a start.
- (38) Is there an incentive for ac propulsion systems for high-speed passenger locomotives and MU cars? Axle hung ac motors of lighter weight may be an advantage.
- (39) Question of use of PCB impregnants in transformers and other rail-road equipment. EPA is looking at penalties. PCB is prohibited in Switzerland. Sweden allows it only in high-voltage capacitors. ASEA cannot fill the transformers in Sweden. Must be filled in Germany. Silicone oil is a good alternative. It has the same fire behavior as PCB and is environmentally safe. PCB can burn and explode as well. Germany is sharpening its objection to PCB. Japan bars it. The combination of high voltage and limited space favors oil filled transformers.

Just the waste water from washing hands of workers will meet the EPA limit. EPA will take a strong standpoint at the factory. Burpers on the Metroliner transformers put out more PCB than the limit. The use of equipment at 60 Hz will reduce the size and make alternatives possible on-board, such as dry-type transformers. The combination of high voltage and limited space favors oiled filled transformers.

- (40) In the U. S., axle hung motors are used for every class of service, including freight. Advantages are low first cost and not affecting U. S. track structure. In the world market, there is a different opinion, Very high tractive efforts are required in the U. S. for long heavy trains. Motors operate uniquely in high tractive effort at low speed. With Truck-hung motors, a transmission must be used to get the tractive effort at the wheels. GE builds truck-hung motors for the transit industry. They are built for the export business to meet the requirement for low axle weights.

- (41) The cost of railroad electrification includes the cost of the wire (catenary), plus locomotives, plus all else. Since 1890 GE has been in the electrification business. In 1968, GE built the 25 kV Muskingham locomotive with new technology such as thyristors and vacuum breakers. In 1969-1970, GE developed a new locomotive, the 50 kV Black Mesa. It was successful; more were ordered.

In electric locomotive business around the world, only one tender was available in the world in 3 years in Taiwan. GE got the order against the world competition. A German consultant acted for Taiwan. GE competed against truck-hung motor vendors. It is difficult for GE and EMD to compete with countries that have house companies, such as France, Germany and Sweden. They can bid in the third world market. On diesels, 90% are GE and EMD around the world. In South America, there are 3000 V dc systems.

- (42) Comparing railroad operations in Europe vs. U.S., the unions in the U. S. require change in crews every 150 miles. Crew costs are important. The answer is to lengthen the train and drag down the speed on the ruling grade. U. S. freight operation serves a bulk haul market. European railroads run goods trains.
- (43) R&D can have an effect on labor relations.
- (44) If the union agreed to a work rule change, the railroads would probably run more trains of less cars with the same total number of workers.
- (45) In the U. S., freight runs up to 2000 miles occur. Nothing as long in Europe. Union Pacific runs 70 mi/h freight. The increase of speed from 30 mi/h to 70 mi/h adds 10 to 15% in energy.
- (46) To run higher speed in the U. S., the railroads must change the loading, use lighter locomotives, lighter trains, up-grade the track and track maintenance. Result will be increased energy use.
- (47) There is a market for high-speed piggy-back freight equipment.
- (48) Burlington Northern operates a coal train of 100 T cars at 40 mi/h top speed. They use 6 to 7 - 3000-hp 6-axle locomotives for the 14,000 T train. Slave locomotive units in the train to reduce stress on couplers are controlled with radio.
- (49) No technical problem on braking. Diesels use dynamic braking. U. S. practice is to use air brakes on cars, electric braking on locomotives. Air brakes are good for slow-speed freight operation. Regenerative electric locomotives are no problem. Problem is that there may be no use for the energy.

- (50) Possible fruitful application of electromagnetic brakes at high speed.
- (51) Question of linear braking applied to the rail is being addressed in Europe by Siemens.

Rail expansion problem from the heat. High electrical energy is required for brake windings. How do you get electric power on the freight cars? Rail currents can interfere with signaling systems. Need survey of what has been done.

- (52) Speed of response for pneumatic brakes on a long train is a problem. Condition of track is a factor in braking.
- (53) Dynamic braking is already developed. Regenerative braking is no challenge where it is economical. Depends on train locations with respect to each other and the substation spacings. Is there a payoff on energy? Most utilities do not want it returned to their systems.
- (54) Russians claim a saving with regeneration of 10% on energy.
- (55) In the GE experience, utilities are willing to provide power for electrification. One exception was a public authority, which was behind in generation capacity for load growth.

Pantographs - Catenaries (No. 3 on list in Table A-1)

- (1) GE has a license for the Faiveley pantograph which is good up to 200 mi/h. Way down on the limits of safe design for freight operations. Uses springing on the shoe. No problems with the pantograph. Need civil engineering work on catenaries. At 50 kV, catenary wire size is no problem; the problem is to hold the wire in the air.
- (2) For the contact strip: some use steel strip; some use carbon. The selection of material is part speed, pressure, emotion.
- (3) Wire size is set by mechanical, not electrical factors. France is trying a single wire system. Need experience in U.S.
- (4) Catenary and catenary feeds pose problems of inductive interference. Great deal of work in Europe.
- (5) Test track in Erie backs up to buildings, communications equipment houses, TV, etc. Conducted 50 kV interference tests. Inductive interference experience is varied: Britain uses booster transformer. France uses none. Various techniques are available. U. S. must study the knowledge already accumulated.

- (6) GE had one case at 50 kV where dense train situation made electrical rather than mechanical requirements control the catenary design.
- (7) In France, 70 mi/h on a single wire.
- (8) Penn Central - highest reach in the world with a single pantograph. Metroliner operates the pantograph at the highest speed. (Qualified at 150 mi/h). The one stage is relatively economical.
- (9) New U.S. electrification construction would try to minimize the variation of catenary height. High speed operation might need a two-stage pantograph. For high-speed passenger service, the Metroliner-style pantograph could be used.
- (10) Bad wear rates are seen under certain conditions on the Metroliner. May be problems on 14-mile headway.
- (11) Metroliner pantograph has run 167 mi/h, and is qualified for 200 mi/h. Qualified for operation means that it rides acceptably on the wire.
- (12) Boissonnade developed the catenary for SNCF.
- (13) In the Midwest and far west, the pantograph will not see the same excursions as on the Penn Central (NE corridor).
- (14) Need R&D on pantographs for high-speed operations. Much work in Europe. The French pantograph uses 1/2 to 1/4 the mass of the Metroliner pantograph for a second stage.
- (15) No real experience at 150 mi/h in the NE corridor. Bechtel says that the pantograph is on the edge of performance. Faiveley pantograph is needed for so long an extension. The spacing is restricted on the supports for the catenary. Need heavy conductor for electrical requirements in the NE corridor. Operation will be below the critical speed of the catenary. Europe operates above the critical speed of the catenary. U. S. has tall freight cars which forces catenary height upward. Europeans are talking about 150 mi/h operation.
- (16) Europeans (French) say that they can operate up to 400 km/h with a passive pantograph.
- (17) Electrification for first 22,000 miles in U. S., except for 1,000 miles, will be for freight, not high-speed passenger service like the Tokkaido line. Japanese service the catenary every night.

- (18) Each railroad will be required to learn how to maintain its own pantographs depending on the severity of the service it receives. GE knows about no active pantographs.
- (19) Drag train service requires multiple locomotives operating at 65,000 lb/axle. No problem on phase breaks because only one locomotive will pass through at a time. EMD says same number of electric locomotives will be required as diesels.
- (20) Development is required to reduce insulator cost. Standard transmission line insulators are used for 50 kV. Need construction that holds wire up if the insulators are shot out. BICC uses horizontal post insulators in some tunnels to locate catenary wire close to ceiling.
- (21) EMD has a half-mile catenary of BICC design at their plant. Insulators were imported from France. Uses tension weights.

Traction Motors

- (1) AC system (inverter-ac motor) will not be economical in the foreseeable future. German company built a locomotive with one inverter for 4 or 6 motors to save cost. The system will not give the individual motor wheel-slip control. No better forward motion characteristic than the series motor for freight. AC motors will only go up to synchronous speed when they slip. Need better wheel slip characteristic for series motors. GE built the best system for wheel slip on the Black Mesa locomotive with series motors. GE does not agree that the separately excited dc motor can be forced to match the series motor.
- (2) In an ac-motor traction system, you probably want a synchronous motor rather than an induction motor.
- (3) The place for DOT is to draw on the research of over 50 to 75 years of the participating companies. Work is needed on systems that combine the best abilities of the participating companies. Industry will not research the system aspect, only their specialties.

A brand new type of electrified railroad may emerge for the future.

EMD 6000 HP Electric Locomotive

The dc traction motors for the EMD locomotive are built with laminated interpoles. A slightly modified truck is used because the motors have ball bearing mounted on the axles. Otherwise, it is the same truck as is used for the high-traction EMD passenger and high-speed freight diesel electric. Traction tests are being conducted with a test car and two diesels in dynamic braking. The motors are regular EMD motors

with rewound high-resistance fields for independent excitation. ASEA field and armature controls are used. The locomotive operates out of Harrisburg, and has had some revenue service. Maximum speed is 70 mi/h. It did 76 mi/h on Penn Central track by cutting out overspeed protection. There has been no trouble with the trucks.

Tasks for Pueblo

- (1) Industry needs a test track to test an electric locomotive in a complete wayside electric, signaling and communication system.
- (2) Test interference between the locomotive and the wayside system.
- (3) Test sections of catenary of various designs.
- (4) The results of the tests will provide industry with data so that overdesign might be avoided.
- (5) Difficult to test on a customer's railroad. The conditions cannot be controlled and the facilities are needed for regular operation.

Shops (No. 5 on list of Table A-1)

- (1) Railroads would have to make shop changes to handle new electrical components. Railroads would remove facilities for modifying engines, but would keep the same for brakes, trucks, and other standard parts.

For the GM-6, EMD required redesign to be able to drop the motor. Under the ASEA design, the shop must lift the body and lift the motor. Shop needs special equipment for larger motors. Catenary must extend into the shop.

- (2) Railroads have the shop capability today. May transfer work to back shops. Some shops are poor today; they were built for steam. Harrisburg is already an electric shop. Shop at Dale St., St. Paul, MN, would need extensive work for electric locomotives.
- (3) Testing equipment will be required for solid state equipment. Railroads now replace diodes on failed basis. EMD supplies testers for PC boards, but cycles them back for repair. For the GM-6, EMD did not test the solid state devices that were previously tested at ASEA. First tests were made after installation.
- (4) EMD facility for module-building is only about three times the size of the conference room. Need intensive personnel training. A U. S. railroad would have to face maintenance for a 600-800 electric locomotive fleet. Penn Central went back to manufacturers on the electrics for some work, but do their own motor work. Manufacturers would maintain large components on a unit-exchange basis, as they do for diesels.

- (5) Railroads do a qualification test on components on diesels. Re-education will be required of maintenance personnel, such as occurred during steam to diesel change in 1945 to 1955. For a new electrification the railroad would erect the catenary and start operation at one time on the line. A U. S. railroad never will become 100% electrified. Same maintenance will be required on diesel electrics. Routine inspections will be the same. May need work on effect of diesels operating under catenaries.
- (6) Effect on maintenance-of-way equipment will be considerable. Contact shoes must be replaced for as low as 4000 miles of operation. The two pantographs on each locomotive provide redundancy. Diesels are inspected once per month by law. Equipment must include work and test cars for an electric railroad.

Yards (No. 6 on Table A-1)

- (1) Railroads will not electrify the yards. They will use diesel switchers. Considerable sections of Philadelphia, Enola, and Trenton yards are partially electrified. Penn Central would probably not do it all over again. On vans trains (Piggy-back) on Penn Central they do not change over from diesel to electric. In the Enola classification yard, 95% is not being run with electrics.
- (2) Hybrid locomotives are compromises. Each type, electric or diesel, is already packed with equipment. The FL-9 locomotive is a hybrid to get into Grand Central on the 600 V dc third rail.
- (3) Interference has occurred between high-voltage power lines crossing yards and train control circuits (wheel detectors).
- (4) A case occurred outside U. S. of a 3-phase power line paralleling the railroad. The line was changed from delta to grounded wye. Unsafe failures occurred of track detection circuits from power-line caused rail currents. It could have been avoided, if the railroad had been told in advance.

Signaling (No. 4 on list in Table A-1)

- (1) EMI problems with electrification will require upgrading the signaling systems.
- (2) Types of systems: Signal injected in track at one location and detected a few thousand feet away. Absence of signal means train in section or fault in rail. Use insulated joints. Pair of autotransformers on both sides of the joints provide an electric path, impedance bonds. Autotransformers are now epoxy filled and weigh less than 100 lb. They may have extra windings for signal injection. Operate on basis that propulsion current is in the same

direction in both rails, but opposite in signal paths. They also detect a failed insulated joint. Signal may be continuous or keyed, ac or dc. DC signals are not used in ac electrification. AC signals use a different frequency than power, for 25 Hz power use 60 Hz signal; for 60 Hz power use 100 Hz signal. Must shorten signal loops as the frequency is raised. Operation is vulnerable to the weather, because of leakage currents from rails and unbalance.

- (3) Communication people can do much to reduce EMI. In 1918-1919, California Railroad Commission published the first quantitative analysis of EMI. Twisting of signal conductors can help, but the track and catenary conductors cannot be twisted. Must work on the susceptible circuits. Interference depends on length of exposure and spacing between signal conductors, but still have a common mode voltage to ground EMI suppression. Must be designed for worst case, say fault in the catenary, before the breaker clears. EMI reduction includes putting signal circuits in cable, twisting, shielding. Degree at cost trade off. Woodbridge & Klewe, British Railways, did work 15 years ago on an isolated section.
- (4) Standard practices established between Bell Telephone and EEI. New paper was approved at the September AAR Meeting, Signal & Communication Section. Another source of standard practices is the CCITT International Directives published by UN, Geneva.
- (5) If propulsion current in tracks divides equally as forced by the autotransformers, there still may be ballast leakage, unbalance in impedance bonds. Also coupling to signal circuits from catenary and adjacent tracks. There is always unbalance. The track signals must be at a higher level than interference.
- (6) R&D should include consideration of economics. Alternator-rectifier-dc motor locomotive on the SP introduced false signals in the ATO overlay currents, from circulating current in the frame of the locomotive. Penn Central experienced disturbance from a loop in the return cable from motor to the frame which wiped out the cab signals.
- (7) Vital circuits are vulnerable to interference from electric locomotives. In case of short circuits, open circuit, or hardware failures, the vital circuit should fail safe. Solid-state sensors for coded signals are subject to interference.
- (8) Technology exists to handle electrification, but it needs integration. Failure may be too frequent with solid state equipment.
- (9) Recommended tests at Pueblo: use two systems of power, ac and dc. Set up typical test loops of 6000-8000 ft. length circuits.

Railroads sometime want to raise loops to 13,000 ft. The interference must be tested to maximum capability.

- (10) Testing must be done to establish the levels of susceptibility of the signal and communication system, and the influence of the interfering source. Characteristics of the interfering signal determines the degree of influence. A field of study is the integration of the best of all of the companies techniques and equipment.

- (11) Results of the work may be a set of Standards.

Standards would be helpful to establish the degree of filtering required on locomotives, pickup cable signal levels on the train and MU cars. Standards could be a joint activity. Monitor the signal first that the locomotive puts out. Presently do not have a facility to do this.

- (12) DC choppers on dc system are a recent problem. Railroads do not want to use harmonics of the supply line frequency for signaling. How good a filter is needed for non-harmonics? For example, the frequency 6030 Hz is non-harmonic, but has narrow separation from 6060 and 6000 Hz. Another problem is that the high-Q filter will have ring-up time and ring-from noise. Industry needs quantitative data.

- (13) For coordination with railroads on interference see Electrical Interference Committee of AAR, Chairman, Archer of IC-Gulf. AREA (Civil Engineer of AAR). Committee on Electrification, Chairman, Cogswell.

- (14) The technology is available, but some consideration should be given to reduce the cost of implementation of signaling. Consider conversion of a diesel railroad to electric. A high-volume railroad will use dc coded track circuits to communicate from one section to the next. In order to convert to ac track circuits, need ac power, need compatible detectors. Common detector for 25 Hz signals is a 2-phase induction motor. One signal is taken from the supply line, one from the track. Needs maintenance. Flyballs go out and actuate the contacts. Runs too slowly or tries to run backward (has ratchet) in response to interference and broken insulators. Need 2.5 to 1 displacement for discrimination. 100 Hz is not too bad for 60 Hz electrification. Now use phase-selective circuits on the New Haven, in Turkey, with static devices, including rectifiers, transformers, relay.

