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Initial Assessment of Roadway-Powered Electric Vehicles

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Wide-scale use of electric vehicles (EVs) could result in large reductions in urban air pollution. However, consumer acceptability of battery-powered EVs is limited because of the short range of the vehicles. One possibility for eliminating the range disadvantage of EVs without sacrificing their potential for improving air quality is to supplement battery energy with electricity supplied through the roadway. The costs, environmental impacts, and electric utility impacts of roadway-powered electric vehicles (RPEVs) are assessed. It is concluded that RPEV air quality benefits are substantial and that the technology could prove economically competitive with petroleum-fueled motor vehicles. Continuing research and development is needed to narrow cost uncertainties.

Methanol and natural gas are widely regarded as the leading candidates for near-term petroleum replacement in transportation. However, an increasing number of studies suggest that the environmental and energy security benefits of methanol and natural gas may be relatively modest (*1–8*). Electric vehicles (EVs) provide greater opportunities for energy security and the potential for much larger reductions in emissions. In addition, an electric motor can provide high torque at startup and is technically simple, easy to maintain, durable, efficient, reliable, quiet, clean, and long lasting. EVs themselves are pollution free (power plant emissions are analyzed later), and electricity can be produced from a number of readily available domestic feedstocks.

However, the EV is not without problems. The main impediment to wide-scale consumer acceptance of current-technology EVs in the United States is their limited range. Using durable batteries in existing compact vehicles, the best battery-powered automobiles are capable of traveling only about 75 mi before having to stop to recharge (vehicle air conditioners and heaters reduce range 10 to 15 percent) (*9,10*). A full battery recharge from a typical household electric outlet takes at least 8 hr. Historically, EV battery development has progressed incrementally, and there is no sign of an imminent technological breakthrough.

One prospect for deploying EVs and overcoming the range problem is to replace stored electrical energy on board the vehicle with distributed energy from an electrified roadway. In this scenario a roadway-powered electric vehicle (RPEV) draws energy directly from the electricity grid while it operates over an energized roadway. The vehicle relies on battery reserves when operated off the electrified roadway network and possibly during peak periods of electricity generation. RPEV batteries can be charged while the vehicle travels over the electrified roadway or while immobile. An RPEV transportation system can solve the battery-powered EV range problem while providing air quality and energy benefits.

RPEV TECHNOLOGY

At the center of the RPEV system is the inductive coupling system (ICS), which provides the means for transferring electric power from the roadway to the vehicle. The ICS is often compared to a transformer—an extremely efficient electrical device that employs the principle of mutual inductance to convert variations of current from a primary circuit to a secondary current. Indeed, the ICS functions as an air-core transformer. The roadway contains the primary winding and a pickup inductor on the vehicle contains the secondary winding. However, unlike a regular transformer, the two inductors have different electrical and physical designs. The main difference is the length of the coils—the roadway inductor is many times longer than the pickup inductor.

The cables (or bus bars) embedded in the road are excited with AC electricity by an external power source through power conditioners located along the roadway. When the pickup cables (or bus bars) located underneath the vehicle are over the roadway element, there is inductive coupling and electrical energy is transferred to the vehicle. The magnitude of the gap between the roadway and the vehicle pickup inductor will depend on the system design; however, the largest gap spacing will probably be no more than 3 cm to maximize efficiency (ideally the gap height will be adjustable from within the vehicle to accommodate for various road conditions) (*11,12*).

Figure 1 (*13*) shows the ICS design being used in an RPEV project sponsored by the Program on Advanced Technology for the Highway (PATH). Iron cores made of grain-oriented silicon iron laminations are placed around the aluminum roadway cables and pickup cables to provide magnetic flux paths and increase coupling efficiency. Aside from the physical aspects of the hardware that determine the flux density in the cores and the effective current density in the inductors, inductance efficiency is primarily a function of the pole width of the cores (i.e., the mutual surface area) and the size of the air gap between the roadway and the pickup inductors. Because the transfer of energy is inductive rather than conductive, there is no contact, and thus components wear slowly. Furthermore, there are few potential electrical hazards because all the electrical elements are well insulated and buried in the roadway.

