The Roadway-Powered Electric Transit Vehicle—Progress and Prospects

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In this paper, progress in the development of the roadway powered electric vehicle (RPEV) technology for use on a transit bus is reviewed, and the possible future applications of this technology are explored. The paper focuses on the Santa Barbara Electric Bus project, for which this development work was conducted. The various phases of this project are reviewed, and the baseline roadway powered electric vehicle system for Santa Barbara is described. Its costs are compared with those for more conventional bus technologies. The implications of the progress made in the Santa Barbara project for the future of roadway powered electric vehicle technology are explored, leading to an evolutionary step toward highway automation.

The roadway powered electric vehicle (RPEV) system is an electric-electric hybrid vehicle system that uses a fairly standard battery-electric powertrain to handle the full dynamic range of an urban driving cycle and that receives its energy supply at a relatively steady rate from a special electromagnetic inductive coupling system. The overall design of the RPEV system is described by Lechner and Shladover *(1)*, while the inductive coupling system is explained by Lashkari et al. *(2)*.

RPEV technology has advanced from its initial laboratory implementation to the prototype development and testing stage on a transit bus. At this point, the RPEV system represents one of the most promising developments in the long path leading to a practical electric automobile. The electric automobile has not yet become practical because of the limitations of the available storage batteries, particularly their limited energy density. This means that electric automobiles are heavier and less powerful and have much less operating range than their conventional counterparts. The RPEV system overcomes these limitations by providing a semicontinuous charging current to the vehicle's battery whether the vehicle is moving or parked. In this way, the vehicle can operate with virtually unlimited range on a relatively moderate-sized battery. It can operate for significant periods of time on the energy stored in its battery, so that its operations are not restricted to the powered roadway.

The RPEV system includes vehicles and fixed facilities in the roadway and alongside the road, as shown in Figure 1. Each vehicle is propelled by a separately excited DC motor that draws current from a lead-acid battery by means of a transistorized motor control system. In addition to the battery-electric powertrain, the vehicle also contains a pickup inductor to interact with the magnetic field produced by the roadway inductor and a custom-designed onboard circuit to control and condition the output of the pickup inductor so that it can be used to charge the battery. The onboard control circuit provides rectification, ripple filtering, and computer-controlled power factor correction from a switchable capacitor bank. The roadway inductor, like the pickup inductor, is composed of laminations of grain-oriented silicon steel, for high magnetic permeability and low losses, and large-gauge cables to carry electric current. The roadway inductor is energized by a

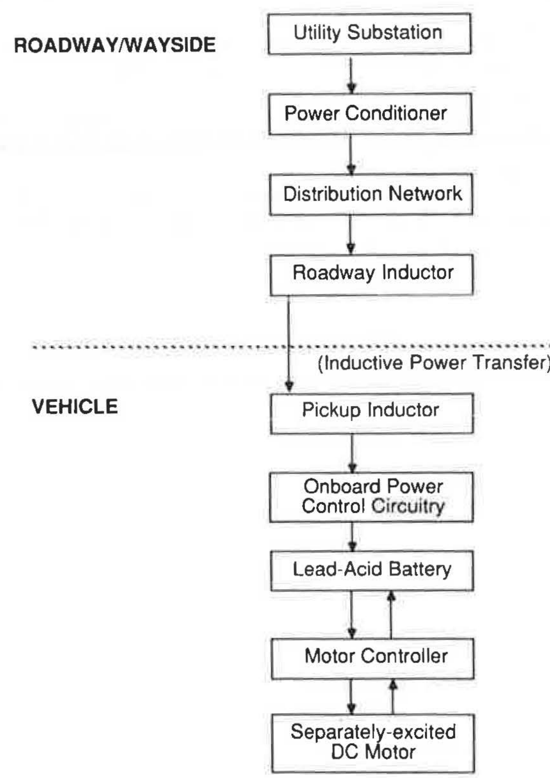

FIGURE 1 Power flow through RPEV system elements.

solid-state power conditioner, a rectifier-inverter system that converts the standard 60-Hz mains power to 400 Hz and isolates the roadway power system from the local electric utility. For the electric bus system described in this paper, the roadway inductor is about 37 in. wide and 4 in. deep, and is buried immediately below the road surface coating. Its cables carry about 1,000 amps at 400 Hz, and the system is capable of transferring 67 kW of power across an air gap of 3 in. to the pickup inductor on the vehicle, at an efficiency of about 95

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percent. The 3-in. air gap height is maintained to within acceptable tolerances by simply suspending the pickup inductor beneath the vehicle, without any special provisions for controlling the gap height. The cross sections of the roadway and pickup inductors are shown in Figure 2.

By providing the electric vehicle with practical daily range, the RPEV technology makes it possible to enjoy the inherent advantages of electric propulsion with respect to internal combustion engines (ICEs). These advantages include greatly reduced noise and mobile-source pollution for use in sensitive locations, such as enclosed areas, pedestrian malls, parks, and historic districts. In the longer term, the electric power train is much more amenable than the ICE to the tight closed-loop spacing control that will be needed to effect highway automation.

An overview of the development of the RPEV technology for an urban transit bus system in Santa Barbara, California, is presented. The technological features of this system have been described elsewhere, in the references cited throughout this paper. The emphasis here is on explaining the background of the development work, its current status, and the steps remaining to full-scale implementation. The economics of the system at its present early stage of development are described, with comparisons to competing standard technologies, and the prospects for future development and application of the RPEV system are then explored.