- (15) Has been some work on other methods of signaling, such as ultrasonic. There are problems of joints, noise, etc. Present track circuit checks the circuit electrically and checks the roadbed most of the time. False alarms are always a problem. The level must always be high enough for good reliable operation. With too high a level the signal may jump a broken rail.
- (16) British Rail estimates 20% of cost for electrification for signaling.
Must separate out the cost for upgrading from electrification to get the true cost.
- (17) Booster transformers as used by the British and Russians must be checked against the other methods of suppression.
It is best to keep the currents in the rails, rather than in parallel paths.
- (18) Can get cancellation of 40 to 50 db in twisted pairs over parallel conductors. Mumetal shield is 90% effective, but depends upon the grounding. It is expensive to ground frequently. Cable in trench with bare conductors on top provide 25% suppression.
- (19) Problem of solid-state equipment is that it must be protected against lightning. AAR requires protection for 3 kV surges.
- (20) Summary: Noise sources must be quantified by signal level over the frequency range of the signaling. Signaling systems must be tested for susceptance over the frequency spectrum and amplitude range.

TABLE A-3

ATTENDEES R&D ELECTRIFICATION MEETING AT FRA
NOVEMBER 4, 1975

Matthew Guarino, Jr. (Chairman)	DOT/FRA
Keith Chirgwin	Garrett AiResearch
E. P. Foley	Gibbs & Hill
M. Clifford Gannett	DOT/FRA
F. D. Houser	Transportation Research Board
A. Kusko	Alexander Kusko, Inc.
Charles Miller	Bechtel, Inc.
V. D. Nene	Mitre
Frank L. Raposa	DOT/TSC
Blair Ross	American Electric Power
Peter Shaw	Electrak, Inc.
Clement Skalski	Mitre
R. T. Spada	Laramour Douglas Popham
Curt Spenny	DOT/TSC
Carl Swanson	Mitre
Kenneth Thompson	Garrett AiResearch
R. A. Uher	Carnegie Mellon University
Phillip F. Valence	A. D. Little, Inc.
Raymond Wlodyka	DOT/TSC

MINUTES - NOVEMBER 4, 1975 MEETING

Utility Plant

Area defined as extending up to the substations that feed the catenary directly, or feed dedicated transmission lines or feeders on the R/W.

- (1) Little R&D is necessary or required in the area of the utility plant on the primary side of the substations. Principal problems are: impact of negative sequence current and voltage unbalance from 1-phase loading. This was well researched and documented in the period 1910 to 1920. Ability of motors and 3-phase apparatus to withstand unbalance varies from device to device. Standard methods of testing could be set up on effects of unbalance, and data collected in foreign countries on their work. U. S. manufacturers would not stand behind standards based only on foreign experience. Other problems include harmonics, telephone, and radio-TV interference. These have been well researched. Loads which generate harmonics occur in the mining industry, served by the utilities. Research has been done on harmonics and interference done. Utilities recognize the effects of negative sequence generator currents in amortisseur winding and end-turn heating. Utility problems are engineering - economic type, rather than technological.
- (2) DC power for railroad lines can be provided by converters that reflect a balanced 3-phase load to the utility. Questions still remain of what types of harmonics are tolerable with thyristor or diode converters. What filters should be used? To supply 1-phase railroad load from weak utility systems, conversion from 3-phase to dc, then to 1-phase power can be used. Swedish railroads use 3-phase to 1-phase motor-generator sets on weak systems. R&D is needed to avoid heavy transmission lines parallel to the R/W. For example, in the area of Lincoln, Nebraska, to Alliance a new transmission system is required. U. S. has the technical capability to build such a station, 60 to 60 Hz rotating, or solid-state, using blocks of known components.
- (3) AEG (Germany) is developing an electronic switching system to distribute 1-phase load to 3 phases.
- (4) Why does the railroad industry not use 34 kV or 69 kV, which are standard utility voltages, instead of 25 kV or 50 kV?

- (5) Because of frequent faults on railroad, utility would not want to feed catenary from subtransmission facilities, but would want a transformer for a buffer.
- (6) DC transmission lines are at too high a voltage to be tapped for railroad service.
- (7) High voltage dc catenaries have been looked at. Locomotive manufacturers will not commit themselves to build a suitable locomotive. It is difficult to convert 50 kW downward on a locomotive.
- (8) DC is economical; can achieve four times the 1-phase ac substation spacing. There is a push to solid state in rolling stock, but no inverter that is reliable enough to put in a locomotive to operate from 25 kV by 1990. Answer is not obvious yet of ac vs dc for the catenary.
- (9) Railroad would possibly be penalized (surcharge) for 1-phase load taken from utilities. Some federal and state agencies believe that a surcharge is justified. No idea of the charge. It depends on the utility. A charge is made even with the utility plant in place. Where reinforcement is required, the railroad would have to pay for some or all of the cost. The charge would be reduced as the non-railroad load on the reinforced lines built up.
- (10) Penalty in efficiency of 3 to 4% in double conversion of 3-phase-dc-1-phase. It may be worthwhile as a tradeoff to reduce system reinforcement for 1-phase load. No transmission lines in west where electrification is being studied.
- (11) No overall standards on 1-phase load yet. Utility variation on standards. On the AEP system, 1-phase induction furnaces, welding loads require reinforcement. There are standards on harmonics; TIF is spelled out. Standards are used by the Bell vs utility lawyers.
- (12) Two problems are harmonics and unbalance. Harmonics are produced by thyristors on railroads. The standards need updating. Harmonics are also fed back by industrial loads. They constitute a slipping virus on a weak system. If harmonics are not drained by system capacitance, they can cause trouble.

Neither harmonic nor unbalance problems justify R&D expenditure, except in specific cases for weak systems.

Isolating converter stations are a low priority on R&D.

R&D may be needed to avoid over design.

Conversion equipment design is an economic problem.

Arc furnace loads are handled on the AEP system.

- (13) Need rates to start to study economics of electrification. Try EEI first. Wide variation depending upon utility.

Burlington and Santa Fe got rates quoted to them.

Con Edison rates for 1-phase 25 Hz power up to 13 ¢/kWh
Connecticut DOT has developed rates for 12 kV, 60 Hz, power including facilities.

Railroads can't qualify under any of the 5 tariffs; they are a special case. Minor chance that they can be served under heavy industrial tariff.

CL&P owns substations. New York MTA owns substations. Rates depend on ownership.

It would be good to try to get agreement on rates for all railroad applications.

- (14) Comparison between tapping the utility or building a dedicated way-side system. Tap if the utility has the short-circuit kVA. Voltage, 138 kV and higher. Need a dense grid for enough tapping points. Dedicated transmission lines are a waste of money. In the western states, the grid density is too low. Study should be made to see if any new lines can also serve the growth of utility loads, say 1980-85-90, in addition to their railroad function.

In Russia, new transmission lines for railroads in low density areas encouraged the development of industries. Same in India and China; railroad lines served local loads.

Should have serious overall planning of transmission lines into the overall economic development of region.

- (15) Preference to take loads from higher voltages, e.g., tap from 138 kV.

Utilities are willing sometimes to provide load from 69 kV, 34.5 kV, subtransmission. Run transmission lines along available railroad R/W. Use same poles. Chicago South Shore is an example.

- (16) Buy transmission-line R/W easement along the railroad, such as in the middle west. Save money by building H frame or wood pole transmission line and separate catenary. It will be cheaper than combined structures. The transmission line can have much longer

spans. Catenary structures known to fail. Voltages of 69 kV maybe, or 138 kV.

German state railway runs 110 kV, 16 2/3 Hz on common towers.

In mountains they use separate transmission line towers.

Trouble with Indians in getting R/W in the west.

- (17) Regeneration from locomotives; no credit from utilities; there may be a penalty. The current waveform is poor, because of the solid state converters. Solid state steel mill drive doesn't regenerate. M-G sets tended to regenerate, but receive no credit. Large drag lines may regenerate. Customers are charged because regeneration raises the voltage, producing a greater dip effect. Utilities could absorb the power; it depends on the strength of the utility. For metering at substations, the utility will ratchet the meters.
- (18) In the west, contracts are required with each utility property. Can deal with REA central office. Also depends upon the relationship between Public Power Districts and Coops. Depends on states. Rural Coops have bulk power purchase agreements with private or public companies.
- (19) Supply stations to a railroad could be located 40-50 miles apart. Railroad could use line along own R/W without individual agreements with intervening utilities.
- (20) National effort to set rates a waste of time. Two private companies cannot quote a joint rate. Problem in SEC and legal area, rather than in engineering.
- (21) \$1/3 to \$2 million for utility connection.

Upper number is too low. Some state public utility commissions require that the customer pay all of the incremental cost of the power plant, transmission reinforcement, and full price for extensions. New customers are not entitled to grow at the expense of existing plant. Commissions favor the residential customer. The charge to the railroads could be \$700/kW for the full 20,000 kW of a substation, compared to an average of \$200/kW over the system. Tapping fee only from the connection point. Arizona has done it. For clarification, approach FPC, EEI, REA, American Public Power Associates, NRECA .

- (22) Perhaps an article should be written in IEEE publication on rate structure problems for railroads.

Recorded personal instances of actual problems in Nebraska, Iowa, by the Burlington Northern.

Other railroads can furnish experiences.

Substations

- (1) Technology is good; little R&D is needed. The use of standard transformers needs investigation, because of the duty cycle load. Railroad transformers are made different than utility transformers. The core and coil bracing is for more severe service, such as close-in short circuits. Don't believe in special equipment, but duty is more severe.
- (2) Some debate on value of solid state relaying. Most people have gone over to it, if only to eliminate the effect of dust.
- (3) Needs to be work on protection, such as on discrimination between faults and load. Problems of heavy freight trains, long catenaries, and load currents, greater than faults. Swedish railroad had trouble, but it is possible to discriminate. Trouble when a heavily loaded locomotive crosses a phase break.

- (4) Existing developments on substations. Reduced size of substations through use of SF-6.

Modular form of substations.

No R&D needed because modules exist.

Design should be done once, rather than many times.

Comes under design, rather than R&D program.

Gibbs Hill rearranges modules for each site.

- (5) No requirement for R&D on ac substations. May need R&D on dc or special converter substations.

On system studies, including economics of dc vs. ac systems read the Battelle report of the 1950's. Compared 3 kV dc to ac. It was a huge paper exercise.

- (6) British Report - came up with 3 kV dc as the wrong standard; admitted it afterwards. (Blue letter on white cover). Answer depends on when a dc system would be ready for installation.

- (7) DC distribution has advantages: unbalance missing, rid of reactive drop, substation cost/miles reduced, regeneration on vehicle less complex, inverter drive of wheels.

Hughes will sell a dc breaker.

Must project technology for dc catenary. Need solid state equipment on locomotives.

Consider insulation joints vs. impedance bonds on wayside. Inverters already tested by WABCO on CTS and Garrett in San Francisco.

Need big chopper to transform 25 kV dc to motor voltage.

- (8) Where are the costs: \$50,000/mile for catenary, \$2 - 2 1/2 M per substation. Spacing of 35 to 40 miles. 50 kV catenary. For the NE Corridor, \$600,000 for the utility connection, \$900,000/substation, 25 kV catenary, 25 mile spacing, 115 kV primary service. Utility cost increases with voltage.

Could reach the cost of installation in an undeveloped country, \$800/ to \$900/kW. Multiply 20,000 kW x unit plus catenary.

Ultimate extreme costs.

- (9) Tap changing under load not required at railroad substations, but may be required by other customers. Locomotive is designed to withstand wide voltage variations. In parts of United States, every substation has had tap changers to accommodate the voltage variations in the system. Look carefully at requirements. Load tap changers not required in their experience at Gibbs and Hill. Voltage range of +5 to -30% for locomotives.

21 to 29 kV on Russian system at catenary on 25 kV.

25 kV nominal system has 27.5 to 18.5 kV overseas, India, Great Britain, South Africa.

British report for 25 kV nom, actual 27.5 kV. Some places they use 26.25 kV nominal. Minimum 18.5 kV for nominal 27.5 kV for Great Britain. System designed to operate with one substation out in emergency. May have to reduce train performance at end of catenary.

Catenary

- (1) Bechtel study of NE corridor showed that the high speed catenary for United States is not like Europe. They are not sure the European design will work.

NE Corridor requires a large excursion pantograph to accommodate tunnels, large freight cars, etc., and to operate at 150 mi/h. Excursion in the NE Corridor is 6 to 7 ft., compared to the Tokaido line of 19 in.

- (2) Out west for slower speed freight and higher tunnels, there may be no problem with excursion. Catenary-pantograph systems for U. S. application should probably use a large spanlength for economy and a large pantograph to handle the large excursions. Pantograph-catenary systems designed for high speed usually utilize light pantographs and short spanlengths. It was stated that in England and Japan catenaries are operated through the critical speed (the speed at which serious catenary oscillations occur). Trains are run through the critical speed quickly. Vibrations are said to last for approximately 5 seconds.
- (3) Metroliner cars operate at three different points on the catenary curves as the tension varies between winter and summer. Data is available.
- (4) Heavier wire is used on the Penn Central to change the resonance.
- (5) Electrak is developing pantographs and catenaries for NE Corridor. Their concept of the design is to pull the curves down and minimize the effects of passing through the resonance zone by use of heavier conductors. Must use larger trolley wire initially to account for wear. Retain the same wire size for 25 kV as for 11 kV; the wire is not at very high tension. Design the resonance band away from the operating speed. Resonance problems are relevant to high-speed passenger service. It is not reached in slow-speed freight service. Consequence of operation at critical speed is arcing.
- (6) Burlington Northern and Santa Fe will run freight and passenger trains at same speed of 70 mi/h. Plan to run coal trains at 75 mi/h from the western mines to Chicago. Presently, there are problems of track. Trains of 110 coal cars operate in some areas at 40 mi/h. Chance of derailment is proportional to the square of speed.
- (7) As the trolley wire wears, tension decreases because of stretch. The sag varies because the weight supported by the messenger is reduced.
- (8) Divergence between the United States with little experience in catenaries and Europe with much experience. Britain favors the light catenary and pantograph which can pick up much power. United States people think they need a heavy catenary system.

- (9) Short trains operating with a single locomotive in Europe can use a single catenary conductor.

It is cheaper to use a feeder line alongside the track to support the electrical load of a single conductor catenary than carry the support on the towers. The French are working on this arrangement.

Estimated saving is 10% for a single conductor catenary. A publication cites 35% saving in the brackets and conductors, not in the poles and foundations. Poles have to be taller to carry electrical support. Germans do not include poles and foundations in the catenary cost, but put them in the civil engineering cost. One must dig deeply into cost studies.

- (10) Bechtel has looked at new catenaries for the NE Corridor, what is in place, variation of pantograph height. Freight is hauled over short distances along the Corridor. Economics dictated the present design to handle freight and passenger trains. United States designs are way down on the wire stress-strain curves. How far up can you go? Need R&D on wire loading to determine what should be used. Also need work on other problems for which there are diverse opinions.
- (11) Problem in catenary design is to identify what is needed. Each owner wants something different. European R&D is directed toward high-speed operation. Work needed on new materials for insulators, reduction of electrical clearances. R&D started in 1960's now completed. AAR clearances are based on work done elsewhere, then verified here.
- (12) There are three modes of operation for electrification: Freight; freight and passengers; passengers.

Electrification for passenger service suitable for all modes. Cost of 5% more for the catenary to run passenger and freight together. Difference of physical characteristics of railroads. NE Corridor 22 ft; 26ft in the midwest; NY tunnels 15-16 ft.

U. S. freight trains are heavily loaded. For example, on a moderate grade, 125 cars use 3-6000-hp(?) diesels, a much higher load than Europe. Operate locomotive at full throttle to accelerate out of a siding. Power requirements: acceleration, 1 1/2 hp per ton; 3 hp per ton on grade.

- (13) Concept of electrification in United States is to operate 50 to 60 mi/h up and down grades. Different than present operation with diesels, where train slows down as it climbs a grade.

Ability to accelerate is one reason to electrify.

- (14) Concept for hybrid operation is to use 4 electrics and 2 diesels. Electrify only the main lines. Use diesels as helpers to the electrics and on the unelectrified tracks. Berti, of the UP, presented the idea at a meeting in Chicago.

Another concept is to operate 1 diesel and 1 electric in a married pair. Use the motors on both locomotives on electrified sections. Electrify only the main line. Unit cost per mile of electrifying the yard is 50% more than the main line. Can eliminate yard electrification. Because of steep grades, Bessemer and Lake Erie studied the married pair concept with GE.

The married pair provides 3000 hp on the diesel motors, 6000 hp on the electric, total of 9000 hp. The use of a diesel-generator on a tender to provide supplementary power to an electric locomotive was discussed.

Electric locomotive already has adhesion problems at its horsepower. It cannot use supplemental power from another source, such as a diesel-electric locomotive. It is better to use the weight of the diesel locomotive to secure adhesion from the diesel motors, with power supplied from the electric.

- (15) Problem is to identify what is needed in this country in catenaries. For example, 100 mi/h one style; 150 mi/h with another style.