Although the RPEV system enables an electric vehicle to be operated entirely on distributed energy supplied by the grid rather than through energy stored on board, an RPEV is a hybrid vehicle because it maintains a battery for travel

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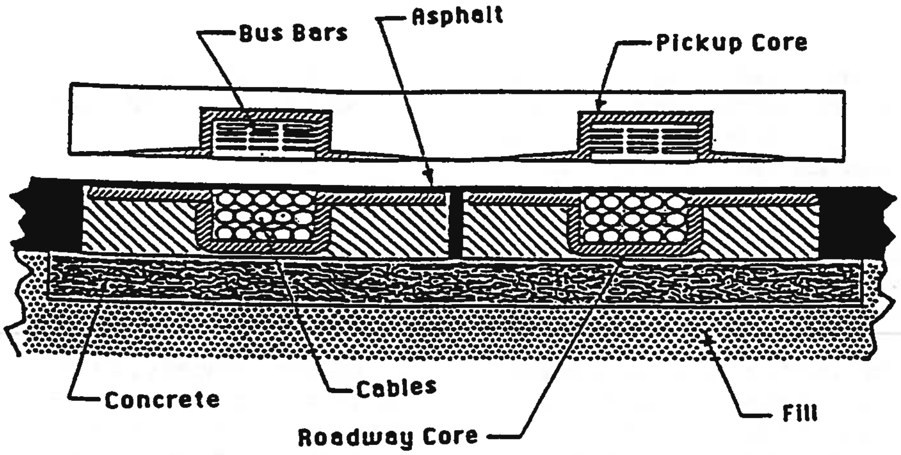

FIGURE 1 Cross section of roadway and pickup inductors (*13*).

off the electrified roadway network. However, unlike a battery-only electric vehicle, an RPEV does not have to be "plugged in" to be recharged; it can be recharged through the inductive coupling system. In addition to providing propulsion power to the vehicle, energy transferred through inductive coupling can also be diverted to the battery for storage. Battery charging through the RPEV system can be accomplished dynamically or statically.

Dynamic battery charging takes place when energy provided by the roadway is greater than what is necessary to propel the vehicle. The excess energy can then be used to charge the batteries while the vehicle is en route. Static inductive battery charging is possible if the vehicle is parked directly over an inductive coupling device. In this case all energy transferred to the RPEV would be used to charge the batteries (RPEV batteries can also be recharged by using a typical household electric outlet). Static inductive battery charging is currently used for large automatically guided vehicles at Disney World and in automated manufacturing plants in the United States, Canada, and Europe. Inductors could be installed in public parking spaces to maximize static recharging opportunities.

Roadway power used by the RPEV is supplied through a distribution network that delivers electricity generated at the power plant to a utility substation. The electricity is routed from the substation to power conditioners located along the roadway at specified intervals. The electricity is then routed in parallel to segments of adjacent roadway; electrification of a roadway lane does not exclude use by other vehicle types. Figure 2 (*14*) shows the electrified roadway energy distribution network. The distance between power conditioners will probably be determined by the maximum allowable voltage in the roadway element, which is a function of the system design and the number of vehicles drawing power from the roadway. The power conditioner spacing will probably be less than 2 km for roadways with fairly high traffic volumes.

This network provides a "fail-safe" design in which the effects of a malfunction are confined to a relatively short distance (i.e., in the case of a power conditioner failure, only 2 km of roadway would lose energy). Unless the RPEV battery is completely discharged (an unlikely circumstance), no problem should be encountered in reaching the next section of electrified roadway or the driver's residence in the event of a power outage.

HISTORY OF THE RPEV CONCEPT

The RPEV concept is not new; in fact, patents for electric vehicle operation by means of inductive coupling date back to the 1890s. Abundant, inexpensive petroleum supplies, however, suppressed the development of such a system for decades.