THE SANTA BARBARA ELECTRIC BUS PROJECT

The development activities reported here were performed as part of the Santa Barbara Electric Bus Project, sponsored by the Santa Barbara Metropolitan Transit District (SBMTD), with funding from the Urban Mass Transportation Administration (UMTA), the California Department of Transportation (Caltrans), and the city of Santa Barbara. The history of this project from its inception through the present, and then its future anticipated completion, are reviewed in the next section, followed by a description of the baseline system design and a status report on the accomplishments to date.

History of Santa Barbara Electric Bus Project

The concept of inductive transfer of electric power to a vehicle is not new but was the subject of patents dating back to the turn of the century. The modern incarnation of this technology began at the Lawrence Berkeley Laboratory and the Lawrence Livermore National Laboratory (LLNL), under the primary sponsorship of the Department of Energy, during the period 1976 to 1982. That work was effectively reported at the 1982 TRB meeting by Carl Walter of LLNL *(3)*. Little was accomplished on the project subsequently because of funding limitations.

While the LLNL work was in progress, the city of Santa Barbara was developing plans for a new downtown circulation bus service, focused on the State Street Mall. At this location, urban redevelopment activity had created an attractive pedestrian-oriented environment, with fountains and carefully coordinated street furniture enhancing the atmosphere for shoppers and tourists. State Street was reduced to a single lane in each direction, with additional right-turn pockets, for the approximately 1-mi length of the mall, but vehicular traffic was not otherwise restricted. The environmental sensitivity of the citizens of Santa Barbara ruled against the use of either diesel buses or trolley buses along the Mall, the former because of their noise and smell and the latter because of the unsightliness of their overhead wires. Battery electric buses were not a reasonable alternative because of their severely limited range, so the developing RPEV technology appeared to be a promising alternative.

A feasibility study of the use of the RPEV technology for the bus service in downtown Santa Barbara was conducted for SBMTD, with funding from Caltrans, in 1979 and 1980. This study, which has since been referred to as Phase 1 of the Santa Barbara Electric Bus Project, included planning, some computer simulations to predict system performance, an overview of the technological and environmental issues surrounding the RPEV technology, and an outline of the subsequent phases needed to bring the complete project to fruition *(4)*.

Phase 2 of the project, involving detailed planning and preliminary engineering work, was funded by Caltrans and the

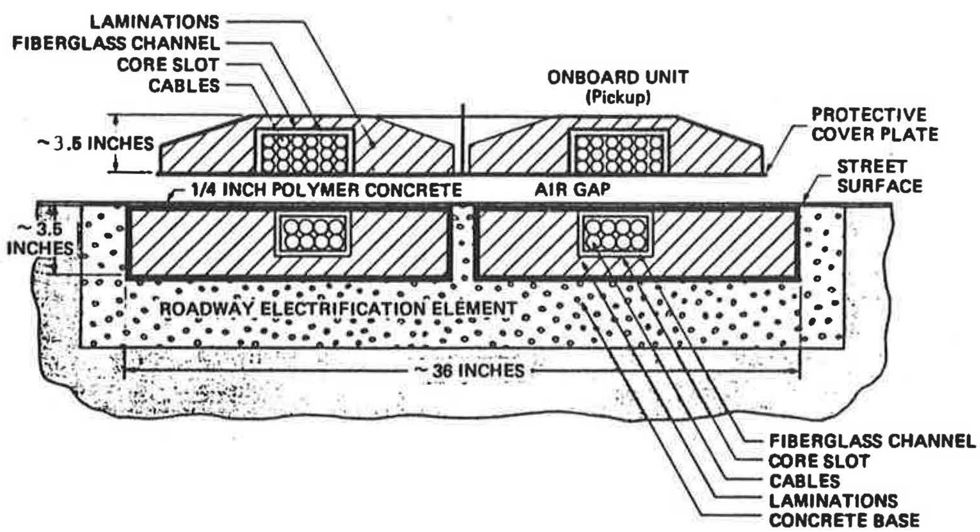

FIGURE 2 Schematic diagram of roadway and pickup inductors.

city of Santa Barbara. This work, conducted between July 1981 and June 1982, led to more detailed and quantitative analysis of RPEV service on specific bus routes in downtown Santa Barbara, with the benefit of specific design and engineering information about the prototype vehicle and inductive coupling system. The basic vehicle and route service characteristics assumed today were originally developed during Phase 2 and can be found in the Phase 2 final report *(5)*. During this time, the much more complicated Phase 3 work plans and institutional arrangements were also under development.

Phase 3 of the project was divided into two parallel programs, distinguished from each other by their funding sources but closely coordinated technically. The Prototype Development and Test Program of Phase 3 was funded by UMTA and the Santa Barbara Redevelopment Agency, while the Test Facilities Development and Testing Program was funded by Caltrans. Although the latter program was performed under a single long-term contract, it was necessary to split the former program into four separate increments, corresponding to the four federal fiscal years of funding to be supplied by UMTA. These four increments, known as Phases 3A, 3B, 3C, and 3D, corresponded to the federal fiscal years 1982, 1983, 1984, and 1985, respectively.