Limited research needed on interactions between pantographs and catenaries. Economics of high-speed passenger and freight service shows that there may be 25 to 30% incremental cost to be paid from passenger service. Difference ampacity tables are used for trolley conductors around the United States.

One new form of trolley wire uses extruded aluminum on a steel key to take wear. Kaiser extruded a mile at their mill about 3 years ago, but abandoned the work when they found no market.

Manufacturers of wire have no market to buy the results of R&D. Design should head for lightweight catenary, vandal proof insulators, new wire.

Where carbons are used on the pantographs, instead of steel, the steel insert may increase the wear on the carbons. Some ceramics have been tried in England and Japan. Double or triple carbon strips are used on the pantograph. They are about 1 inch thick and permit 50-year life of the trolley wire. The carbons take 10 minutes to change. They are inspected every 10 or 20 days and changed when they will not last to the next inspection.

The wear rates on the Penn Central with mixed steel and carbon shoes are 7 times greater. Steel roughens the trolley wire, and wears the carbon. Have to use all carbon, rather than mixed shoes.

- (16) The subject of phase breaks was discussed. The usual phase-break length is 15 ft. A sample of a phase-break section was passed around the room for all to inspect. It consists of a core made of fiberglass approximately $\frac{3}{8}$ on an inch in diameter. On the outside of this fiberglass core are ceramic beads approximately 1 inch in length and having an outside diameter in the order of $\frac{3}{4}$ of an inch. These appeared to have been fastened to the fiberglass using epoxy cement, etc.

Phase break must be longer than pantograph spacing with two pantographs on same locomotive. On a 100-car freight train, two locomotives would be used for redundancy. One can always be under power at a phase break.

Pantographs can be operated independently at phase breaks. One method now used in Europe is to have track magnets operate the circuit breaker on the locomotive. On grades, two adjacent substations can be supplied from the same phase to avoid power shutdown at the phase break.

- (17) Problems of catenary design:

- (a) Physical size of the catenary such as the height and span is affected by the percentage of straight track and curved track. For example, the Burlington Northern is 75% straight. Spans can range up to 300 ft.
- (b) Current capacity - some need 400 to 600 A, some 1800-2200 A. Variation of conductor size affects the size of supports. The Illinois Central Gulf needs 450 A at 50 kV. The Burlington Northern needs 1200 to 1800 A. The Corridor needs 2500 A.

Electrak experience is that the electrical requirements set the wire size.

Problem in meeting the needs of each of the railroads. Catenary design is not an R&D area, but have to collect the requirements of all the railroads.

- (18) Electric requirements are set by ampacity. Mechanical requirements are set for all weather contact. Are we overdesigning? At 70 mi/h, start with the electrical requirements. The result shows equal considerations of mechanical and electrical requirements. At 150 mi/h, the mechanical requirements override the electrical.

Signal and Communications

- (1) Regarding communications, harmonics produced by locomotives need exploration. Concerned agencies are the AAR, AREA, and AT&T.

There is a lack of standards for railroad applications. In Europe, there are no proper standards. There are international limits on noise levels for cooperation between countries. Within each country limits are set by own discretion.

International limits and standards are a starting point.

- (2) In the United States, interference has to be compensated in the communications system. It should be reduced at the source. For the locomotive manufacturer, the requirements are not clear. He has no incentive; the limits are not well known.
- (3) For communications, the railroad itself; Bell and others must determine limits. Cure interference by both the railroad approach and suppression in the telephone plant. French Postal system which operates the telephone system has done good work on interference. ASEA has done work on cleaning up the RC locomotive. Interference affects communications and signaling.
- (4) Must set interference levels that are acceptable to the railroad and Bell. The levels may not be the same. On the Penn Central, if they can use the communications system, the interference is acceptable.
- (5) In France, they switched from voice (carrier) to PCM to handle higher noise levels.
- (6) AEP and Bell frequently end up in court on interference problems.
- (7) Ideas for organizations to publish standards on interference and also to police the standards:

RFI on abutters to the railroad will come under the Federal Communication Commission.

Problems of a clean locomotive: still can be accused of interference.

The effect of a rectifier can be measured before and after installation.

International Telephone and Telegraph showing active interest in rectifier locomotive at 60 Hz.

Pueblo loop will be a good place to test interference.

Good idea to work with the Bell Labs. Bell wanted to test on AEP 50 kV railroad (Muskingham). AEP turned them down.

- (8) Talked to National Bureau of Standards about corona. Line is always blamed. Same will occur for new locomotives.
- (9) For railroad lines, 55 to 60 kV caused no corona. Higher voltages are not suitable.
- (10) Complaints on new projects. Tried dummy unpowered trains to prove that interference was not caused by the train.
- (11) In choosing the frequency for signaling, the system must be safe in the face of all interference possibilities.
- (12) Suggest meeting at a future date and including AT&T (Bell) representatives.

Suggest including at the meeting the chairmen of IEEE committees concerned with interference.

Shops

- (1) For electric locomotives, reduce facilities 50% because of less service, plus 50% reduction of locomotives, from diesels.
- (2) Plan shops on an area basis for a large integrated railroad. Concept of electric railroad operation is entirely different than diesel or steam operation. Use regional shops. Service electric locomotives anywhere, rather than at home shop.

Yards

- (1) The largest classification yard built recently in South Africa cost \$700 M.
- (2) Some railroad people want to electrify an entire yard. In Europe they have ceased to electrify yards, except for Swiss Federated Railways.
- (3) Suggest electrifying only the receiving and departure yards. Use diesel switches in the yard.
- (4) No new yards being built in Europe. More tendency to use point-to-point trains.

One container yard does the work of more regular yards.

Greater trend in Europe to containers than in the U. S.

- (5) There is too much equipment running around yards as a hazard to the overhead catenaries.
- (6) Use shorter trains, running more often, to spread demand and reduce the yard size. Depends upon manning rules. Great Britain has some two or three man crews per train, operating up to 150 miles.
- (7) No R&D required on yards, only cost benefits studies.

Electrification

- (1) Need a model of an electrified railroad in the United States to see how the operation compares with present diesel railroads.
- (2) Factors to promote electrification over diesel operation:
 - (a) Higher acceleration of trains.
 - (b) Short-time overload, 10-15 minutes on locomotives.
 - (c) Braking using dynamic or regenerative braking. Diesels also have resistors to hold speed on grade. Use friction brakes to stop.
 - (d) Improved availability of electric locomotives.
 - (e) Need 60% of the diesel locomotive number.
 - (f) Can operate different types of trains in narrower speed band, say 45 mi/h, minimum. More tons per hour on route. 20% to 40 or 50% improvement over diesel operation. Steep grades are a factor. Civil restrictions on speed are also a factor.
 - (g) Fewer passing tracks are required. Can use passing zones, say 10 miles long, to pass on the fly instead of stopping.
 - (h) Environmental advantages of exhaust and noise.
 - (i) Improved reliability. Reduction of incidents per 1000 miles over diesels. More on-time arrivals; increases confidence; reduces cost.
 - (j) Once an electrified railroad is installed, it has greater inflation resistance than diesel railroads. This does not impact on managers looking ahead only 10 years. Feeling in country is against expendable things. Replacement of

electric motive power in 30 years instead of 15 years for diesels. Electric require 30% of the maintenance cost of diesel locomotives. Fixed investment in electrification is made once and becomes worth "more" as it grows older in the face of inflation.

- (k) Industries, such as automobiles, use railroads as the storage medium for parts and assembled vehicles. Could reduce their inventories with shorter transit time.
- (1) Electrification provides benefits to railroad owners, to the other industries of the United States, and to population as a whole. All of the people should provide the investment.

Civil Engineering

- (1) Must separate the east coast from the rest of the United States. In the east we have to cater to existing clearances. Future standard is 22 ft. clearance in rest of the country. AAR clearance diagrams have been provisionally accepted.
- (2) Can rail be used with electric traction?
- (3) In the United States, locomotive and cars both average 20 to 40 T per axle. For example, a 100-T car on 4 axles, a 200-T locomotive on 6 axles (E-44).
- (4) No relationship between adhesion and track.
- (5) One problem is interference of catenaries and towers with equipment for track maintenance.
- (6) Ballast maintenance machines, snow plows, etc. Need 20 ft. clearance to side of track instead of 10 ft.
- (7) Cost of civil improvement and signal and communications improvements should not be charged to electrification. Clearances must be charged to electrification.
- (8) An example of civil-related work is the advance in time for replacement of bridges, etc., at time of electrification.
- (9) Track conditions are more comparable in the United States to non-European countries. United States track is generally good, with some exceptions. Track for electric operation need not be better than for diesel operation.
- (10) Electric engine will generally pick up current at any speed that it can stay on the track. Example of the German coal mines was cited, where the track is so poor that the electrics must operate at 5 mi/h.

- (11) Comparison (Report) between United States and European track. United States track causes a rock and roll effect of freight trains at low speed. NE Corridor track is wavy.

Design Aspect

- (1) Use a computer program to locate substations along the route.
- (2) Standardize designs. For example, design a minimum number of catenary structures, design substation modules. To design an electrification project, you need profiles, routes, allowable speeds, schedules, and selection of the voltage. Also have to choose a system.
- (3) One suggestion for new designs and pieces of hardware is vandal proof insulators.
- (4) Railroads are not experienced to handle design projects. Few contractors in the United States have the experience to work on an operating railroad. Railroads have to control the access to the R/W and the schedule. Railroad personnel must be in charge at the site. Structures can be installed with off-track equipment.
- (5) Russians demonstrated electrification construction with a 2-hour window.
- (6) United States railroads have similar windows that can be moved about in time. Junctions between railroads and lines are difficult to establish windows. Some places have water on both sides of the roadbed. Crews have to work from the track.
- (7) Only two or three contractors in the United States with experience. Experience comes from transmission line construction. Need special abilities, nevertheless.
- (8) Lack of personnel is found over the spectrum of electrification work from engineers to technicians.
- (9) Must train supervisors, labor, etc., on electrification work. Electrak has set up schools in other parts of the world to train personnel.
- (10) Reading on extent of new electrification in the United States: Black Mesa, Muskingham, Erie test track at GE, NE Corridor design, GM test track. Two test tracks on UP. Ten and twenty mile 25 kV tracks, Monticello and Martin Lake, in eastern Texas, built for Texas Utilities Service Corp. Carol Lake line in Labrador, 18 miles at 2.5 kV. Climax Mine, 15 miles, 1500 V dc. Reading line 5 1/2 miles to airport, ultimately 25 kV, going out for bid.

West coast line in Taiwan, 745 miles at 25 kV. Locomotives will be supplied by GE in U. S. and GE (not affiliated) in U. K.

Locomotives

- (1) More horsepower is developed in an electric locomotive than in a diesel. Need more adhesion to use it. Drawbar pull in a diesel is 18% of the weight. Electrics in Europe develop 25% to 30% drawbar pull. Russians can develop 1200 kW per axle on electrics, which is beyond dc motor capability. On the R&D list should be the development of ac traction motors for 1 to 2 MW per axle.
- (2) Garrett air-cushion LIM (linear induction motor) has a 6 MW inverter with 10 kV dc link voltage.
- (3) On adhesion, do not build another locomotive like the GE units for Amtrak. Go to Europe as GM did and get ASEA designs with individual motor control.
- (4) Need to develop a true electric locomotive with future sales in mind. For example, use larger wheels and a fully suspended motor.
- (5) Three types of motors can be used: dc separately excited; squirrel cage induction; synchronous.
- (6) For slip control, ac motors need individual inverters with individual frequency control. It doesn't cost more to split the power conditioners into individual inverters for the motors. No particular advantage in one large unit.

In the locomotive, the ASEA "furniture" mounts over each motor and supplies its power. It includes the blower for the semi-conductors and 600 hp motor. The transformer sits in the middle of the locomotive above and below the floor.

- (7) One-hour rating per motor on a diesel is 600 hp. No change in rating for separate excitation. With larger wheels, the rating can be increased up to 1000 hp. An ac motor can double the horsepower by using the commutator and brush space, and operating at higher peripheral speeds. Russians run the ac and dc motors at about the same speed, 1200 to 2000 r/min. Axle needs extra gearing for higher motor speed.
- (8) Work on ac drives for MU cars: Garrett's first foray was with a system using ac pickup and ac traction motors. It was abandoned in favor of dc systems. WABCO did the same with Cleveland and abandoned it. GE has abandoned ac systems. GM Santa Barbara was funded on a drive for SOAC (state-of-the-art-car), to be

tested at Pueblo. Have to power all of the axles on an MU car for acceleration. No incentive to increase the horsepower per axle on SOAC.

- (9) Six hundred to 1000 hp per axle is the crossover point from dc traction to ac traction.
- (10) BBC Mannheim built a diesel-engine locomotive with ac electric drive. Metre gauge. Same horsepower as the dc drive.

DC traction motor is a work of art. We can foresee the time when people will not be available to give a dc motor TLC (tender loving care).
- (11) Russians did not try to save weight by using ac motors.
- (12) Reliable inverter can be designed to 20,000 hr MTBF (mean time between failures). Requires development work. Reference Federal Aviation Administration (FAA) inverters with 200,000 hr MTBF, using redundancy.
- (13) Question whether induction motor with a steep torque-speed curve is better for adhesion than series motor? Washes out with the control system. AC industrial drive-systems cost about 50% more than dc drive systems.
- (14) In present systems, the slip control compares acceleration between the wheels to detect slip.
- (15) Replace 1000 diesels with 500 to 600 electric locomotives. Railroads keep old diesels for switching. Same number of locomotives for drag service, but at higher speed.
- (16) How does an inverter-ac motor locomotive get built? Who will fund it and who will build it in the United States?
- (17) Get 4-ton of traction motor weight off the axle and on the truck to reduce track pounding. The motor weight still provides adhesion.
- (18) Must make an economic case for the ac motor locomotive. For example, perhaps you can sell a 4-axle locomotive with ac drive instead of a 6-axle locomotive with dc drive.
- (19) Axle hung motors are popular because everyone knows how to build them.
- (20) For an MU car like the Metroliner, concentrate more power in a few axles; it is cheaper than powering all the axles. Acceleration is not the limiting requirement and the drive is not adhesion limited. An ac drive may be desirable.

- (21) Consider larger wheels. Some effect on wear; some on adhesion. The GG-1 had 60 inch wheels. Try 36 inch to 40 inch wheels. Europe uses 42 to 45 inch wheels. Originally, the need for more space for diesel engines forced the wheel size down. Diesel locomotives started as switchers.

Braking

- (1) French built dc-excited linear induction motor inside the truck for braking an MU car. It was mounted on an equalizer beam and acted on the rail between the wheels. Braking effect faded as the speed came down to 60 to 70 mi/h. Question of the temperature effect of the energy pumped into the rail from a high-speed train.
- (2) At lower speeds, use the alternative of friction brakes or an on-board propulsion inverter plugging on the LIM brakes.
- (3) Regenerative locomotive braking depends upon whether the utility will accept the energy or whether the energy must be dissipated on the roof of resistors.
- (4) French eddy-current disks don't have the concentration of heat and stress problems of a friction brake. The windings can apply the torque all of the way around the disk, whereas the friction brake applies it at the shoe.
- (5) A traction system in braking should follow the same constant horsepower line in the speed-tractive effort domain as in motoring.

TABLE A-4
 ATTENDEES R&D ELECTRIFICATION MEETING AT AAR
 MARCH 30, 1976

Matthew Guarino, Jr. (Chairman)	DOT/FRA
R. J. Berti	Union Pacific
L. S. Crane	Southern Railway Company
M. Clifford Gannett	DOT/FRA
E. T. Harley	Consolidated Rail Corporation
Wm. J. Harris, Jr.	American Association Railroads
D. C. Hastings	Seaboard Coast Lines
Richard John	DOT/TSC
T. J. Lamphier	Burlington Northern, Inc.
R. R. Manion	American Association Railroads
Jack R. Martin	Southern Railway Company
T. D. Mason	Santa Fe
D. K. McNear	Southern Pacific
M. B. Mitchell	DOT/FRA
R. Parsons	DOT/FRA
Frank L. Raposa	DOT/FRA
J. J. Schmidt	Antrak
W. W. Simpson	Southern Railway Company
C. G. Swanson	Mitre
G. H. Way	American Association Railroads
A. D. Williams	Union Pacific
Donald L. Wylie	Milwaukee Road

SUMMARY - MARCH 30, 1976 MEETING

The R&D subjects and estimates of the potential benefits which resulted from the first two workshops (see Appendix D) were presented at a third workshop held at the American Association of Railroads' office in Washington, D. C., on March 30, 1976. No additional R&D issues related to electrification resulted.