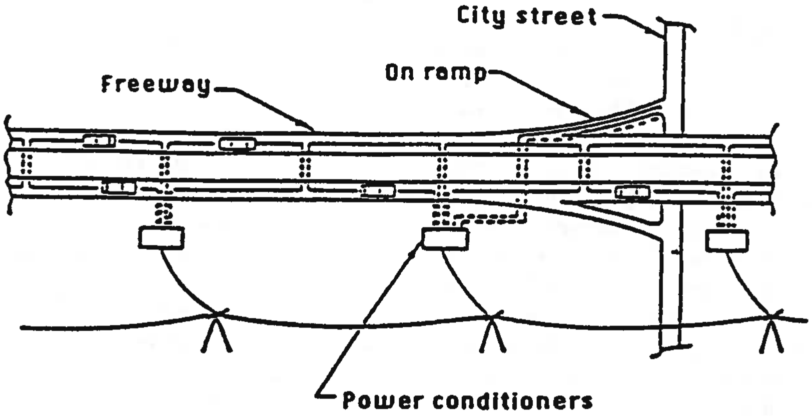

FIGURE 2 Electric roadway schematic (*14*).

In the early 1970s John Bolger designed an ICS that regulated voltage control from the roadway to the vehicle battery—an inherent problem in previous designs. The new design, along with the energy crisis, renewed interest in the RPEV concept. From 1976 to 1982 the U.S. Electric and Hybrid Vehicle Program, with funding from the U.S. Department of Energy, the U.S. Department of Transportation, and the state of California, spent about $1 million on a feasibility study, designing and testing a prototype power coupling and designing and fabricating a test-bed RPEV (*15–17*). The culmination of this program in 1981 was the construction of a modest test vehicle and a 160-ft section of powered roadway at the Lawrence Livermore National Laboratory.

One of the most significant ongoing developments of the RPEV system concept is the Santa Barbara–PATH Bus Project, which began in 1977. The downtown area of Santa Barbara, California, was developed as a sensitive pedestrian-oriented environment. To maintain the congenial atmosphere of the downtown area yet serve the travel needs of shoppers and tourists, city officials elected to implement a mass transit system that would be free of emissions, have a low noise level, and be aesthetically pleasing. This desire for an efficient and environmentally benign mass transit system matched well the attractions of RPEV technology.

In 1979, with the endorsement of the city of Santa Barbara, the Santa Barbara Metropolitan Transit District (SBMTD) was granted a contract by the California Department of Transportation (Caltrans) for the development and demonstration of the RPEV system. The same year a multiphase program was implemented, which consisted of a feasibility study, detailed planning, preliminary engineering, and prototype development and testing of an RPEV bus. The final product was to be a small fleet of RPEV buses continuously operating 10 hr/day over a 5½-mi route (including two electrified miles) in downtown Santa Barbara.

However, because the development of the technology proceeded too slowly for the needs of Santa Barbara, the technology development portion of the project was transferred to PATH at the University of California. A 400-ft test track (with two 20-ft static charging areas) was built in Richmond, California, in late 1989 for the testing and demonstration of the existing RPEV bus.

Efforts are already under way to further improve RPEV technology. In August 1989 a new project, the Playa Vista Electrification Project, was initiated with the objective of advancing RPEV technology. This $2 million project funded by two utility companies—Southern California Edison and the Los Angeles Department of Water and Power—is focusing on reducing fabrication and installation costs of RPEV roadway elements and on the development of automobile-size RPEVs that operate at highway speeds. The project, located in southern California, will involve testing two RPEV vans and a bus on 1,000 ft of electrified roadway. Completion of the facility and initial testing is scheduled for October 1990.

The Playa Vista project is the first stage of a much larger RPEV project that is currently being supervised by an engineering consulting firm in California. The proposed project, with funding provided by a consortium of industrial firms and government agencies, is expected to cost $30 million to $40 million and take 4 years to complete. The objectives of this research and development effort are to build an electrified arterial system to demonstrate RPEVs on a large scale and to prepare the technology for commercialization.