Phase 3A, conducted between September 1982 and February 1983, began the detailed analysis and design of all of the RPEV system equipment. Mathematical models were developed of the inductive coupling system and of the performance of the complete vehicle system as well, and capital and operating cost comparisons were made with other transit bus technologies. The design and specifications for the prototype electric bus were developed, and concentrated study of the available storage battery technologies was undertaken. The systematic trade-offs among the many different attributes that influence performance of the entire system were begun and were reported at considerable length in the Phase 3A final report *(6)*.

A lengthy funding hiatus ensued before Phase 3B could be initiated in August 1983. During this phase, the prototype vehicle was built, the onboard control system to regulate the power supplied to the battery was designed and its hardware acquired, batteries were tested, and an environmental assessment of the system was prepared. The analyses and predictions of system and subsystem performance were continued with ever greater precision and sophistication, to ensure that the RPEV technology would satisfy the system requirements. This work, which was conducted in parallel with the Caltrans-funded program until August 1984, was reported in detail in the Phase 3B final report *(7)*.

The Caltrans-funded Test Facilities Development and Testing Program began concurrently with Phase 3B in August 1983 and continued to the end of June 1985. This program encompassed the development of the inductive coupling technology, from initial design to comprehensive laboratory testing. Computer models were used to analyze the magnetic fields in and about the roadway and pickup inductors, and these analyses provided vital input to the designs and specifications for construction of these inductors. The inductors were built at full scale, and a laboratory facility was designed and constructed to house a roadway section about 20 ft long, as well as a complete inductive pickup of a size suitable for powering the prototype electric bus (13 ft long). A power conditioner was specified, fabricated, and installed at the facility, and about 5 months of intensive testing were performed to prove the performance of the inductive coupling system under a wide range of conditions. The results of this work were reported at great length in the Static Test Report *(8)*.

Phase 3C of the project was conducted between August 1984 and April 1986. This phase focused on testing and refinement of the technology developed in the earlier phases. The prototype electric bus was tested under battery power on the baseline route in Santa Barbara, and the test results were used to confirm the prior predictions of its performance. The full-scale inductive power transfer system was tested extensively in the laboratory in Sacramento, with the on-vehicle electric circuitry, including the complete battery system, connected to it. Successful operation of the system was demonstrated, with the battery being charged by the inductive coupling system, under the control of the microcomputer system that will be used on the vehicle. The results of this phase of the project have already been reported *(9)*.

Completion of the RPEV technology development for the Santa Barbara Electric Bus System will require work planned for Phase 3D of the Prototype Development and Test Program and the parallel development of a long test facility (of about 500 ft) on which the prototype vehicle can be operated at speed, while collecting power from a roadway inductor. The existing short test facility developed by Systems Control Technology, Inc., at the Caltrans Transportation Laboratory (Translab) in Sacramento has been used for extensive testing already, but that facility does not have the length needed for testing power collection while the vehicle is in motion. Once these technology development activities are complete and the funding and sponsoring agencies have found the results to be satisfactory, it will be possible to proceed into Phase 4, Construction, and then Phase 5, Demonstration Operation of the complete system.

The Baseline Santa Barbara Electric Bus System

The Santa Barbara Electric Bus System was selected as the initial demonstration site for the RPEV technology for a variety of reasons. Much of the discussion in this paper is therefore focused on the Santa Barbara application. However, this site is just the initial demonstration site, and it does not represent the full potential of the RPEV technology. The baseline system was designed to meet the specific requirements of this application, not to show the full range of what could be done by the RPEV. It is necessary to demonstrate the RPEV on this limited scale, in a relatively benign environment, as a first step before addressing broader applications of the RPEV. Of course, each different application would have somewhat different requirements and a somewhat different optimum system design.

Santa Barbara proved to be a promising demonstration site because of the limited scale of the bus service that was contemplated, the environmental concerns of its citizens, its mild climate, and the open-mindedness of its public officials. In this setting, the RPEV development could be nurtured before the rigors of northern winters, desert summers, large-scale and high-visibility transit operations, or big-city politics were dealt with.

The baseline bus service application is a 5.5-mi round-trip downtown circulation system in Santa Barbara, along the route shown in Figure 3. Only 40 percent of this route, primarily the part along the State Street Mall, needs to be equipped with the roadway inductor. For the remainder of the route, the vehicle operates as a battery bus, using only the energy stored in its battery. The route is essentially flat along the beachfront on Cabrillo Boulevard, with the grade gradually increasing to about 3 percent on the last uphill block on State Street. Tourists are expected to represent a significant portion of the ridership, which is the reason that the route extends along the waterfront to several hotels and a convention center that is under construction in the vicinity of Punta Gorda Street and Cabrillo Boulevard.

Bus service is to be provided at 5-min headways for 10 hr per day. Frequent stops are anticipated along State Street with its many shops and restaurants, making the vehicle's duty cycle particularly rigorous and limiting the effective average vehicle speed. A complete round trip is expected to require 40 min, including layovers at both ends of the route, so it will be necessary to have eight buses in service continually to maintain the desired 5-min headway. This short headway is needed to make the service sufficiently convenient and attractive to the shoppers and tourists that they will all park their cars in one place and use the bus system for their movements within the shopping district.