APPENDIX B - IDENTIFICATION OF R&D AREAS

The topics listed in this appendix have come from discussions on railroad electrification with individual representatives of the manufacturing, engineering, railroad operating and electric utility industries, and from the workshops summarized in Appendix A. Section 2 and 3 are structured to follow the format of Appendix B and, as such, Appendix B is a reasonably concise summary of the R&D defined by this report. The topics are divided into non-hardware and hardware-related items, The times for solution are divided into near-term, mid-term and far-term and keyed to the electrification implementation model of Appendix C. Topics requiring solution by the near-term are based on problem areas known today. Topics for the far-term are based on new concepts, for which technology and equipment are not available today.

B.1 Non-Hardware Issues

The problems in this category must be addressed primarily in the near-term period (results by 1980), and prior to extensive effort and expenditures in the technical hardware-oriented areas of the electrification program.

B.1.1. Socioeconomic Problems

The following problems may not be amenable to a cost-benefit analysis on the narrow scale of the railroad industry, but should be viewed from the standpoint of the overall transportation industry, and the nation as a whole:

- (1) Impact of electrification on the environment.
- (2) New employment and shifts in employment.
- (3) Shifts in railroad equipment industry product mix.
- (4) Long-range utility plans for system expansion.
- (5) Retraining of railroad industry employees.
- (6) Public-agency regulations for railroads.
- (7) Public-agency regulations for utilities serving railroad load.

B.1.2. Standards

Preparation of standards for electrification facilities that are safe, compatible with other services, and utilize reasonably uniform equipment will require extensive tests on prototype equipment at controlled facilities, such as at Pueblo. As is now done, the standards would be

prepared and approved by the public agencies and by industry groups.
Areas for standards are:

- (1) Telecommunications interference.
- (2) Voltage unbalance in the electric utility system.
- (3) Current harmonics at the locomotive.
- (4) Current harmonics at the electric utility interface.
- (5) Catenary nominal voltage levels.
- (6) Substation and catenary voltage fluctuations.
- (7) Mechanical and electrical clearance.
- (8) Electrical safety.
- (9) Reliability of subsystem and system equipment.

B.1.3. Systems Engineering

The rapid buildup of an electrification program in the United States will require systems engineering that is common to all routes and properties. The topics that must be addressed include:

- (1) Review and adaption to United States of foreign technology.
- (2) Models of electrified railroad operation.
- (3) Interfacing between railroads and electric utilities.

B.2. Hardware Issues - Near Term and Mid Term

These known problems require solutions by 1980, when the construction of electrification will start. The solutions require analysis and testing. The equipment and technology is already available in the United States and Europe.

B.2.1. Utility Connections and Substations

- (1) Reduction of peak demand at the electric utility interfaces.
- (2) Phase balance improvement of the electric utility load.
- (3) Use of standard electric utility voltages.
- (4) Reactive power reduction and control at substations and locomotives.
- (5) Use of standard electric utility equipment.
- (6) Improved methods for protection of equipment against faults.
- (7) Regenerative braking and regenerated power management.

B.2.2. Catenary Systems

- (1) Development of construction equipment and techniques.
- (2) Standardization of design.
- (3) Maintenance procedures and development of special equipment.
- (4) Economical catenary development.

B.2.3. Motive Power

- (1) Improved wheel slip control systems for increased adhesion.
- (2) Development of separately excited dc motor systems.
- (3) Improvement of motor and power-train configurations.
- (4) Develop methods for diesel-electric locomotive conversion to all-electric operation.
- (5) Increase locomotive power density (hp/Ton) - traction motors and power conditioners.
- (6) Improve locomotive availability and equipment reliability.
- (7) Improve locomotive braking systems - linear brakes, electro-pneumatic train brakes, etc.

B.2.4. Signaling and Communications

- (1) Reduction of catenary (locomotive) and substation harmonics (EMI).
- (2) Reduction of signaling and communications facilities susceptibility.
- (3) Development of signaling circuits for 60 Hz electrification.
- (4) Development of rail bonding methods for new track circuit.
- (5) Improve loose wheel, broken flange, and hot box detectors.
- (6) Develop speed-profile control systems.
- (7) FSK track circuit development.
- (8) Improve radio communications in tunnels.
- (9) Improve cab displays and alarms.

B.3. Hardware Issues - Far Term

These items are the results of technology development, not based on equipment already available:

B.3.1. Improved Locomotive Equipment

- (1) Pantographs.
- (2) Linear motors for supplemental tractive and brake effort.

B.3.2. DC Catenary Systems and Equipment

- (1) DC circuit breakers.
- (2) Voltage selection.
- (3) Electrical system design.
- (4) Protection.
- (5) Inverter - ac motor locomotive.
- (6) Chopper - dc motor locomotive.
- (7) Rectifier stations.

B.3.3. Signaling and Communications

- (1) Multiplexing for wide area control.
- (2) Non-radio wayside-train communications.
- (3) Car and train identification at high speed.
- (4) New signaling methods for high-speed operation.

APPENDIX C
CAPITAL AND OPERATING COST SUMMARIES
FOR AN ELECTRIFICATION NETWORK MODEL

C.1 ELECTRIFICATION OF 8500 ROUTE MILES

A baseline electrification network model is required to determine the cost benefits that could be derived if various R&D programs, related to railroad electrification technology, were to be undertaken. To provide this baseline, capital costs and operating costs were developed on a year-to-year basis as if the most heavily traveled 8,500 route miles of U. S. railroads (i.e., 4.25%) were to be electrified during the years 1980 to 1990.

The electrification rate accelerates from 100 mi/y in 1980 (available in 1981) to 1,000 mi/y in 1986, and then remains constant at 1,000 mi/y through 1990. Traffic density is assumed to be greater than the national average by a factor of 3.5, and a traffic growth rate of 3% each year is assumed. The 2,000 hp line diesel locomotives are replaced by purchase of 6,000 hp electrics through 1985, 10,000 hp electrics thereafter. Use of 25 kV, single phase, 60 Hz utility power, supplied by 20 MVA substations spaced 20 miles apart are included in the baseline cost model. Utility system reinforcement costs for single phase loading are included.

The required capital costs for electrification and the expected savings in operating costs over operation without electrification are summarized for each year in Table C-1.

Capital costs for each year are determined by finding the costs to build catenaries, tie into the utilities for power, and other modifications, on a per route mile electrified basis. Electric locomotive capital costs are based on the amount of electrified traffic and electric locomotive needs as more miles are electrified each year.

Operating costs for each year are determined both with and without electrification. These costs include maintenance of roadway and structures, maintenance of equipment, transportation expenses, traffic expenses, and general and miscellaneous expenses. Operating costs are summed for the electrified and unelectrified portions of the 8,500 route mile model for each year of the electrification project.

When electrification is completed for these 8,500 route miles (y 1991) Table C-1 shows that annual operating costs will be reduced by \$599 M. These savings are described in greater detail in Table C-2.

The detailed assumptions and ground rules for computing the capital costs and operating costs are shown in Tables C-3 and C-4, respectively. Capital costs are divided into fixed capital costs and locomotive costs. The fixed capital costs, in turn, consist of:

- a. catenary construction costs
- b. utility and substation costs
- c. signaling, control, and communications costs
- d. shop conversion costs
- e. civil engineering modifications costs (bridges and tunnels)
- f. yard modification costs
- g. engineering and design costs

The annual operating costs are summarized by the ICC cost categories:

Cost Category I	-	Maintenance of Roadway and Structures Accounts
Cost Category II	-	Maintenance of Equipment Accounts
Cost Category III	-	Transportation Expense Accounts
Cost Category IV	-	Traffic Expense Accounts
Cost Category V	-	General and Miscellaneous Expense Accounts

Reference sources for some of the assumptions used in these cost models are listed in Section 7 (19) (20) (21) (22) (23).

The graphical representation of the 8,500 mile baseline model and details of the yearly capital and operating costs are shown in Figures C-1 through C-5:

- Figure C-1 - Electrification Plan for 8,500 Route Miles
- Figure C-2 - Annual Operating Costs
- Figure C-3 - Annual Total Energy Costs
- Figure C-4 - Annual Locomotive Maintenance and Depreciation Costs
- Figure C-5 - Annual Capital Costs

From Figure C-1, electrification greatly reduces the required number of line locomotives. When electrification is completed (1991), 6,329 line diesels (2,000 hp) are replaced by 1,715 larger electric locomotives, consisting of 821 6,000 hp units and 894 10,000 hp units. On the average, each electric locomotive replaces 3.7 of the smaller diesel locomotives.

Reductions in operating costs (Figure C-2) when electrification is completed (1991) total \$599 M, or a 13.7% saving of all operating costs. These savings should become even larger in later years, since diesel oil costs are assumed to escalate faster than utility power costs (7% vs 5%).

Figure C-3 shows the phase-out of diesel fuel with electrification. A fuel cost differential of \$323.8 M by 1991 accounts for 54% of the total operating cost savings when electrification is completed. (Yard fuel costs are the same since the yards are not electrified.)

Figure C-4 shows how locomotive operating costs are reduced by lower maintenance and depreciation costs as electric locomotives are phased in. When electrification is completed (1991), the savings in line locomotive maintenance are \$135.7 M, and savings in line locomotive depreciation of \$26.5 M are also realized.

Figure C-5 shows how the investment costs are divided between fixed costs and locomotive costs, with the cumulative locomotive costs roughly 22% of the entire investment. Without electrification, the increase in the diesel fleet to allow for traffic growth would have required roughly \$30 M each year. In all fairness only the difference between the two locomotive investments is due to electrification. The fixed cost investments are broken down into five categories, which are similar to the categories mentioned earlier, excepting three small categories which have been combined:

- Shop conversion costs
- Civil engineering modification costs (bridges and tunnels)
- Yard modification costs.

TABLE C-1 - ELECTRIFICATION COST SUMMARY FOR 8500 ROUTE MILES

<u>Year</u>	<u>Annual Capital Costs</u> \$M	<u>Annual Savings in Operating Costs Due to Electrification</u> \$M
1980	106	0
1981	358	2
1982	542	12
1983	638	31
1984	736	56
1985	836	90
1986	938	136
1987	949	199
1988	961	273
1989	973	363
1990	987	471
<u>1991</u>	<u>0</u>	<u>599</u>
Totals	\$8,024	\$2,232

TABLE C-2 - ANNUAL REDUCTION IN OPERATING COSTS IN 1991
 FOR 8500 ROUTE MILES (COST REDUCTIONS DUE TO
 ELECTRIFICATION)
 (MILLIONS OF DOLLARS)

Category I	Cost Reductions (Maintenance of Roadway and Structures) Added catenary maintenance at \$2,000/route mile	(\$ 17. M)
Category II	Cost Reductions (Maintenance of Equipment) Locomotive depreciation Locomotive maintenance	\$ 26.5 M \$135.7 M
Category III	Cost Reductions (Transportation Expenses) Other than train and yard fuel Train fuel	\$122.6 M* \$323.8 M
Category IV	Cost Reductions (Traffic Expenses)	\$ 7.3 M*
Category V	Cost Reductions (Miscellaneous and General Expenses)	<u>0</u>
	Total Savings	\$599 M

* These savings with electrification are due to the reduced electrified traffic (GTM/y) for the same gross trailing tons, since electric locomotives are lighter than diesel locomotives.

TABLE C-3 - ASSUMPTIONS FOR 8500 ROUTE MILE CAPITAL COST MODEL

General

1. All costs are in 1976 dollars (no inflation).
2. All build cycles are one year.

Electrified Trackage and Traffic

1. Electrify most heavily traveled routes first.
2. All route miles are of a 2-track configuration.
3. Mileage electrified during one year enters service the following year.
4. Traffic growth for United States will increase by 3% each year.
5. United States average traffic density in 1973 was 10 million gross ton mi/mi/y.
6. Electrify 8,500 route miles with the following schedule:

<u>y</u>	<u>per y</u>	<u>cum available</u>
1980	100	0
1981	400	100
1982	600	500
1983	700	1,100
1984	800	1,800
1985	900	2,600
1986	1,000	3,500
1987	↓	4,500
1988		5,500
1989		6,500
1990		7,500
1991		8,500

7. Traffic density factor for 8,500 mile route is 3.5, based on average traffic density in United States.
8. Electrified traffic (in GTM/y) is reduced by a locomotive weight factor (ϕ) of 0.912 (=1.067/1.17) since electric locomotives are roughly 60% lighter than diesel locomotives for the same trailing gross tonnage (TGT).
9. The yards and sidings will not be electrified.

TABLE C-3 (Continued)

Locomotive requirements

1. Use a 2,000 hp diesel for estimating all diesel locomotive requirements, both for line and yard use.
2. With no electrification, 15% of the diesel locomotive fleet is used for yard service, 85% for line service.
3. Electric locomotives purchased during one year enter service the following year.
4. Purchase 6,000 hp electric locomotives through 1985; 10,000 hp locomotives thereafter.
5. Use a tractive force of 38,000 lb for the 6,000 hp electric locomotive, based on continuous operation at 50 mi/h.
6. Scale tractive force of 2,000 hp and 10,000 hp locomotives from tractive force of a 6,000 hp locomotive, based on (hp/speed) ratio, as shown below:

<u>Locomotive hp</u>	<u>Tractive force-lb</u>	<u>Scaling speed-mi/h</u>
2,000	25,333	25
6,000	38,000	50
10,000	57,575	55

7. Locomotive average speeds when in service are:

2,000 hp locomotive:	20 mi/h
6,000 hp locomotive:	25 mi/h
10,000 hp locomotive:	30 mi/h

8. Availability factor (A) for diesel locomotives is 0.50; for electrics 0.75.
9. The ratio of trailing load (lb) to tractive force (lb) is 100 to 1. This is equivalent to a tractive force of 20 lb for each trailing gross ton (TGT). Assuming a drag force of 8 lb per TGT, the reserve tractive effort for climbing grades steeper than 0.6% is obtained by climbing at lower speeds than the scaling speeds used to determine tractive force.
10. The ratio of gross tons (GT) to trailing gross tons (TGT) is 1.067 for electric powered trains and 1.170 for diesel powered trains.
11. Individual locomotive capabilities, based on the above, are:

2,000 hp diesel locomotive:	130×10^6 GTM/y/locomotive
6,000 hp electric locomotive:	333×10^6 GTM/y/locomotive
10,000 hp electric locomotive:	605×10^6 GTM/y/locomotive
12. Regional unbalance of freight traffic increases locomotive horsepower requirements by an unbalance factor (U) of 1.2.
13. Annual traffic peaks increase locomotive horsepower requirements by seasonal factor (S) of 1.35.

TABLE C-3 (Continued)

14. Fleet-averaged locomotive capabilities, reduced by regional unbalance (U) and seasonal traffic peaks (S), are:

2,000 hp diesel:	80 x 10 ⁶	GTM/y/locomotive
6,000 hp electric:	200 x 10 ⁶	GTM/y/locomotive
10,000 hp electric:	333 x 10 ⁶	GTM/y/locomotive

15. Electric locomotive unit cost is \$125 per rated hp, diesel locomotive unit cost is \$100 per rated hp. Therefore, locomotive costs are:

2,000 hp diesel:	\$0.2 M
6,000 hp electric:	0.75 M
10,000 hp electric:	1.25 M

Fixed Cost Items

- Catenary costs are \$0.2 M/mi (2-track), equally divided between labor and material.
- Utility and substation costs are \$26 M/100 mi (2-track), based on 20 mile spacing and \$5.2 M per 20 MVA substation. Utility and substation costs are divided as shown:

Utility interconnection cost	\$1.2 M
Utility reinforcement cost	3.0 M
RR substation cost (20 MVA)	<u>1.0 M</u>

Total	\$5.2 M
-------	---------

- Signaling costs are \$0.14 M/mi(2-track), equally divided between labor and material.
- Maintenance shop conversion costs are \$5000/mi(2-track).
- Civil engineering modification costs (bridges and tunnels) are \$10,000/mi(2-track).
- Yard modification costs are 5% of the total fixed capital costs (all but locomotives).
- Engineering and design costs are 15% of total fixed capital costs, plus a \$10 M effort prior to electrification of each increment.

TABLE C-4 - ASSUMPTIONS FOR 8500 ROUTE MILE OPERATING COST MODEL

1. All costs are in 1976 dollars (no inflation).
2. All route miles are of 2-track configuration.
3. The ICC categories for operating costs are adopted:
 - I - Maintenance of Roadway and Structures Accounts
 - II - Maintenance of Equipment Accounts
 - III - Transportation Expense Accounts
 - IV - Traffic Expense Accounts
 - V - General and Miscellaneous Expense Accounts
4. The 1973 operating costs for each of these categories, for all U. S. railroads, were:

I	-	\$	2,041	M
II	-		2,599	M
III	-		6,061	M
IV	-		332	M
V	-		865	M
			865	M
Total			\$11,898	M

These costs are used as a base for projecting future operating costs.
5. Operating costs are computed both with and without electrification, to find savings achieved when electrified.
6. Category I costs, exclusive of electrification costs, are proportional to the total (fixed) route miles and the projected traffic to the one-fourth power.
7. Category I costs are increased with electrification by a catenary maintenance cost of \$2,000/mi/y for the available electrified route miles.
8. Category I savings due to reduced traffic load (when using the lighter electric locomotives) are not used since these savings are only 2%.
9. Category II costs without electrification include: line diesel locomotive maintenance, line diesel locomotive depreciation, and "all other" equipment maintenance costs. This last category includes the yard diesel maintenance and depreciation costs.