SYSTEM DESIGN

The design of an RPEV system consists of many complex trade-offs between efficiency and cost and is strongly influenced by institutional constraints and financing strategies. At this relatively early stage in the technology development process, attention is focused on relationships between cost, performance, and efficiency. Much research is still needed. For instance, reducing the air gap increases the energy efficiency and thus decreases the operating cost of an RPEV but would require the added cost of maintaining a debris-free, smooth-surface electric roadway. Increasing the core pole width also increases coupling efficiency but incurs an additional cost and weight penalty. Other technical trade-offs include better design of the inductor cores (e.g., using better material, different geometric configurations, or better fabrication processes) and increasing the current in the roadway—again, these improvements are accompanied by a cost increase. A more detailed description of system design trade-offs can be found in Shladover (*11*).

The larger strategic issues are the extent ot roadway electrification, financing considerations, and implementation strategies. The first of these issues, the extent of roadway electrification, depends on whether roadway power is intended to supplement vehicle battery power or vice versa. If, for instance, roadway power is designed to supplement battery-powered EVs, then the vehicles will carry large battery packs and only strategically selected limited stretches of roadway will be electrified. The primary financing considerations are who will bear the cost of the necessary infrastructure—the government or users of the system—and through what financing mechanisms. Finally, implementation strategies must be established: what role, if any, should incentives and government mandates play? What role will electric utilities, highway providers, and air quality regulators play? The most workable system design may be one that is amenable to retrofitting battery-powered EVs and RPEV equipment.

In sum, many decisions must be made before the technology problems can be resolved. It would be desirable to clarify the objectives of the RPEV system so that design criteria can be established that give developers of the technology clear goals. Clarification of RPEV objectives is best left to the regions implementing the technology.

LIFE-CYCLE COST OF RPEVs

Ideally, one would calculate the life-cycle cost of a mature, mass-produced RPEV technology and compare it with the cost of owning and operating a conventional internal combustion engine vehicle (ICEV). However, comparing an RPEV with an ICEV is difficult because the latter is a product of more than 100 years of technological evolution, whereas RPEV technology is still in the design stage. Only a special-application RPEV prototype bus has been built for testing and demonstration purposes. Preliminary cost estimates, calculated projections, and engineering principles must be relied on to estimate the life-cycle cost of RPEVs. Although there is a good deal of uncertainty in the estimates, it is important to perform a preliminary cost analysis to determine whether RPEVs can compete with other transportation alternatives. A disaggregate cost model has been developed for this purpose. The key parameters used for the initial evaluation are explained below.

RPEV costs are calculated with respect to a baseline subcompact gasoline vehicle for which all relevant costs are shown in Table 1. Where appropriate and unless otherwise noted, cost items for the RPEV are expressed relative to the baseline ICEV cost components. All costs are given in constant 1989 U.S. dollars. The cost analysis compares RPEVs and ICEVs on equal terms—it is assumed (*a*) that both vehicles are mass produced, have the same interior capacity, and depreciate at the same rate; (*b*) that repair shops and vehicle operators are as familiar with RPEVs as ICEVs; and (*c*) that parts for RPEVs are as readily available as parts for ICEVs.

It was assumed that the RPEV uses an AC power train and regenerative braking and is equipped with a maintenance-free sodium/sulfur (Na/S) battery and on-board charger. Regenerative braking is expected to increase vehicle efficiency by approximately 5 to 15 percent under normal driving conditions (*18–21*). Na/S batteries are advanced high-temperature batteries currently being tested in many prototype EVs; battery assumptions were based on near-term performance goals. On-board transformerless battery chargers integrated with the controller electronics are beginning to replace large expensive stationary battery chargers. These on-board chargers are inexpensive and do not add significant weight to the vehicle. The integrated on-board charger in the electric Chrysler TE-Van is estimated to increase the cost of the vehicle by less than $50 (K. Winters, unpublished data, November 26, 1989); a mass-produced off-board charter would increase the cost by approximately $1,100 (*22*).

