flections into the power system is, as a general rule, mitigated to a considerable extent by the inherent capacitance of the commercial power network; if this is not sufficient, filtering capacitors can be installed at the railway substation. Further, it is believed that proper use of neutralizing transformers in the telecommunication system or booster transformers and return feed on the railway can, in considerable measure, eliminate harmonic problems or reduce them to tolerable levels.

Impact of Research and Development on Railroad Electrification

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

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

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

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

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

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

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

Electrification of U.S. railroads could begin immediately if the existing technology from the European, Russian, and Japanese rail systems were adapted. This assumes that design variations resulting from the uniqueness of U.S. railroads are minimal. However, the long-

term implications deserve further attention. Careful consideration should be given to the constraints imposed by adapting existing equipment, particularly if a commitment is made to large-scale electrification in the United States. At the other extreme, it would be unwise to put off electrification until a major evaluation of technological requirements is completed. There are no technological breakthroughs on the horizon that would make obsolete an electrification system that used current technology. If feasibility studies determine that electrification of a sector is justified using the current technology, it should be implemented.

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

TOPICS FOR RESEARCH AND DEVELOPMENT

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

Systems Analysis and Engineering Studies

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

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

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

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

Electrification Standards

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

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

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

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

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

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

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

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

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

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

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

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

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

Improvement of the Interface With the Utility

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

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

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

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

If a synchronous three-phase machine is operated at the point of connection of the railroad load, the machine will provide a path for negative-sequence currents paralleling the paths through the three-phase network. Such a machine will reduce the magnitude of negative-sequence currents in the utility network, but the machine must be sized to accept the unbalanced currents safely. Various circuits that use static inductors, capacitors, and transformers can connect a single-phase load to a three-phase source in such a way that the three-phase source perceives a balanced load. If it can be verified that these types of equipment are economically attractive and meet

the conditions of variable loading and a variable power factor, it may be practical to have three-phase to single-phase conversion without rotary equipment or active components.

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

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

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

Catenary Improvements

Automated Catenary Installation

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

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

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

Economical Catenary Design

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

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

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

Locomotive and Multiple-Unit Motive Power

Improved Adhesion

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

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

The object of research and development in this area should be to raise the average adhesion limit by at least 25 percent by considering, for example, correlation of the theory of adhesion with experimental measurements,

study of the theory of micro-slip adhesion, determination of parameters for use in control-system design, development of rugged but sensitive sensors for use on motor and wheel shafts, development of circuits for use with the sensors to indicate relative wheel velocities and accelerations, and design of propulsion control systems. The results should be applicable to both alternating- and direct-current traction-motor locomotives.

Improving Power Density

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

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

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

Regeneration in Electric Locomotives

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

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

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

Control of Power Harmonics and EMI

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

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

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

IMPACT OF RESEARCH AND DEVELOPMENT ON THE ECONOMICS OF ELECTRIFICATION

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

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

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

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

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

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

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

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

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

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

ment cost associated with implementation).

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

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

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

PLANNING RESEARCH AND DEVELOPMENT

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

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

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

CONCLUSIONS

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

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