TABLE C-4 (Continued)

10. Category II costs with electrification include: diesel locomotive maintenance and depreciation for fewer line diesels, plus maintenance and depreciation of the electric locomotives. The size of the yard diesel fleet is unchanged by electrification, and maintenance and depreciation of the yard diesels is in the "all other" cost category, as before.
11. Category II line locomotive maintenance costs are proportional to the number of line locomotives in service, the unit mi/y traveled by each locomotive, and the average maintenance cost per unit mile. The following factors were used for each type of locomotive:

Loco. Type	Maintenance cost* per/unit mile	Loco. Unit mi/y	Loco. Maint. Cost \$/y/loco.
2,000 hp diesel	\$0.52	54,070	28,110
6,000 hp elec.	0.22 ⁽²⁾	101,400	22,310
10,000 hp elec.	0.22 ⁽²⁾	121,700	26,780

* Although average maintenance cost per unit mile would depend heavily on the average age of the fleet, this factor was not included.

12. The locomotive unit mi/y is found from average train speed and the number of hours used per year, considering availability factor (A), regional unbalance factor (U) and seasonal peak load factor (S), as defined in the Capital Cost model.
13. The category II locomotive depreciation costs per locomotive are based on a stright-line method, with the following factors.

Loco. type	Expected life-y	\$/rated hp	Loco. dep. cost \$/y/loco.
2,000 hp diesel	15	100	13,330
6,000 hp elec.	30	125	25,000
10,000 hp elec.	30	125	41,670

14. Category III costs (Transportation Expense Accounts) are separated into fuel and non-fuel costs. The non-fuel portion is proportional to traffic (GTM/y), based on the 1973 costs per GTM/y. Since electrified traffic is lower for the same trailing gross ton (lighter locomotives), electrified non-fuel category III costs are thereby reduced.

TABLE C-4 (Continued)

15. Fuel conversion effectiveness:

Diesel = 4.545 gal/10³ GTM
Electric = 56.36 kWh/10³ GTM

16. Fuel costs:

Diesel = \$0.276/gal (1975), increasing 7% each year
Electric = \$0.026/kWh (1974), increasing 5% each year

17. Yard fuel (with or without electrification) is 10% of the train fuel (used for line service) when there is no electrification.

18. Category IV costs (Traffic Expense Accounts) are proportional to the total traffic carried each year. Due to lighter electric locomotives, this expense is slightly less with electrification.

19. Category V costs (General and Miscellaneous Expenses) are proportional to track mileage only, and are, therefore, constant (ignoring inflation).

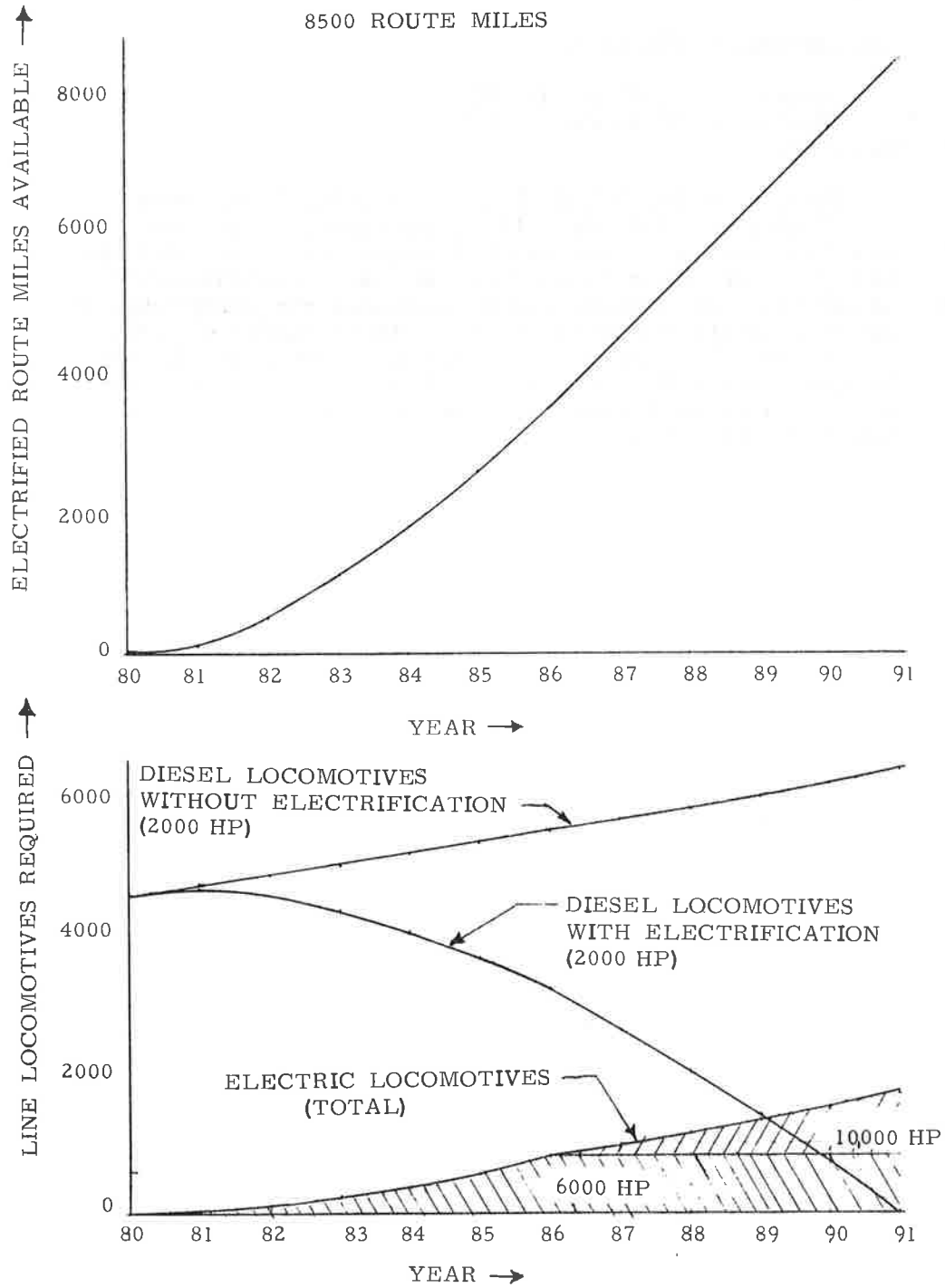


FIGURE C-1 ELECTRIFICATION PLAN FOR 8500 ROUTE MILES

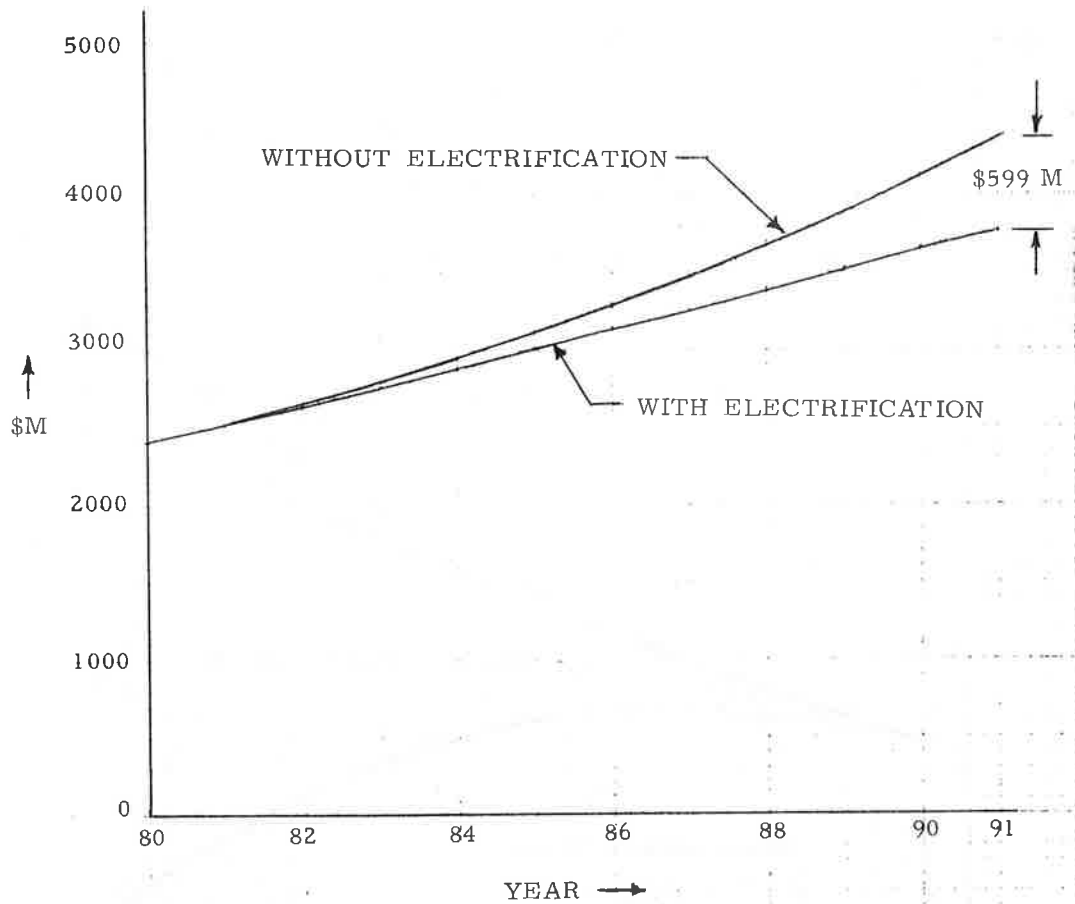


FIGURE C-2 ANNUAL OPERATING COSTS OF 8500 ROUTE MILES DURING ELECTRIFICATION (MILLIONS OF DOLLARS).

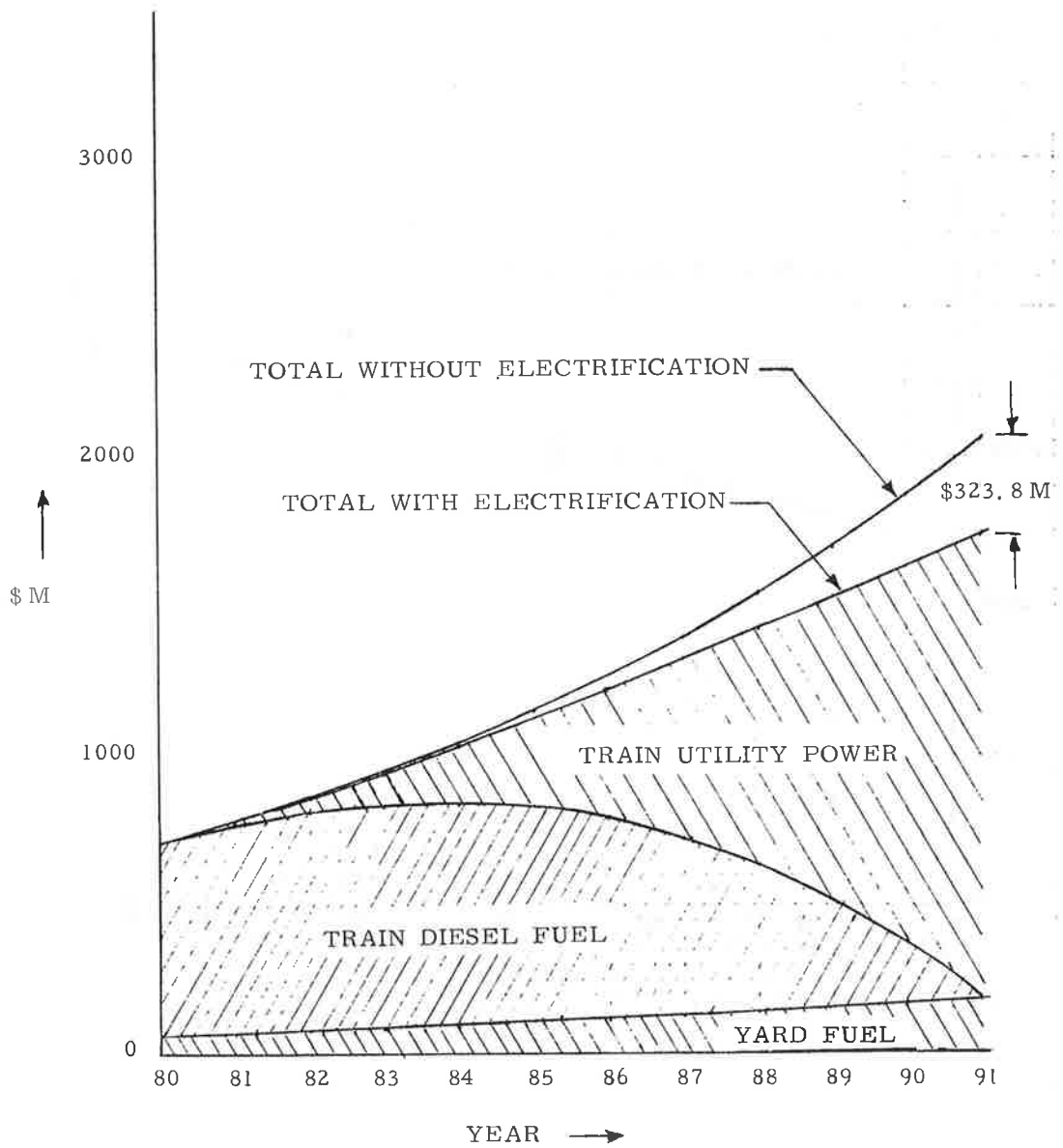


FIGURE C-3 ANNUAL TOTAL ENERGY COSTS FOR 8500 ROUTE MILES (TRAIN FUEL PLUS YARD FUEL) (MILLIONS OF DOLLARS)

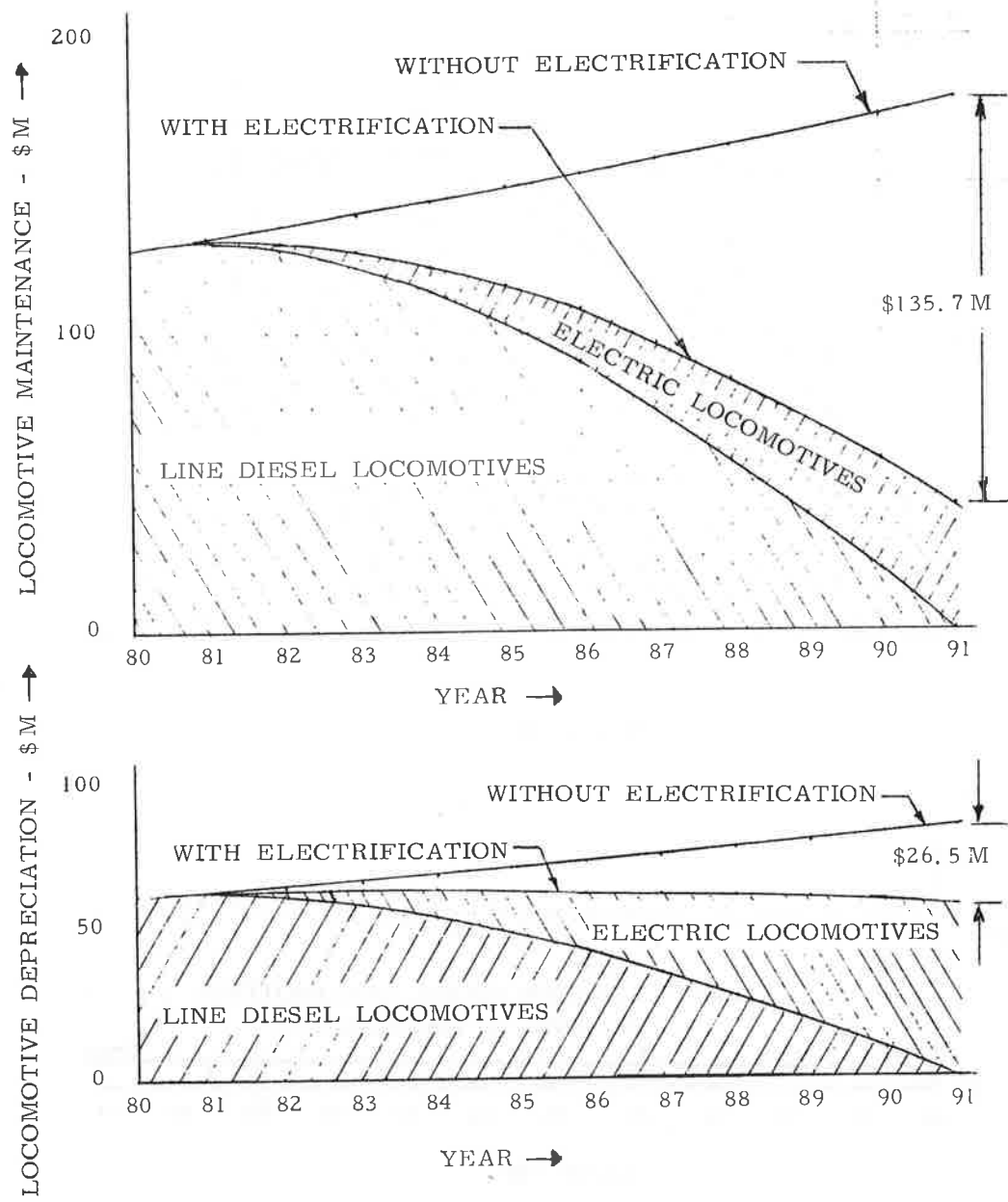


FIGURE C-4 ANNUAL LOCOMOTIVE MAINTENANCE AND DEPRECIATION COSTS (FOR 8500 ROUTE MILES) (MILLIONS OF DOLLARS)