Baseline Gasoline Vehicle Assumptions

Baseline vehicle assumptions were intended to apply to a new gasoline vehicle in 2000; RPEVs will probably not be commercially available before then. A wide range of $0.90 to $2.00 per gallon in estimated fuel costs was used because of the high uncertainty associated with future gasoline prices. Fuel economy for gasoline vehicles in 2000 was projected at about 35 mi/gal (*23–25*). It was assumed that life expectancy, salvage value, and the real cost of a new gasoline vehicle will not change significantly over the next 10 years.

Average annual vehicle mileage has been fairly constant for 40 years at 10,000 mi, and there is no reason to expect this to change. On the other hand, the real annual interest rate for automobile loans fluctuates considerably, and therefore a wide range of 5 to 9 percent was used for this input variable. Insurance, maintenance, tires, accessories, and parking and toll costs were based on information from FHWA (*26*).

Vehicle registration fees and sales tax were based on the national average (*27*), and inspection and maintenance costs for pollution control devices were projected on the basis of states that have already implemented such programs. Finally, the national average combined state and federal gasoline tax is approximately $0.20 per gallon (*28*). A range of $0.20 to $0.30 was used to account for likely increases (many states have proposed gasoline tax increases).

The total life-cycle cost of operating the baseline gasoline vehicle, defined by the assumptions given in Table 1, is about $0.30 to $0.37 per mile.

TABLE 1 GASOLINE BASELINE REFERENCE CASE

High	Low	Reference Case Input Data
2.00	0.90	Retail price of gasoline, $/gallon, taxes excluded
35.00	35.00	Overall lifetime vehicle fuel economy, miles/gallon
11,000	11,000	The initial price of the car including tax, $
120,000	120,000	Miles driven over life or until resale
0.00	0.03	Vehicle salvage/resale value, fraction of initial cost
10,000	10,000	Miles driven per year
2,600	2,600	The loaded driving weight of the vehicle, lbs
0.090	0.050	The real annual interest rate for auto loans (equal payments over vehicle life) or foregone consumer savings (full payment at purchase)
71.50	71.50	Insurance payments, first n years with collision insurance, $/month
8.00	5.00	n, years collision insurance is carried
44.36	44.36	Insurance payments, subsequent years without collision insurance, $/month
484.50	484.50	Maintenance costs, $/year, including taxes
10.60	10.60	Parking and tolls, $/month
320.00	320.00	Four replacement tires, $/set, including taxes
50,000	50,000	Life of tires, miles
18.50	18.50	Accessories, $/year
30.00	25.00	Oil, $/year, including taxes
25.00	25.00	Registration fee, $/year
25.00	25.00	Inspection and maintenance fee, $/year
0.30	0.20	Gasoline tax, Federal + State, $/gallon
1.05	1.05	Sales tax on incremental vehicle cost, (1 + %tax)

Notes: Gasoline tax from USDOC (1989); registration fee and sales tax from Intellichoice (1988); insurance information, maintenance, tires, accessories, and parking and tolls from FHWA (1985); real annual interest rates for high-yield consumer savings and auto loans calculated from U. S. Department of Commerce (1989).

Initial RPEV Cost

The initial RPEV cost was disaggregated into four components—vehicle, pickup inductor, on-board controller (OBC), and battery. The costs of these items were amortized over their respective lives (using the discount rate specified in Table 1) and summed to obtain the life-cycle cost of purchasing an RPEV. The cost assumptions are summarized in Table 2.

Vehicle

The initial vehicle cost of an RPEV, excluding battery, pickup inductor, and OBC, was entered relative to the cost of an ICEV. Ford and General Electric, developers of advanced EV test vehicles, suggest that an advanced EV (excluding battery) will cost no more than a comparable ICEV at a "reasonable" production volume (*29*). Pentastar, a Chrysler corporation and developer of the state-of-the-art TE-Van, also suggests that a mass-produced EV without the battery will cost no more than an ICEV (K. Winters, unpublished data, May 19, 1989), and the General Research Corporation concluded the same based on a cost model it developed (*30*). Other EV analysts, including one who contends that EV vans can be manufactured for the same cost as ICEV vans at a production volume as low as 10,000 units/year, concur with these projections (*31–33*; G. Cole, unpublished data, 1989). It is estimated that a production volume of 250,000 vehicles is sufficient for recovering retooling costs necessary for producing a new type of vehicle (*34*). Although the above cost projections are for an EV, they would essentially apply to an RPEV without the pickup inductor, OBC, or battery. It was assumed that an RPEV, without this power supply equipment, will cost the same as an ICEV.