The prototype electric bus, shown in Figure 4, is a mid-sized vehicle 28 ft long, with room for 17 seated passengers and 18 standees. Its floor is less than 15 in. above the street level (less than half the height of the floor on a conventional bus) to promote ease of access by elderly and handicapped riders. The low floor and medium length of the bus help it to maintain a low-profile appearance so that it will not be intrusive on the State Street Mall. The vehicle's curb weight is 25,400 lb, and maximum gross vehicle weight is 31,200 lb. These weights include about 6,000 lb of lead-acid batteries and 2,200 lb for the inductive power transfer system (together representing 32 percent of the curb weight and 26 percent of the gross vehicle weight). A conservative battery selection was made for the prototype vehicle to minimize technical risks in the development program. The tubular lead-acid industrial battery used here has a specific energy of only 23.5 W-h/kg, which means that battery weight could be halved by the use of more advanced batteries that are now in demonstration use on some

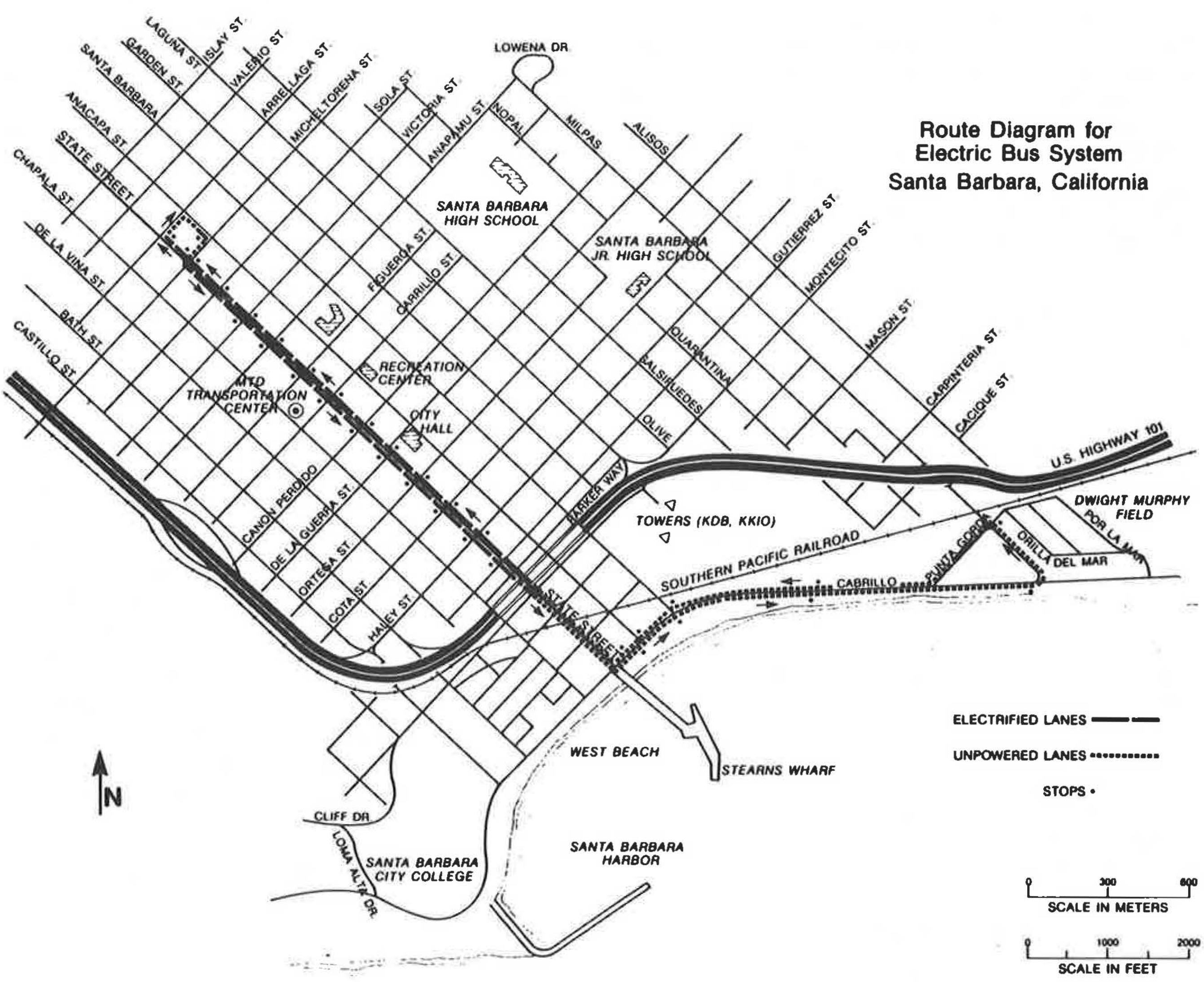

FIGURE 3 Baseline Santa Barbara electric bus route.

FIGURE 4 Prototype Santa Barbara electric bus.

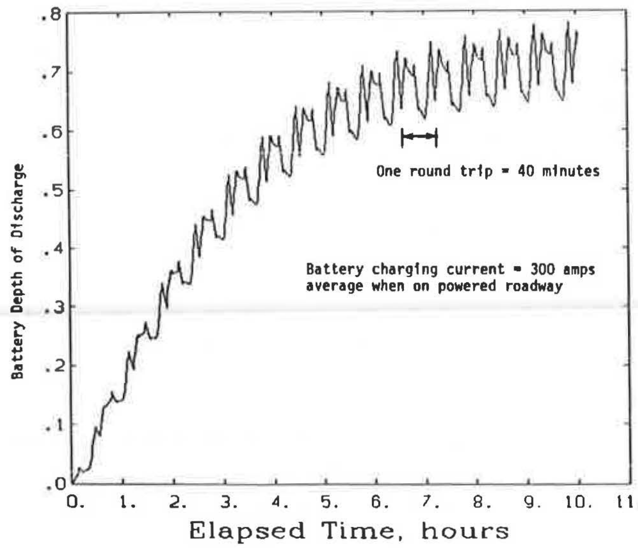

FIGURE 5 Simulation of battery depth of discharge for a full day of bus operation.

electric vehicles. Expected future improvements in battery technology should further reduce battery weight and improve performance of the RPEV system, which will continue to require less onboard battery capacity than a battery-only vehicle system.