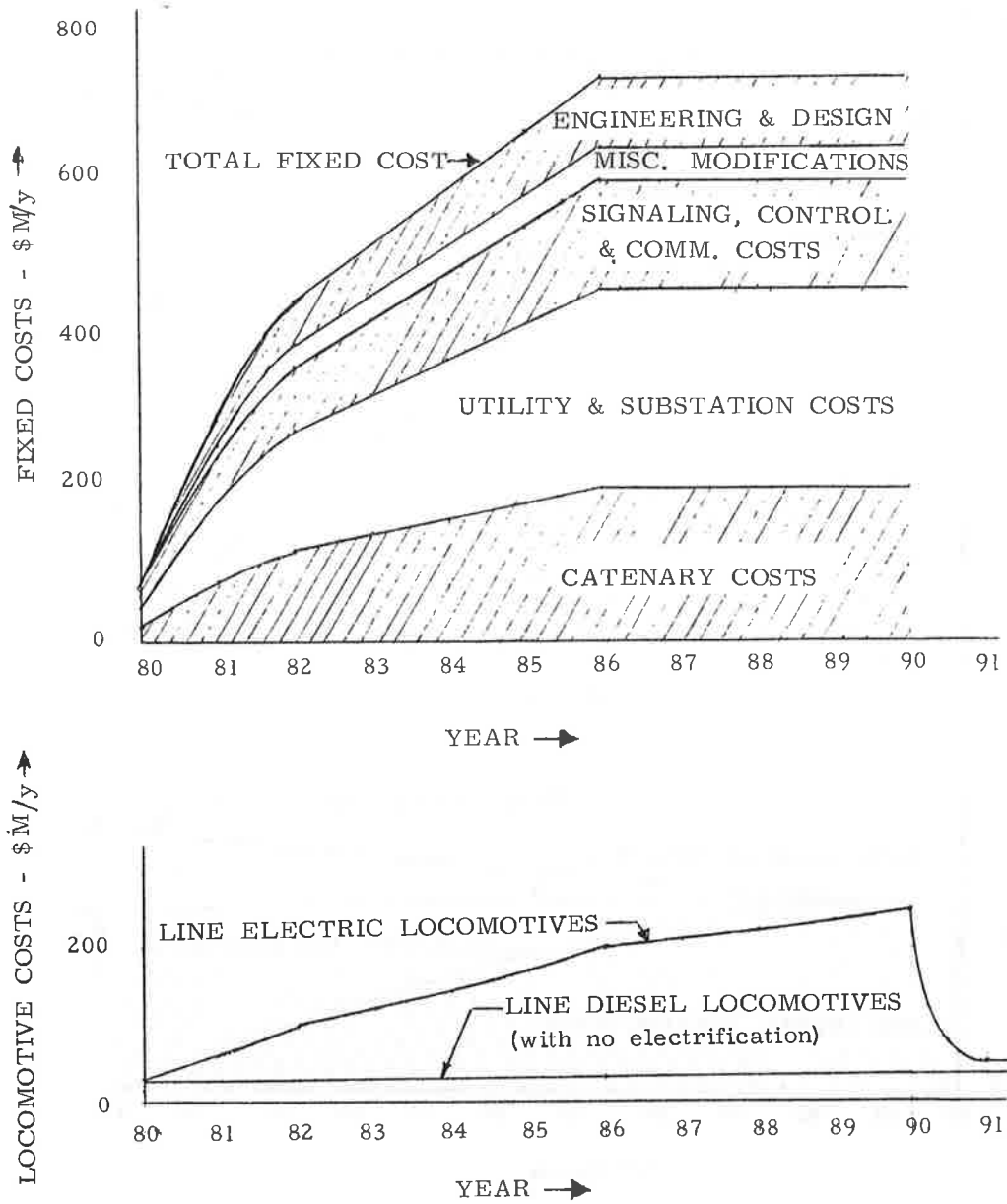


FIGURE C-5 ANNUAL CAPITAL COSTS FOR 8500 ROUTE MILES: FIXED COSTS AND LOCOMOTIVE COSTS (MILLIONS OF DOLLARS)

C.2 ELECTRIFICATION OF AN ADDITIONAL 10,000 ROUTE MILES (1991-2000)

A second baseline electrification network model has also been developed to determine the cost benefits from later or longer term railroad electrification R&D programs that would not be expected to produce any savings until the 1990's. This so-called "second increment" of electrification would be carried out under the same ground rules as used for the "first increment" electrified in the 1980's, with the following three changes:

1. Electrify 10,000 route miles during year 1991 through year 2000 at a constant rate of 1,000 mi/y.
2. Use a traffic density factor of 2.5 instead of 3.5.
3. Purchase 10,000 hp electric locomotives only (no 6,000 hp locomotives).

The procedures used to find the needed capital cost investments in locomotives and electrification of the roadway are the same as those used for the "first increment." The operating costs are also found in the same manner as the operating costs for the first increment.

The annual capital investments required for electrification and the expected savings in operating costs over operation without electrification are summarized for the "second increment" in Table C-5.

At the completion of electrification of these 10,000 route miles (y2001) annual operating costs will be reduced by \$1,630 M or 22.7% below projected operating costs without electrification. These savings are described in greater detail in Table C-6.

Figures 6 through 10 describe the "second increment" electrification model and summarize details of the required capital costs and the operating costs during each year of the 10-year conversion project:

- Figure C-6 - Electrification Plan for 10,000 Route Miles
- Figure C-7 - Annual Operating Costs
- Figure C-8 - Annual Total Energy Costs
- Figure C-9 - Annual Locomotive Maintenance and Depreciation Costs
- Figure C-10 - Annual Capital Costs

Figure C-6 shows that electrification with large locomotives sharply reduces the number of locomotives required to carry all traffic over the 10,000 route miles. In y 2001, 7,150 line diesels (2,000 hp) are replaced by only 1,566 electric locomotives (10,000 hp), or one electric replaces nearly 4.6 of the smaller diesels.

Figure C-7 shows that savings in operating costs when electrification is completed (y 2001) will total \$1,630 M or 22.7% of operating costs without electrification in that year. The further spread between utility power costs and diesel oil costs by this date accounts for \$1,314 M, or over 80% of these savings (see Figure C-8).

Figure C-9 shows that savings in locomotive maintenance by y 2001 are \$152 M or over 9% of the total savings from electrification. Also, savings in locomotive depreciation by y 2001 are \$30 M or nearly 2% of these total savings. Figure C-10 shows that annual fixed capital costs for the "second increment" are constant at the same values used for the latter half of the first increment, since the same rate of electrification (1,000 route mi/y) is used. The line electric locomotive costs increase each year in a compound manner, due to traffic growth and an increasing number of route miles electrified each succeeding year.

TABLE C-5 - ELECTRIFICATION COST SUMMARY FOR 10,000
ROUTE MILES

<u>Year</u>	<u>Annual Capital Costs</u> \$M	<u>Annual Savings in Operating Costs Due to Electrification</u> \$M
1991	888	0
1992	898	56
1993	906	127
1994	917	214
1995	926	322
1996	938	452
1997	948	611
1998	961	799
1999	972	1,029
2000	986	1,294
2001	0	1,630

TABLE C-6 - ANNUAL REDUCTION IN OPERATING COSTS IN
2001 FOR 10,000 ROUTE MILES

Category I	Cost Reductions (Maintenance of Roadway and Structures)	
	Added cost of catenary maintenance at \$2,000/route mile	(\$20 M)
Category II	Cost Reductions (Maintenance of Equipment)	
	Locomotive depreciation	\$ 30.0 M
	Locomotive maintenance	159.1 M
Category III	Cost Reductions (Transportation Expenses)	
	Other than train fuel and yard fuel	138.6 M*
	Train fuel	1,313.9 M
Category IV	Cost Reductions (Traffic Expenses)	8.4 M*
Category V	Cost Reductions (Miscellaneous and General Expenses)	<u>0</u>
	Total Savings	\$1,630.0 M

*These savings with electrification are due to the reduced electrified traffic (GTM/y) for the same gross trailing tons, since electric locomotives are lighter than diesel locomotives.

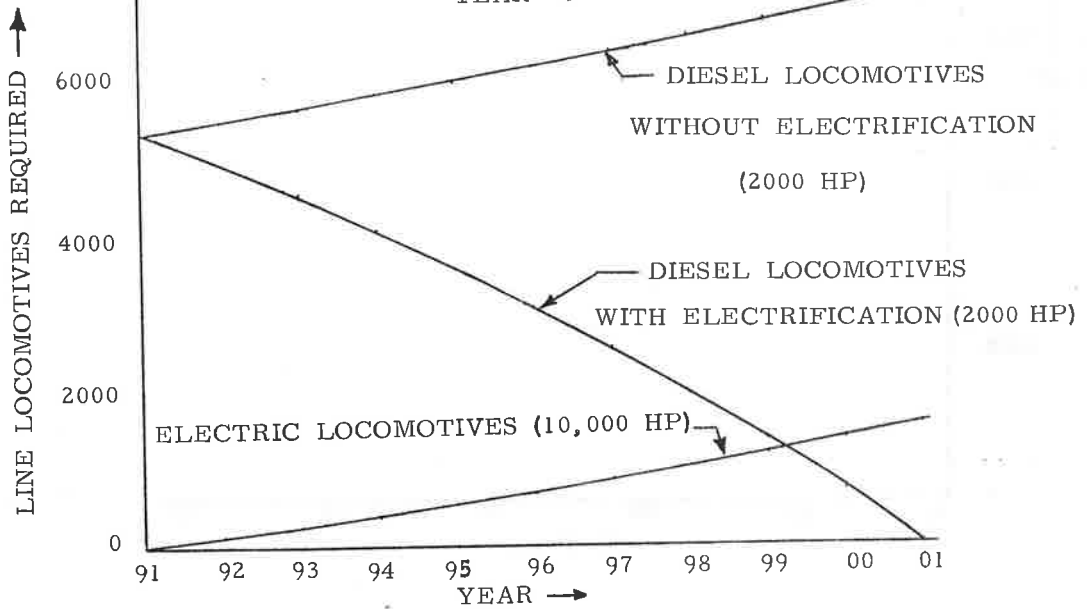
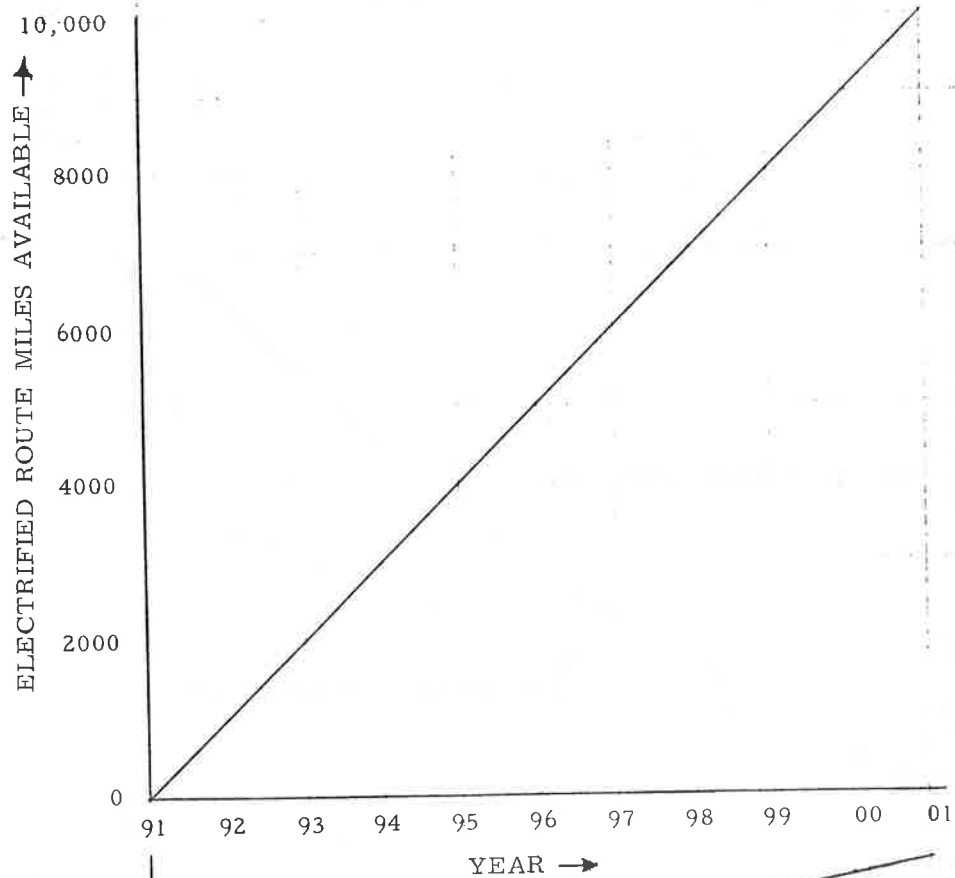


FIGURE C-6 ELECTRIFICATION PLAN FOR 10,000 ROUTE MILES

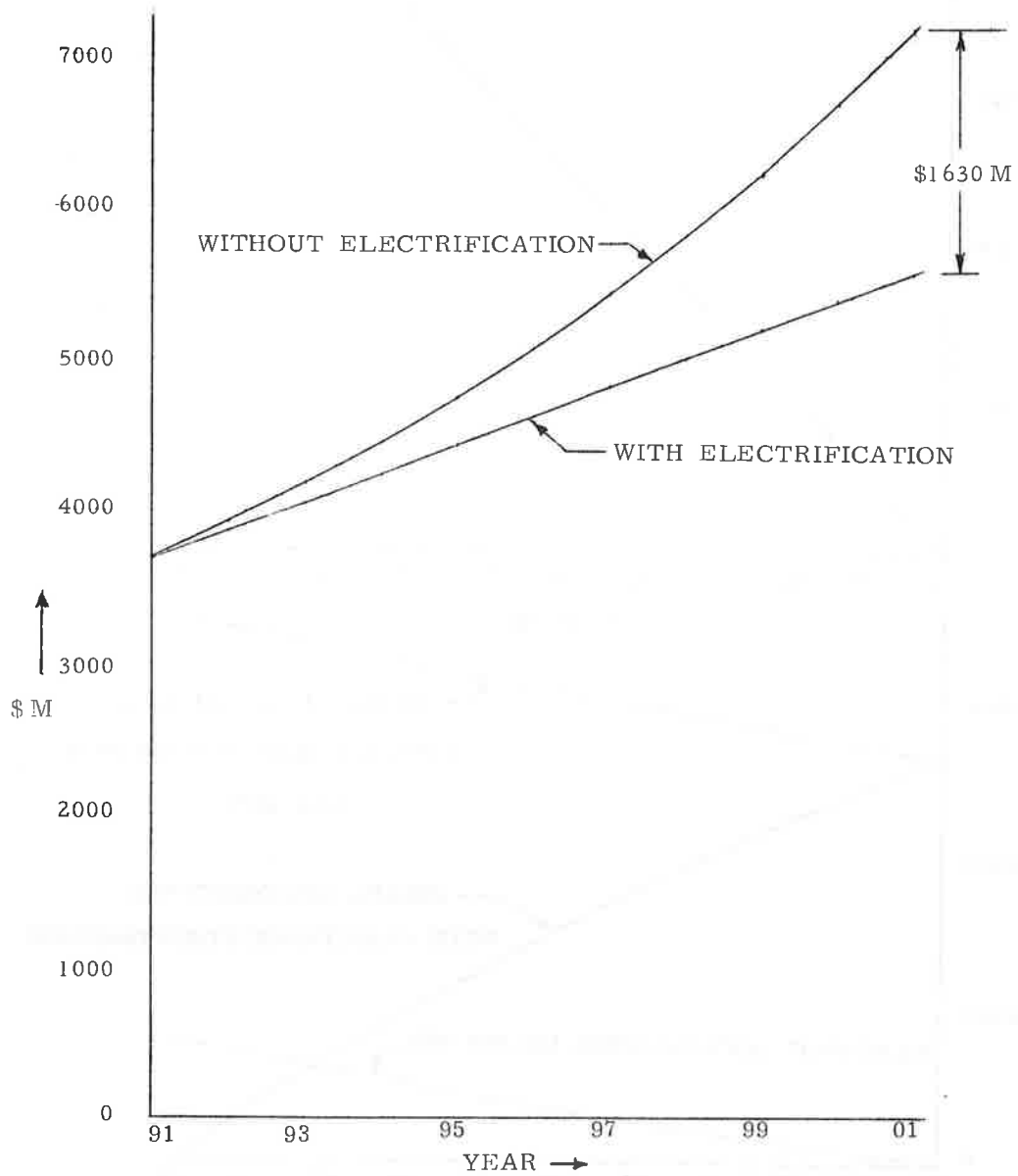


FIGURE C-7 ANNUAL OPERATING COSTS OF 10,000 ROUTE MILES DURING ELECTRIFICATION (MILLIONS OF DOLLARS)