Pickup Inductor

The fabrication cost will probably determine the total cost of the vehicle pickup inductor. On the basis of the cost of the pickup inductor being used on the PATH bus and estimates from Inductran, Inc.—an engineering firm that specializes in inductive coupling technology—the cost of a pickup inductor with suspension system on a subcompact vehicle is estimated to be $1,500 to $4,000 (J. Bolger, unpublished data, 1989; PATH, public demonstrations, 1989).

TABLE 2 RPEV COST ASSUMPTIONS

High	Low	RPEV Input Data
7.00	5.00	Cost of electricity at the outlet or power conditioner, cents/kWhr
10.00	8.00	Cost of peak-hour electricity at the power conditioner, cents/kWhr
0.85	0.90	Efficiency of battery charging
0.70	0.85	Efficiency of RPEV system from power conditioner input to vehicle battery or powertrain
0.70	0.75	Efficiency of battery
5.80	6.40	Ratio of efficiency of RPEV powertrain w/ regenerative braking to ICEV powertrain efficiency
40	40	Desired urban vehicle range on battery only, miles (at DoD below)
0.80	0.80	DoD at desired driving range
Na/S	Na/S	Battery type
0.00	0.03	Battery salvage value, % of initial cost
400.00	250.00	Weight of pick-up inductor & suspension system, lb.
75.00	40.00	Weight of onboard controller unit, lb.
10.00	6.00	Cost of pick-up inductor incl. suspension system, $/lb
650.00	350.00	Cost of onboard controller unit, $
120.00	85.00	OEM battery cost, $/kwh nominal deliverable capacity
1.50	1.40	Ratio of retail to OEM battery cost
0.00	0.03	Pick-up inductor salvage value, % of initial cost
0.00	0.03	OBC salvage value, % of initial cost
80.00	120.00	Battery energy density, max. delivered wh/kg
700	1000	Battery cycles per life, at DoD stated above
0.00	0.00	Cost of RPEV (incl. tax & onboard charger, excl. pick-up inductor, OBC, & battery) minus cost of ICEV, $
10.00	7.00	Number of years collision insurance is carried on RPEV
0.50	0.50	% total annual miles from roadway power
0.50	0.50	% of electric roadway miles during peak hour rates
1.25	1.50	RPEV life/ICEV life
1.05	0.95	RPEV test wt. (excl. battery, OBC, & pick-up inductor) as % of ICEV weight
0.80	0.60	Percent decrease in fuel efficiency per 1 percent increase in vehicle weight
0.85	0.50	Maintenance costs, fraction of gasoline vehicle
2.00	1.00	Cost of building electric roadway lane, $million/mile
10.00	25.00	# of RPEVs using electrified lane each day per lane mile (x 1000)
20.00	25.00	Life of electric roadway, years
1780.00	1465.00	Electric roadway maintenance cost greater than conventional maintenance, $/year/lane mile

OBC

The second largest cost item for an RPEV, excluding the battery, is the OBC. The OBC includes the on-board control computer (OBCC) and the rectifier unit. On the basis of the best available engineering estimates and the PATH bus experience, it is believed that an OBC for an RPEV automobile will cost between $350 and $650 (J. Bolger, unpublished data, 1989; S. E. Shladover, unpublished data, 1989).

Battery

Battery cost is a function of battery size, efficiency, longevity, energy density, specific power, depth of discharge, and salvage value. To accurately size the battery, assumptions must be made about the overall design of the RPEV system and the vehicle range requirement.