The prototype vehicle is a high-quality, heavy-duty vehicle and not a minibus. Its heavy-duty design and special low floor configuration contribute significantly to its cost and weight, independently of the use of RPEV technology. A diesel-powered version of this vehicle would have a curb weight of about 19,000 lb and would cost about $150,000.

The RPEV system has been designed assuming a top vehicle speed of 20 mph in the stop-and-go operations on the State Street Mall and 30 mph on Cabrillo Boulevard, although the vehicle has been driven at speeds up to 35 to 40 mph (the speed limit) during testing along Cabrillo. As already mentioned, approximately 40 percent of the bus route is to be supplied with the roadway inductor, representing the layover points and the State Street Mall, where the speeds are lowest. For the remainder of the route, the bus will operate entirely off the stored energy in its battery. When it is driving along the powered roadway, the vehicle's onboard control system will draw as much power from the roadway as its battery can accept. This means that some of the driving time will represent net battery charging (cruising downhill, for example) while some of the driving time will represent net discharging (accelerating uphill). The system has been designed so that the vehicle's battery will not be discharged by more than 80 percent of its capacity after 10 hr of operation, including all of the alternate charging and discharging it will experience as it traverses the route. Extensive computer simulations, validated by data from testing of the prototype vehicle and the inductive coupling system, have shown how the battery state of charge will decline gradually in the course of a 10-hr operating day (Figure 5). Without the inductive coupling system for recharging the battery, it would be depleted within little more than 2 hr of operation on the baseline route.

Present Status of Development Work

Most of the technology development work on the RPEV system for the Santa Barbara Electric Bus has been completed. The history of this work was covered in a previous section, while its present status is reviewed here.

The prototype electric bus has been designed, built, and tested under battery power. It has been driven around the baseline route while measurements were made of its speed, steering accuracy, road surface clearance, and energy consumption (battery voltage and current). These measurements have been used to refine the computer models that were used to design the entire system, and the models have continued to predict that the system will perform as desired.

The inductive power transfer system was designed from scratch, using computer models based on electromagnetic theory and electric circuit design principles. The results from the computer modeling formed the basis for specifications for the full-scale hardware, which was then built and tested. The roadway and pickup inductors, in particular, were of such a unique design that special methods were developed to fabricate them. The testing of the inductive power transfer system confirmed its ability to deliver the required power with acceptable efficiency and no adverse environmental impacts. The test results were extremely close to the original design predictions, so that the design models needed only minor adjustments.

The separate testing of the prototype vehicle and the inductive power transfer system has greatly increased confidence that the entire RPEV system will meet its performance goals. Some of these test results were reported by Lechner and Shladover *(1)* and Lashkari et al. *(2)*; complete results can also be found elsewhere *(7–9)*. Virtually all the known areas of technical risk have been investigated, and the risks have been found to be minimal in terms of potential environmental impacts of the magnetic fields, power transfer efficiency, safety, component sizes and weights, tolerance to off-nominal conditions, ability to control power output, and so forth.

It is still necessary to test the power transfer system installed on the vehicle, coupling power while the vehicle is driving. This cannot be accomplished until a test facility longer than the present 20-ft-long facility is available. The longer test facility will also be used to develop the electric power distribution system that connects the entire system of roadway inductors to the power supply. It is expected that the development of the long test facility (500 ft of electrified roadway to represent one full block in downtown Santa Barbara) and the comprehensive testing using that facility will require 2 years more of work. Once that is completed to the satisfaction of all the agencies involved, the detail design of the final system can be specified and construction of the roadway electrification system and the fleet of buses can begin.

ECONOMICS OF RPEV BUS SYSTEM

The RPEV system for Santa Barbara has been designed as a demonstration system to prove the feasibility and applicability of the RPEV technology for use on public vehicles. It was deliberately chosen as a limited-scale system to minimize the risk of introducing this new technology. This factor must be kept in mind when evaluating the economics of the system, because the RPEV technology really needs to be applied on a larger scale to show cost advantages. It is a more capital-intensive technology than the diesel bus, for example, and it cannot be shown to have lower costs than the diesel today. Its substantial benefits can only be realized in a larger-scale system, with a higher density of vehicle usage. Thus, although the demonstration system may appear to be more costly than competing modes, that cost disadvantage should not be present in the longer term when there is an opportunity to apply the RPEV technology on a larger scale, with the roadway costs distributed across a larger vehicle fleet.

Capital Cost of Baseline Santa Barbara System

The capital cost components for the baseline system are primarily the vehicles, the roadway inductor, and the power supply system.