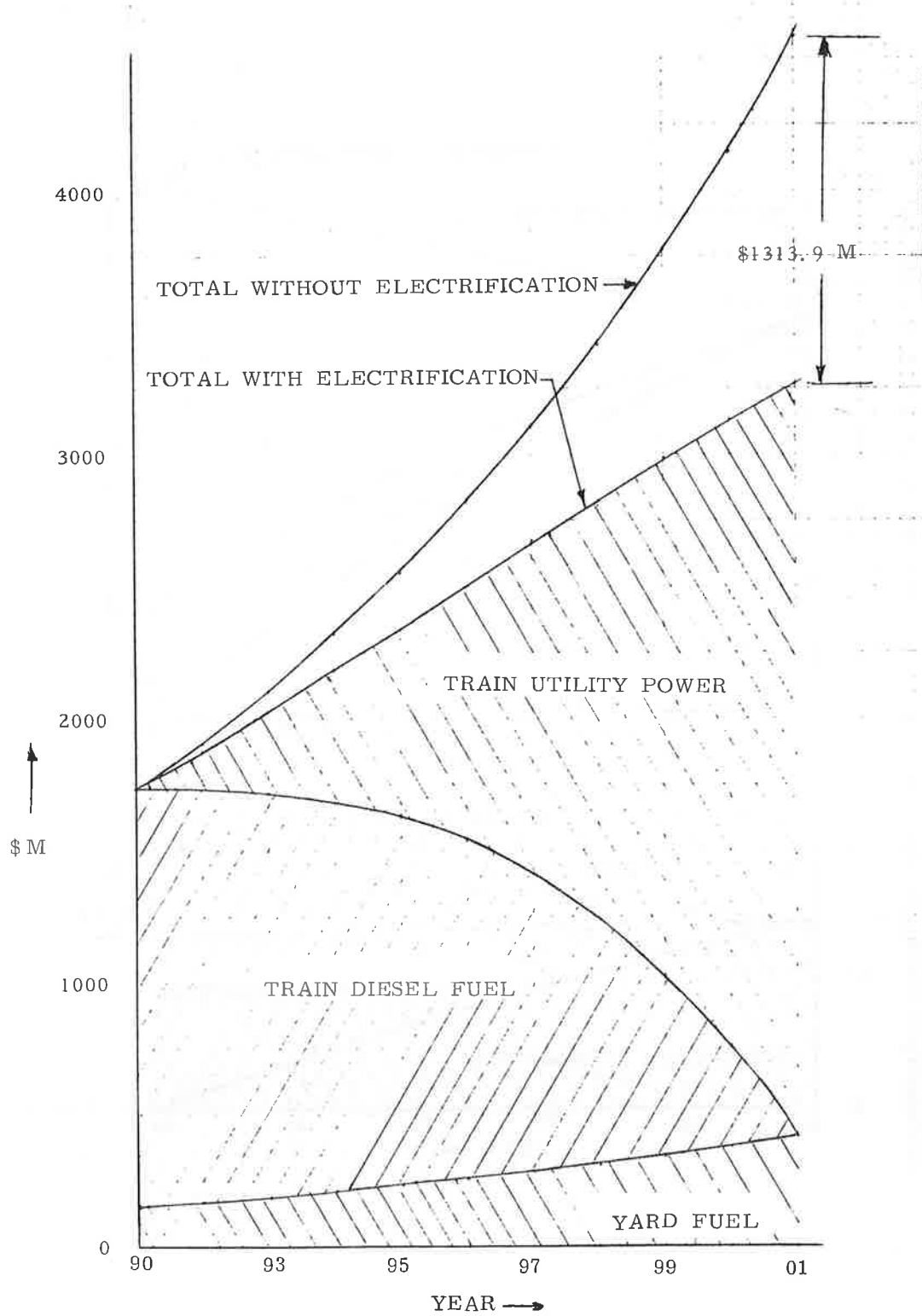


FIGURE C-8 ANNUAL TOTAL ENERGY COSTS FOR 10,000 ROUTE MILES (TRAIN FUEL PLUS YARD FUEL) (MILLIONS OF DOLLARS)

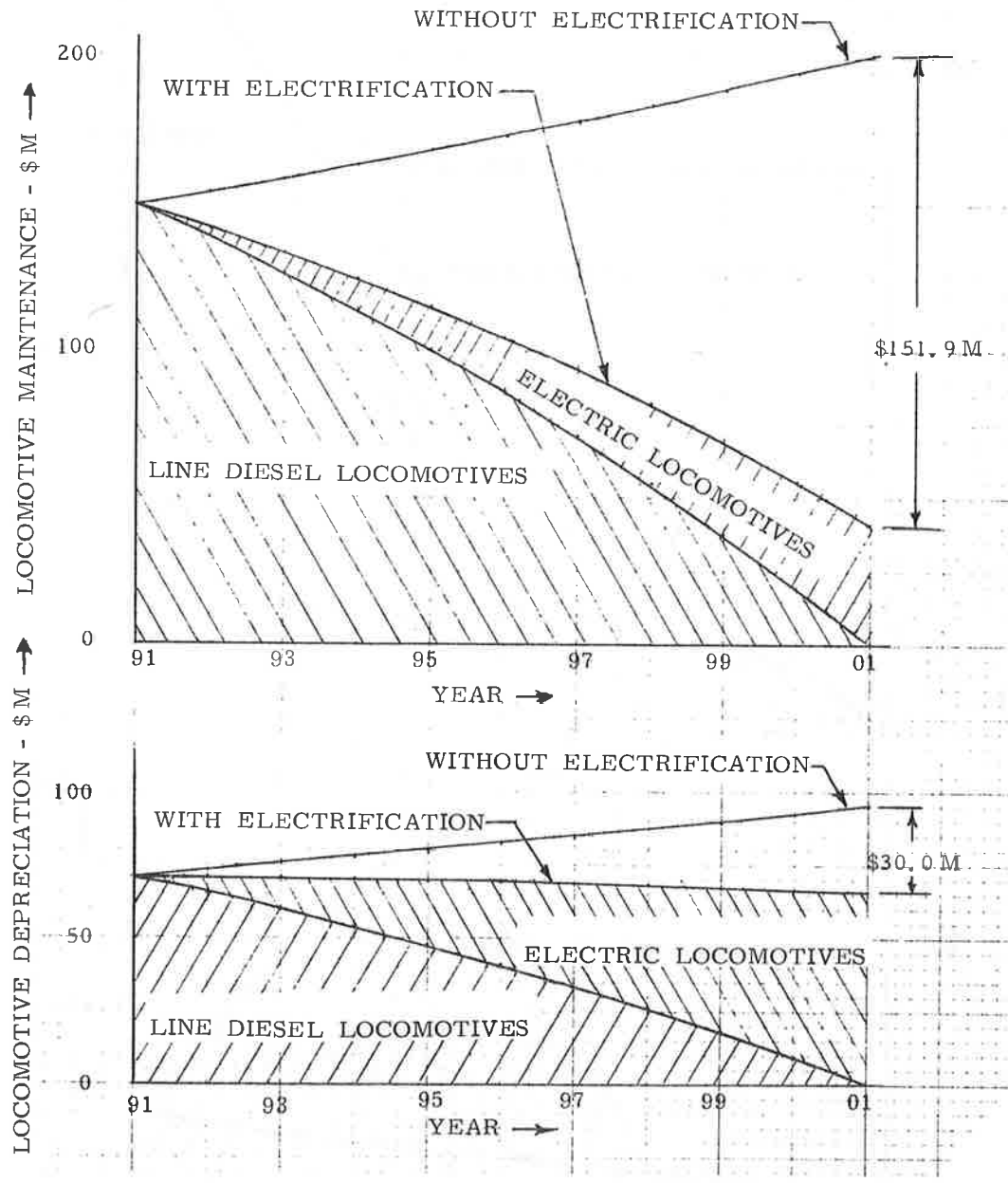


FIGURE C-9 ANNUAL LOCOMOTIVE MAINTENANCE AND DEPRECIATION COSTS (FOR 10,000 ROUTE MILES) (MILLIONS OF DOLLARS)

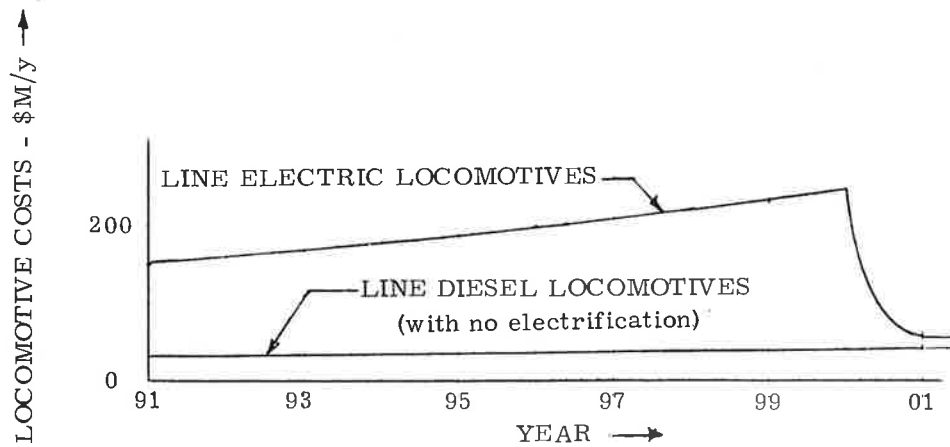
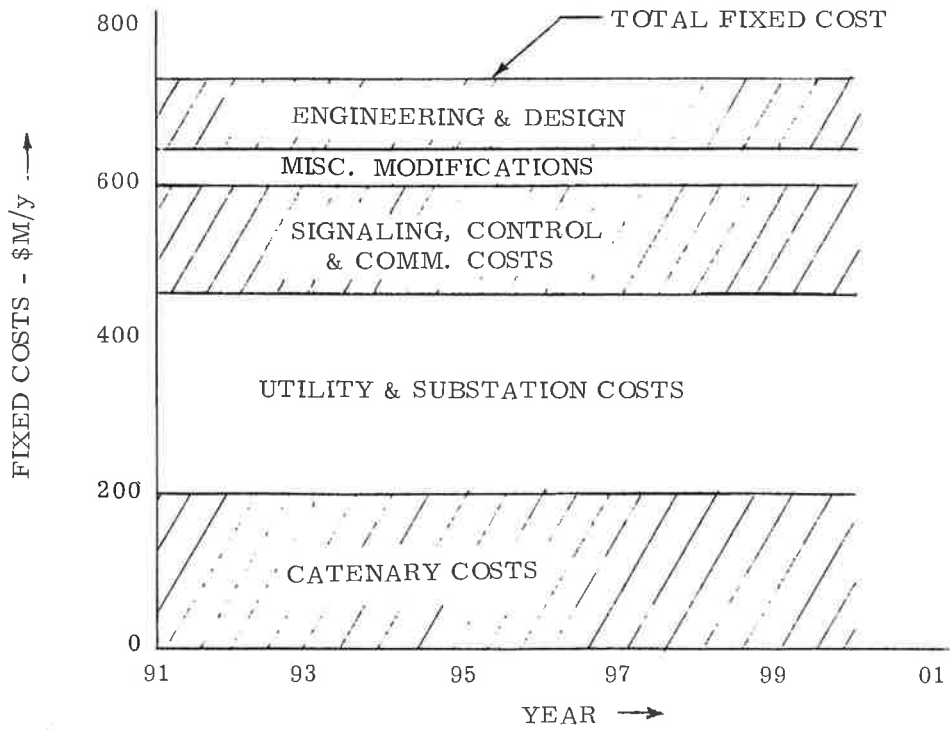


FIGURE C-10 ANNUAL CAPITAL COSTS FOR 10,000 ROUTE MILES: FIXED COSTS AND LOCOMOTIVE COSTS (MILLIONS OF DOLLARS)

APPENDIX D
CALCULATION OF R&D COSTS AND ESTIMATED COST SAVINGS

The cost for R&D and the cost savings that can be accrued by implementing the R&D results are developed in this appendix for selected topics from Appendix B. Table D-1 summarizes the results. Those topics of Appendix B for which costs are not included herein are topics for which the risk of failure of the R&D is too great or the derived benefits are too small to warrant further consideration.

Cumulative base costs for the network from Appendix C are repeated in the first row of Table D-1 to illustrate the relative impact of each R&D topic.

Peak Demand Reduction (Near-Term)

Proposal - Install switched ac capacitors at the substations to neutralize the reactive power load of the locomotives and the I²X of the catenaries and transformers. The capacitors can be included as part of phase balancing, voltage regulating, or filtering equipment.

R&D Cost - Estimate the cost of studies by computer and by test of a sample installation at \$2 M over a 3 year period.

Savings in Cost - The result of the installation can be estimated to reduce the peak demand per substation by 25%, by using 15,000 kvar of switched capacitors.

- (1) Utility connections (save 25%)
cost saving = $425 \times \$1.2 \text{ M} \times 0.25 = \127.5 M
(number of substations = 425)
- (2) Utility reinforcement (save 25%)
cost saving = $425 \times \$3.0 \text{ M} \times 0.25 = \318.8 M
- (3) Reduced peak demand charge (0.3¢/kWh)
cost saving = $\$0.3 \times 10^{-2}/\text{kWh} \times (119.2 \times 10^9 \text{ kWh}) = \358 M

Added Cost - Assume switched capacitors at \$9/kvar.
added cost = $425 \times 15,000 \text{ kvar} \times \$9/\text{kvar} = \$57.4 \text{ M}$

TABLE D-1 - ESTIMATED COST BENEFITS FROM R&D RELATED TO ELECTRIFICATION OF 8500 ROUTE MILES - FROM 1980 TO 1990

	R&D COST \$M	R&D RISK	OPERATING COSTS			CAPITAL COSTS				TOTALS		
			UTILITY ENERGY \$M	ELECTRIC LOCOMOTIVE (WARRANT.) \$M	CATENARY \$M	SIGNAL & COMMUNIC. \$M	LOCOMOTIVE \$M	SPECIAL EQUIP. \$M	ELECTRIFICATION SUBSTATION \$M	UTIL. \$M	OPERATING COST* \$M	CAPITAL COST* \$M
I. Cumulative Base Costs For 10 Years Which R&D Can Impact			6303.8	209.2	1700.	1190.	1749.8	425.	1785.	6513.	6850.	
II. Near-Term R&D												
1. Utility Connections & Substation R&D												
(1) Peak Demand Reduction	2	LOW	-358.									-388.9
(2) Phase Balance Improvement	5	MOD.	-189.									-531.3
(3) Reactive Power Reduction	6	MOD.	-272.									-122.0
(4) Regenerative Power Management	5	LOW										-272
2. Catenary Systems R&D												
(1) Construction Equipment and Techniques	15	MOD.			-170.							-145.
(2) Design Standardization	1	MOD.			-25.5							-25.5
(3) Economical Catenary Design	5	MOD.			-150							-150
3. Motive Power R&D												
(1) Wheel Slip Control Improvement	3	MOD.										-281.4
(2) Power Density Improvement	10	MOD.										-134.1
(3) Diesel-to-Electric Conversion	2	MOD.										+9.9
4. Signaling & Communications R&D												
(1) Harmonic (EMI) Control	4	MOD.										-41.8
(2) Wheel, Flange & Hot Box Detection Development	0.5	MOD.										-23.1
(3) Speed Profile Control Method Development	0.4	MOD.										+9.9
*Negative Cost Indicates Savings or Benefits												

Summary

Savings in utility capital costs	=	\$446.3 M
Savings in demand charges	=	358 M
Added cost for capacitors	=	<u>(57.4 M)</u>
Net savings	=	\$746.9 M

Phase Balance Improvement (Near-Term)

Proposal - Install equipment at each substation to convert the 3-phase utility power to 1-phase 60-Hz power for the catenaries. Consider adjustable static balancers, M-G sets, and solid-state converters.

R&D Costs - Estimate the program to build model terminal equipment and test for reliability, efficiency, harmonics, and overload capability, as \$5 M over a 5 year period.

Savings in Cost

(1) Utility Reinforcement.

Assume a reduction in charge for utility reinforcement of 75% of \$3 M or \$2.25 M per substation.

$$\text{savings} = \$2.25 \text{ M/sub} \times 425 \text{ sub} = \$956.25 \text{ M}$$

(2) Utility Connection.

Assume a reduction in connection charge of 50% of \$1.2 M figure or \$0.6 M/substation. The substations can be connected to the utilities at a lower voltage level and with less system reinforcement than for 1-phase connection.

$$\text{saving} = 425 \text{ subs} \times \$0.6\text{M/subs} = \$255 \text{ M}$$

Added Cost - Assume a cost of \$80/kVA for the phase balancing and converter equipment at the substation.

$$\text{added cost} = 425 \text{ subs} \times 20,000 \text{ kVA/subs} \times \$80/\text{kVA} = \\ \$680 \text{ M}$$

Summary

Savings in utility costs	=	\$1,121.25 M
Added cost of converters at substations	=	<u>(680 M)</u>
Net saving in cost	=	\$ 531.25 M

Reactive Power Reduction (Near-Term)

Proposal - Install on each electric locomotive a switched capacitor bank, either as part of the harmonic filter or independently to reduce the reactive power load (increase PF) of the

locomotive. The effect will be to reduce the per-mile voltage drop in the catenary and reduce the required substation kVA.

R&D Cost - Estimate the program to analyze the circuits for all predictable operating conditions, install the capacitors, and conduct tests, as about \$6 M over a 5 year period.

Savings in Costs - Based on the 8,500 mile electrification model with 425 substations and 1,715 locomotives, the savings will be:

- (1) Substation spacing.
Assume that the installation of 2,000 kvar of capacitors per locomotive will reduce the reactive power at full load of about 50%, and reduce the per-mile voltage drop by 25%. The substation spacing can be increased by 25%, or the number of substations reduced by 20% to 340.
- (2) Substation rating.
The substations must be increased in rating by 20% in kW, but less than 10% in kVA. Assume that the substation cost increases by 5%, but not the utility connection cost. The cost per substation becomes:

$$\text{cost} = \$1 \text{ M} \times 1.05 + \$1.2 \text{ M} = \$2.25 \text{ M}$$

- (3) Total and additional substation cost.
Original cost = 425 x \$2.2 M = \$935 M
New cost = 340 x \$2.25M = (765)
cost reduction \$170 M

- (4) Reduced Demand Charge.
Assume a penalty of .3% per percent of power factor below 90%. For an average power factor of 80%.

$$\text{cost savings} = (.003)(90-80) \times \$6,304 \text{ M} = \$189 \text{ M}$$

Added Cost - Assume the addition of 2,000 kvar of capacitors at \$14/kvar, including switches, to each locomotive. The added cost will be:

$$\text{added cost} = 1,715 \text{ loco} \times 2,000 \text{ kvar} \times \$14/\text{kvar} = 48.0 \text{ M}$$

Summary - Saving in use of capacitors is the following:

Saving in substation cost	=	\$170 M
Reduced demand charge	=	189 M
Added loco cost	=	<u>(48 M)</u>
Net saving	=	\$311 M

Catenary Systems Construction Equipment and Techniques (Near-Term)

Proposal - Consider an R&D program to develop the equipment and construction techniques required for installation, alignment and inspection of catenary at the anticipated rate of 1,000 mi/y. No interference with revenue operation is required during installation. Design and install prototype catenary at Pueblo to demonstrate installation equipment and procedures.

R&D Cost - Cost for this program including analysis, prototype installation equipment and prototype catenary will be \$15 M over a 5-year period.

Savings in Cost - The benefit would be a 20% savings in installation labor over the existing installation procedure.

$$\text{Cost savings} = 0.2 \times \left(\frac{\$1.7\text{B}}{2} \right) = \underline{\$170 \text{ M}}$$

Added Cost - The added cost of investment in automated equipment is \$25 M.

Summary

Cost savings	=	\$170 M
Added cost	=	<u>(25 M)</u>
Net savings	=	\$145 M

Catenary Systems Design Standardization (Near-Term)

Proposal - Consider an R&D program that will establish interchangeability by standardizing functional requirements of catenary components. This would be a continuing effort in which the initial benefit can be measured in terms of percent reduction in capital cost if all segments being electrified can use common equipment.

R&D Cost - The cost of establishing standards would be \$1.0 M and would include selection of design features from the existing equipments of Europe, Russia, and Japan that meet U. S. requirements. The cost also includes some testing that would be performed if a test and demonstration loop is established.

Savings in Cost - Capital cost reduction is estimated to be 3% of the material costs, or

$$.03 \left(\left(\frac{\$1.7B}{2} \right) \right) = \underline{\$25.5 M}$$

The initial effort would require culling out the specifications which can be established prior to electrification of any revenue lines.

Catenary System Economical Catenary Design (Mid-Term)

Proposal - Consider an R&D program to develop a single wire catenary which permits electrified operation at speeds up to 80 mi/h. Design and test prototype catenary to demonstrate performance.

R&D Cost - The cost of R&D for single wire design and test will be over \$5 M over a five-year period.

Savings in Cost - The benefit would be a savings in catenary capital cost of 15% (material and labor). For the remaining portion of the 8,500 miles to be electrified between 1985 and 1990, the cost benefit would be:

$$0.15 \times (\$1.7B - 0.7B) = \underline{\$150 M}$$

Motive Power - Wheel Slip Control Improvement (Near-Term)

Proposal - Improve wheel-slip control methods to increase the adhesion of locomotive wheels, particularly in the low speed region up to rated speed. Each 1% increase in effective adhesion means that the locomotive fleet can be reduced by almost 1%. To improve the control, the drive system must be designed specifically for that function, rather than as an added control function to an existing drive design, as is now done.

R&D Cost - Estimate the program to modify a test locomotive with several types of wheel-slip control schemes and conduct extensive tests as \$6 M over a 5-year period, for use in the locomotives to be delivered in 1980.

Savings in Cost - A target for improvement of the effective adhesion is by 25% of the present values, or say from 25% adhesion to 31.2% adhesion. The fleet can be reduced to 80% of the projected number of locomotives.

locomotive savings = 0.20 x \$1,749.8 M cum. loco. costs = \$350 M
 locomotive maintenance savings = 0.2 x \$209.2 cum. elec. loco.
 mtc. cost = \$41.8 M

Added Cost - The added cost of controls on each locomotive is estimated at \$50,000.

added cost = 0.8 x 1,715 loco x \$50,000 = \$68.6 M

Summary

Savings from reduced fleet	= \$350.0 M
Savings from reduced fleet maintenance	= 41.8 M
Added cost of controls	= <u>(68.6)M</u>
Net Saving	= \$323.2 M

Motive Power- Diesel to Electric Conversion (Near-Term)

Proposal - Convert selected 3,600-hp diesel-electric locomotives to all-electric locomotives instead of purchasing all 6,000-hp electric locomotives for the electrification program. The conversion would be done on diesel units that had been fully depreciated and would need major overhaul of the engines, motors and trucks. The locomotives still have residual scrap value or value to a rebuilder.

R&D Cost - Estimate the program to study the problem, prepare conversion designs, and convert at least one locomotive as \$2 M over a 3-year period.

Savings in Cost - The comparison between purchase of a new 3,600-hp electric locomotive and the conversion of a diesel-electric unit is shown below:

<u>Item</u>	<u>Assumption</u>	<u>Conversion</u>	<u>New Electric</u>
Frame and trucks	Overhaul old unit	\$ 20,000	\$ 50,000
Electrical plant	\$50/hp	180,000	180,000
Traction motors	Overhaul old unit	80,000	160,000
Misc. (Controls, etc.)	Same	<u>60,000</u>	<u>60,000</u>
Total		\$340,000	\$450,000

The diesel-electric units are estimated to have a residual value of \$50,000 each, before conversion.

saving = \$110,000 - \$50,000 = \$60,000/locomotive

Assume that one half of the 6,000-hp fleet in horsepower is replaced with converted diesel-electric units.

$$\begin{aligned} \text{converted units} &= 889 \times 6,000 \text{ hp} \times 0.5 \times 1/3,600 \text{ hp} = 745 \text{ units} \\ \text{savings} &= 684 \times \$0.06 \text{ M/loco} = 41.0 \text{ M} \end{aligned}$$

Added Cost

The additional units of a new size will increase the overall maintenance cost by:

$$\begin{aligned} \text{cost} &= (684 - 82 \frac{1}{2}) \times (8,760 \times .75) \times 25 \text{ mi/h} \times \$0.22/\text{unit-mile} \\ &= 300 \text{ units} \times 120,000 \text{ mi/y} \times \$0.22/\text{unit-mi y} = \$9.9 \text{ M} \end{aligned}$$

Summary

Savings in conversion	=	\$41.0 M
Added maintenance cost	=	<u>(9.9)M</u>
Net Saving	=	\$31.1 M

Harmonic (EMI) Control (Near-Term)

Proposal - Install on each locomotive adequate filters for harmonic and communication-interference suppression.

R&D Cost - Estimate the program to build filters, make measurements, as about \$4 M over a 5-year period.

Savings in Cost - Based on the 8,500 mile electrification model, which includes 425 substations and 1,715 locomotives, the savings will be:

- (1) Substations.
Estimate the reduction in substation filter cost at \$5/kVA, or \$100,000/sub

$$\text{saving} = 425 \text{ sub} \times \$0.1 \text{ M/sub} = \$42.5 \text{ M}$$

- (2) Signal & Communications.
Estimate the reduction in cost of the wayside S&C system as \$20,000/mi.

$$\text{saving} = 8,500 \text{ mi} \times \$20 \text{ k/mi} = \$170 \text{ M}$$

Added Cost - Assume filters cost \$5/kVA and that the locomotives average 8,000 kVA. The added cost is:

$$\text{added cost} = 1,715 \text{ loco} \times 8,000 \text{ kVA/loco} \times \$5/\text{kVA} = 68.6 \text{ M}$$

Summary

Reduced substation filter costs	=	\$ 42.5 M
Reduced signaling and communications costs	=	170.0 M
Added cost on locomotives		<u>(68.6)M</u>
Net saving in cost	=	\$143.9 M

Regenerative Power Management (Mid-Term)

Proposal - On locomotives built for service starting in 1987 (10,000 hp), provide the control equipment for both regenerative braking through the on-board rectifiers to the catenary, and for conventional resistor dynamic braking. The substations built for the new electrified track starting in 1987 will be equipped with means for controlling the utility feeder voltage during regeneration to avoid excess voltage condition. The means can be switched capacitors or tap changing on the transformers.

R&D Cost - Estimate the program to build a test locomotive, modify a substation, and conduct extensive tests of operation, energy recovery, harmonics, and reliability as \$5 M over a 10-year period.

Savings in Cost - Assume a 10% savings in utility charges for the kWhs used by the 10,000 hp locomotives in the 1987-1990 incl. period.

$$\text{saving} = 0.10 \times \$3,288.6 = \$272.0 \text{ M}$$

Added Cost

(1) Substations.

Assume that the additional equipment for voltage control at the substations built in the 1987-1990 includes period costs \$5/kVA.

$$\text{added cost} = 250 \text{ subs} \times 20,000 \text{ kVA/sub} \times \$5/\text{kVA} = \$25 \text{ M}$$

(2) Locomotives.

Assume that the additional control equipment for the 10,000 hp locomotives will cost \$25,000 per locomotive.

$$\text{added cost} = 894 \text{ loco} \times \$25,000/\text{loco} = \$22.3 \text{ M}$$

Summary

Savings in utility charges	=	\$272.0 M
Added cost of equipment	=	<u>(47.4)M</u>
Net saving in cost	=	\$224.6 M

Motive Power - Locomotive Power Density Improvement (Mid-Term)

Proposal - Increase the horsepower applied at the wheels of the electric locomotive per ton of weight to reduce the number of locomotives required, or to increase the average speed of freight operation with the same number of locomotives. The tractive force at low speeds is limited by the adhesion to some percentage of the weight, which depends on track conditions, i.e., wet or dry, so that additional horsepower may not be utilized, even if developed. Improved wheel slip control may increase the usable horsepower at low speed. However, the additional horsepower can be utilized above the rated speed, up to the maximum speed, as additional tractive force.

R&D Cost - Estimate the program to build a test locomotive with several types of ac traction motors and power conditioners, including induction motors, synchronous motors, and voltage-fed, current-fed, and phase-redundant inverters as \$10 M over a 10-year period.

Savings in Cost - The increase in traction force and horsepower in the upper speed region with inverter-ac motors is estimated as up to 50% over the values presently obtained with dc-series and independent-field motors. Assume that the 10,000-hp class of locomotives to be placed in series in 1985 will deliver the rated tractive force up to 150% of rated speed (15,000 hp), and 150% hp up to 200% of rated speed. For example, rated speed is 40 mi/h, constant tractive force up to 60 mi/h, constant horsepower up to 80 mi/h. Further assume that these nominal 10,000 hp, actual 15,000-hp, locomotives will pull 50% more gross ton miles per year, so that 67% of the 10,000-hp fleet will be required.

$$\begin{aligned} \text{locomotive cost savings} &= 0.33 \times \$1,206 \text{ M cost of } 894 \text{ } 10 \text{ khp} \\ & \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \text{loco.} \\ &= 372.5 \text{ M in locomotives} \\ \text{locomotive maintenance costs savings} &= 0.33 \times 69.2 \text{ M} = \$23.1 \text{ M} \end{aligned}$$

Added Cost

The added cost to replace the 10,000-hp rectifier-dc motor drive systems with the 15,000 hp inverter-ac motor drive system is shown below:

<u>Item</u>	<u>Assumption</u>	<u>10,000-hp dc</u>	<u>15,000-hp ac</u>
Frame and trucks	Same	\$ 150,000	\$ 150,000
Electrical plant	\$50/hp dc	500,000	
	\$60/hp ac		900,000
Motors	\$45/hp dc	450,000	
	\$30/hp ac		450,000
Misc. (controls, brakes, etc.)	Same	<u>150,000</u>	<u>150,000</u>
Total		\$1,250,000	\$1,650,000

added cost per locomotive = \$400,000
added cost for fleet = 0.67 x 894 x \$0.4 M = \$238.4 M

Summary

Savings from reduced fleet size = \$372.5 M
Savings from reduced fleet maintenance = 23.1
Added cost for fleet = (238.4)

Net saving in cost = \$157.2 M

Wheel, Flange, and Hot Box Detection Development (Near-Term)

Proposal - Satisfactory methods of detecting loose wheels or wheels with broken flanges on a moving train do not exist. Railroads are presently using their own funds to evaluate devices intended to detect either or both conditions.

R&D Cost - Consider R&D programs to collect and evaluate data on experimental work already done, and to improve those methods showing the most promise. Design and build prototypes and evaluate them on a cooperating railroad. Cost of R&D \$100 K/y for 5 years for a total of 0.5 M.

Savings in Cost - Possible savings are estimated on a basis of 50 less derailments and wrecks/y for all Class 1 railroads at an average cost of \$50,000 each. Savings apply to 15% of total traffic over a 5-year period.

$$\text{savings} = (50 \times .15) \times 5 \times 50,000 = \$1.9 \text{ M}$$

$$\text{Added Cost} - \text{Cost of detectors} = (0.15 \times 1500) \frac{\text{detectors}}{y} \times 5y \times \$1,000 \text{ each} = \$1.1 \text{ M}$$

Summary

Possible savings	\$2.125 M
Added cost	<u>(1.275 M)</u>
Net savings	\$0.85 M

Speed Profile Control Method Development (Near-Term)

Proposal - Present 3-aspect signaling systems consist of "clear," "restricted speed," and "stop" aspects. Restricted speed depends on operating rules of the company but is almost always less than one-half the civil speed limit for the system. With present signals a following train must slow to restricted speed when headway becomes too small. Later the train must again accelerate, using large amounts of energy.

R&D Cost - Consider R&D programs to study a moving speed profile providing the following train with an indication of reduced headway earlier when a small speed reduction can be made over a longer time to regain the required headway. The program should consider methods of providing speed profile data to the engineer as well as the method of modifying existing track circuits. Cost of R&D \$100 K/y for 4 years for a total of \$0.4 M.

Savings in Cost - Possible savings - estimated at 1% of the energy consumption/y over the last 5 y (1987-1990) or # (6303.8-646.9).

$$\text{savings} = 0.01 \times \$5,656.9 \text{ M} = \$56.6 \text{ M}$$