The basic electric bus, in a configuration such as that shown in Figure 4, will cost about $200,000 each for a fleet of 10. This price is more expensive than that of a standard diesel bus because of the unusual low-floor design and the limited production of the electric powertrain components. The inductive power transfer system (inductive pickup and onboard power control system) adds another $45,000 to the cost, based on the costs of the first prototype units. These costs for the inductive coupling equipment are conservative because they include no allowance for production economies or economies of scale. Adding a 10 percent contingency factor to the combined vehicle costs to cover reasonable uncertainties brings the total to $269,500 per vehicle. A fleet of 10 vehicles should be needed, allowing 8 to operate the baseline route at 5-min headways, plus two spares. The capital cost for the entire vehicle fleet should therefore be $2.695 million.

The roadway electrification unit costs have been estimated on a per-foot basis and then multiplied by the length of roadway inductor needed to obtain the total cost. If the experience of constructing the first roadway unit for testing plus discussions with manufacturers about economical means of constructing large quantities of roadway inductors are used as a basis, the materials cost is estimated to be $200/lane-ft, of which three-fourths is for the steel inductor cores. An installation cost of $38 and a 10 percent contingency factor of $24 are added to produce an overall estimate of $262/lane-ft. The total length of the powered blocks on the baseline route is 11,530 ft. However, this length must be adjusted by adding the lengths of the static charging units at the bus stops and subtracting the lengths of the intersections and pedestrian crossings where the inductor would not be installed. After these adjustments, the inductor length is 10,180 ft, which should cost $2.668 million to install.

The fixed wayside facilities other than the roadway unit include the vehicle maintenance and storage facility, the power supply and distribution network, and the battery chargers for overnight recharging. The maintenance facility is expected to cost $150,000, the battery chargers $28,000, and the power supply and distribution system $478,000. Adding these to the roadway inductor cost leads to a total facility cost of $3.296 million. When the cost of the 10-vehicle fleet is added, the system capital cost is about $6 million.

Annual Operating Cost for Baseline Santa Barbara System

The system operating costs are based on the assumed use of eight buses for 10 hr per day, 365 days per year, providing service at 5-min headways. The annual vehicle operating hours will total 29,200, during which the vehicles will travel about 239,000 revenue miles at an average speed of 8.18 mph. This low average speed is characteristic of downtown circulation and distribution systems.

The largest single operating cost component is driver labor, which at an assumed rate of $15/hr totals $438,000/year. This cost component is mode-independent and would therefore be the same regardless of whether the service were provided by a diesel or trolley bus. Maintenance costs are more difficult to estimate for a system that has yet to see any revenue service experience. The estimates have been subdivided into power supply system maintenance and vehicle maintenance. The power supply system is expected to cost only about $6,000/year to maintain, on the basis of the maintenance needs for similar power systems operating around the clock in foundries. The vehicle drivetrain and power transfer system maintenance is expected to require the use of a dedicated specialist in electric vehicle technology because the requisite skills are not typically found in a transit operating agency. On the other hand, much of the normal bus maintenance burden associated with diesel engines and transmissions can be avoided, producing a compensating saving. When these factors are considered, the estimated annual maintenance cost for the vehicle fleet is about $103,000. A special additional maintenance item that must be considered with the RPEV system is battery replacement, because the traction batteries have only a limited life. Each battery costs about $12,000 and is estimated to last for 1,000 deep discharge cycles, corresponding to 1,000 days of operation. This translates into an annual system cost for battery replacement of about $35,000. If the battery life is found to be significantly different from the 1,000 cycles assumed here, this cost factor would be expected to scale accordingly.

The energy cost for the RPEV system includes several different components, the peak power (demand) charge, the energy cost for the roadway power, and the energy cost for overnight battery recharging. The peak power demand for the baseline system is estimated to be 334 kW, which should incur a demand charge of about $15,000/year. The computer simulations of vehicle performance predict an average power draw from the roadway of 20.1 kW/vehicle throughout the day. If a system efficiency of 75 percent and 29,200 vehicle-hr of operation per year are assumed, the cost for the roadway energy will be about $46,600 at the prevailing utility rate of about 6¢/kWh. The energy cost for overnight recharging is estimated to be another $16,000/year. The sum of all of these energy costs is about $77,600/year, which translates into 32.5¢ per vehicle mile (3.8 kwh/mi energy consumption, reflecting the strenuous duty cycle with stops every block along State Street).

The total annual operating costs for the system are the sum of the preceding factors plus an assumed incremental allowance for system administration of 10¢ per vehicle mile. This total is about $684,000, which corresponds to $2.86 per vehicle mile. Of this total, 64 percent is for driver labor, 21 percent is for maintenance (including battery replacement), 11 percent is for energy, and 4 percent is for administration.

The expected capital and operating costs for the system are summarized as follows:

Item	*Capital Costs ($million)*
Vehicles	2.695
Roadway inductor	2.668
Wayside facilities	0.656
	6.019

Item	*Annual Operating Costs ($thousands)*	*Percent*
Driver labor	438	64
Maintenance	144	21
Energy	78	11
Administration	24	4
	684	

Costs to Provide Same Service with Diesel Buses

The diesel bus is a mature technology that has had the opportunity to develop considerable economies of scale during its evolution. It remains the most economical mode to provide urban transit service if its environmental disadvantages do not enter the evaluation. The capital cost for a diesel bus is somewhat more than half the cost of an RPEV bus. Furthermore, the diesel bus does not need the extensive fixed facilities (roadway inductor and power supply system) of the RPEV, so its overall capital cost for the Santa Barbara application would be less than 30 percent of the capital cost of the RPEV system. The diesel bus operating costs are expected to be similar to those for the RPEV. The driver labor should be virtually identical, and the maintenance and energy costs are expected to be within a few percent of those costs for the RPEV. Therefore, the system capital cost remains the disadvantage of the RPEV relative to the diesel for this type of application, as indicated in the following comparative cost summary:

Cost Component	*Cost ($millions)* *RPEV*	*Trolley*	*Diesel*
Vehicles	2.69	2.3	1.5
Fixed facilities			
Continuous power distribution system (inductor or trolley wires)	2.66	2.03	–
Power source	0.48	0.95	–
Maintenance facility	0.18	0.13	0.1
Total	6.01	5.41	1.6

Costs to Provide Same Service with Trolley Buses

The comparison between the costs of the RPEV and the trolley bus is more even because both of these systems require fixed facilities as well as vehicles. The capital cost factors for this comparison are separated into those that depend on the number of vehicles in daily service (the costs for the vehicles and the power supply system) and those that depend on the length of route served.

The capital cost per vehicle in daily service is nearly the same for the RPEV and the trolley system. The trolley vehicles are slightly less expensive, but their power supply systems are somewhat more expensive because they operate on direct current and must be able to supply peak rather than average vehicle power demand. The RPEV roadway inductor costs about 350 percent of a trolley wire system per foot installed, while the length that must be installed is less. For the baseline Santa Barbara application, the actual length of the roadway inductor is about 35 percent of the route length, so its cost is expected to be about 25 percent higher than the cost of a trolley wire installation. However, if the roadway inductor only needs to cover 30 percent of the route length, the capital costs of the two systems should be virtually identical. This highlights an important feature of the RPEV system, the need to electrify only a portion of the route rather than the entire route. In a higher-density application for an urban bus system, with many routes overlapping on some streets, the percentage of the overall bus route lengths needing to be electrified could be reduced dramatically and the RPEV system could display significant economies.

No significant difference is expected in operating cost between the RPEV and trolley bus systems, so this does not appear to be an issue in the comparison between these two modes.

Costs to Provide Same Service with Battery-Only Buses

Battery electric vehicles are plagued with limited range because of the limited storage capacity of the available batteries. The baseline Santa Barbara Electric Bus can operate for slightly more than 2 hr on a single charge of its battery if it does not have roadway power available for recharging. A substantially larger battery would be needed to permit it to operate much longer, but diminishing returns set in as the battery weight increases (because of increasing vehicle weight or decreasing payload, or both). If the baseline downtown circulation bus service were to be provided with battery-only buses in Santa Barbara, it would be necessary to provide substantially more vehicles in the fleet so that some of them could be recharging while the others were operating. The exact numbers would depend on the battery size and type chosen, but it is likely that the fleet would need to be two to three times the size of the RPEV fleet to provide 10 hr of service per day (assuming no battery exchange schemes were attempted). This would lead to system capital costs comparable to the RPEV system costs, with the avoided roadway unit cost replaced by increased vehicle purchase costs. Operating costs would be substantially higher than for the RPEV and the other modes because of increased battery stress (and therefore increased battery replacement cost) and increased driver labor costs for ferrying the buses back and forth between the operating route and the maintenance and recharging facility. This is not an attractive alternative with presently available battery technology.

IMPLICATIONS FOR EVOLUTION OF THE RPEV TECHNOLOGY

The RPEV technology is currently in its infancy, which makes it challenging to predict how it will mature and grow over time. The application to the Santa Barbara Electric Bus Project described in this paper is intended to serve as its initial demonstration, but hardly as its ultimate incarnation. This limited-scope application is an appropriate one for demonstrating the basic feasibility of the RPEV, even while it cannot demonstrate the ultimate benefits of larger-scale applications. As explained, a simple economic comparison with other modes is not especially favorable today because of the relative immaturity of the RPEV technology and the limited scope and density of the Santa Barbara application. This does not mean that the RPEV cannot compete with the other modes.

If only the immediate transit bus service application in downtown Santa Barbara is considered, opportunity recharging of the electric vehicle batteries could probably be provided at lower capital cost (albeit at higher battery stress levels) by installing recharging stations at several carefully selected stopping and layover points, as demonstrated previously in Germany *(10, 11)*. However, unlike the RPEV technology, that approach would not be applicable to more general vehicle fleets and certainly could not be extended readily to the electric automobile, which is the eventual goal of the RPEV development work.

The position of the RPEV technology today is analogous to that of the automobile at the dawn of the 20th century. The people who focused on the cost of transportation in 1900 favored the horse and buggy over the automobile, scoffing at the latter as a toy for wealthy eccentrics. They did not have the vision to see the longer-term advantages the automobile would offer, even though it was not the most economical means of transport at that time. The longer-term promise of the RPEV technology must not be overlooked today simply because it is not now the most cost-effective mode.

Introduction of RPEV technology should be considered now for special applications for which its environmental advantages can be balanced against its high capital cost. These applications can be characterized by their environmental and aesthetic sensitivity, use of special vehicle fleets, and relatively high density. Examples could include national parks and monuments (such as Yosemite Valley), special historical districts of architectural interest (Colonial Williamsburg, Georgetown, and Boston's North End or Back Bay), urban pedestrian malls or shopping districts, enclosed shopping malls, major commercial office parks, amusement parks, and expositions. In many of these applications, the elimination of diesel bus noise and pollution and the avoidance of overhead trolley wires could heavily favor an RPEV system. A somewhat different application with near-term promise is airport circulation service at major hub airports with separate terminals, such as New York's JFK or Los Angeles International, where present diesel buses impose significant pollution burdens on travelers and the operational patterns, including low speeds, much dwell time, and special-purpose bus fleets, tend to favor RPEV.

The RPEV system can evolve beyond use in special activity centers by application to limited-access busways and busway/HOV lanes in freeways. In several California counties (Marin, Contra Costa, Orange), abandoned railroad rights-of-way could be developed for use as busway/HOV facilities in congested suburban areas, where freeways are already saturated. These rights-of-way adjoin suburban backyards, and the residents in those areas will object strenuously to the introduction of noisy and smelly bus traffic so close to their homes. The clean, quiet RPEV system may possibly be able to overcome such objections (if, indeed, any mode can).

The busway/HOV application extends the RPEV envelope to higher speeds than the activity center circulation systems described before, and it also provides the opportunity to widen the RPEV population to include vans used by vanpoolers. As the number of vehicles per electrified roadway mile increases, the economics of the RPEV system improve because the cost of the fixed facility can be distributed more widely. As the fleet of RPEV vehicles expands, the potential for electrification of more roadway facilities also expands. The RPEV system is vulnerable to the classic dilemma of the chicken and the egg. Before private vehicle owners are willing to purchase special RPEV vehicles, there must be enough powered roadway facilities to make it desirable to own these vehicles. On the other hand, there will be little motivation for public agencies to construct powered roadway facilities until there are enough RPEV owners to clamor for these facilities. This cycle can be broken by a careful, evolutionary introduction of RPEV vehicles into large special-purpose fleets such as those owned by public utility companies, telephone companies, the postal service, public service agencies, parcel delivery services, and so forth.

The most dramatic long-term benefits from the RPEV technology will come when urban freeways can be electrified, even if only partially. Substantial mobile-source pollutant emissions could be eliminated and substantial amounts of petroleum could be saved, as long as the electricity supplied to the roadway is generated from other prime energy sources. Even more important, this could be a major evolutionary step toward the automated highway, on which vehicles would travel under automatic steering and spacing control.

The automated highway represents an opportunity to substantially increase the capacity of each freeway lane by enabling automobiles to travel closer together safely. This means that the capacity of existing freeway corridors could be increased without the major capital cost of double-decking the freeways or the inevitable sociopolitical problems of condemning homes and businesses in densely developed neighborhoods for widening the freeways. It does not appear to be practical to automate conventional internal combustion engine vehicles because of their relatively slow and uncertain dynamic response. Electric powertrains are much more amenable to tight closed-loop control and will therefore probably be a prerequisite for complete highway automation. The most practical means for providing automobiles with electric powertrains that can be used on both conventional public streets and the special automated highways appears to be the RPEV. Thus the potential benefits of eventual highway automation must also be considered when the prospects for the RPEV system are being evaluated.

ACKNOWLEDGMENT

This work was sponsored by the Santa Barbara Metropolitan Transit District, with funding provided by the Urban Mass Transportation Administration, the State of California (Business and Transportation Agency, Department of Transportation), and the City of Santa Barbara.

REFERENCES

1. E. H. Lechner and S. E. Shladover. The Roadway Powered Electric Vehicle—An All-Electric Hybrid System. Presented at the VIII International Electric Vehicle Symposium, Washington, D.C., Oct. 1986.
2. K. Lashkari, S. E. Shladover, and E. H. Lechner. Inductive Power Transfer to an Electric Vehicle. VIII International Electric Vehicle Symposium, Washington, D.C., Oct. 1986.
3. C. E. Walter. Inductive Power Transfer for Propulsion: A Status Report. *Journal of Advanced Transportation*, Vol. 16, No. 1, Spring 1982, pp. 73–86.
4. *Santa Barbara Electric Vehicle Project, Phase 1, Feasibility Study—Final Report.* Howard R. Ross Associates, Nov. 1980.
5. *Santa Barbara Electric Bus Project, Phase 2, Detailed Planning and Preliminary Engineering—Final Report.* Ross Associates, Systems Control Technology, Inc., MCR Technology Inc., Inductran Corporation, and KK8NA Inc., June 1982.
6. *Santa Barbara Electric Bus Project, Phase 3A—Final Report.* Systems Control Technology, Inc., Calif., September 1983.
7. *Santa Barbara Electric Bus Project, Prototype Development and Testing Program, Phase 3B—Final Report.* Systems Control Technology, Inc., Calif., Sept. 1984.
8. *Santa Barbara Electric Bus Project, Test Facilities Development and Testing Program—Static Test Report.* Systems Control Technology, Inc., Calif., June 1985.
9. *Santa Barbara Electric Bus Project, Prototype Development and Testing Program, Phase 3C—Final Report.* Systems Control Technology, Inc., Calif., May 1986.
10. Room on Top for Battery Charging in German Bus Experiment. *Electrical Review*, Vol. 211, No. 9. Sept. 24, 1982.
11. F. H. Klein and R. Thomas. Short Term Intermediate Recharging—An Alternative for the Energy Supply of Battery-Electric Buses in Service. Paper prepared for Pb 80 Competition 2, 1980.

Publication of this paper Sponsored by Committee on New Transportation Systems and Technology.