Without speculation as to where and how much electric roadway power will be available, it was assumed that the RPEV owner will desire a battery reserve of at least 40 mi for off-system travel at 80 percent depth of discharge (DoD). Battery cost parameters for a future optimized Na/S battery were specified on the basis of available data (*21*;*35–40*; M. Price, unpublished data, 1990). Na/S batteries are assumed to have a low salvage value because of the low cost of the materials used (*40*,*41*). Finally, a 40 to 50 percent markup from the original equipment manufacturer's battery cost to retail was assumed (*32*,*42*).

RPEV Life

An electric motor lasts much longer than a gasoline internal combustion engine. This is important because engine life often determines the life of an ICEV. One fleet of EV vans used in Britain reportedly lasted three times longer than diesel counterparts that were subjected to the same operating conditions (*31*). Data from actual use suggest that an EV will last anywhere from 25 to more than 100 percent longer than a comparable ICEV (*31*,*32*,*43*). However, it is improbable that RPEVs will double the life span of an ICEV because of the deterioration of other components, such as brakes, steering, body, and vehicle interior. It was assumed that an RPEV will last 25 to 50 percent longer than a comparable ICEV and initial costs were amortized accordingly. Vehicle life is an important variable in life-cycle cost calculations.

Operating Costs

RPEV Maintenance

AC induction motors are not subjected to the extremes of heat, pressure, and synchronized movement that wear down an ICE. There are no explosions or associated stresses, and there are fewer moving parts. Therefore, it was assumed that the electric motor will require significantly less maintenance work and repairs. In fact, many studies, on the basis of data collected from existing EV fleets, indicate that the maintenance cost of an EV is a fraction of that of a comparable ICEV (*31*,*43–46*). The range in the literature suggests that an EV may cost 34 to 75 percent as much as an ICEV to maintain and repair. An RPEV will probably have a smaller maintenance cost advantage than an EV because the RPEV is equipped with a pickup inductor and OBC, which require some additional maintenance. However, iron pickup inductors should be extremely durable and the electronics of an OBC should be relatively inexpensive and easy to replace. RPEV maintenance and repair costs were assumed to be 50 to 85 percent of those of an ICEV.

Fuel Cost

The fuel cost of an RPEV is a function of the vehicle fuel economy, electricity cost, fuel tax, usage, the extent of use on the powered roadway, and the extent of use during peak electricity-generating periods.

The efficiency of an RPEV relative to that of a comparable ICEV is the product of the battery charger efficiency, battery efficiency, ICS efficiency, power train efficiency, and vehicle weight. Charger efficiency is estimated at 85 to 90 percent, and the battery efficiency is estimated at 70 to 75 percent (*21*;*35–38*;*47*; B. Swaroop, unpublished data, 1989; J. McCoy, unpublished data, 1989). Efficiency of the RPEV system from power conditioner input to the vehicle power train was estimated at 70 to 85 percent (*11*; J. Bolger, unpublished data, 1989). Finally, an efficiency weight factor of 0.6 to 0.8 was used, which means that for every 1 percent increase in RPEV weight relative to an ICEV, fuel efficiency decreases 0.6 to 0.8 percent (*48*).

A comparison of energy efficiencies (from fuel origin to the vehicle wheels) between an ICEV and an RPEV is depicted in Figure 3. As can be seen, the RPEV is 19 to 26 percent more efficient when operated from roadway power (from the power conditioner) than when operated from battery power (from the outlet). Figure 3 also indicates that the relative power train efficiency of an RPEV is approximately 5.6 to 6.6 times that of a comparable ICEV (*20*,*37*).

On the basis of projections of electricity cost in 2000 by the U.S. Energy Information Administration (EIA) and the California Energy Commission (*49*,*50*), the cost of electricity was estimated to be 5 to 7 cents/kW-hr for off-peak battery charging and roadway operation and 8 to 10 cents/kW-hr for peak-hour roadway operation (it was assumed the price incentives will restrict home battery charging to off-peak hours). RPEVs can be equipped with meters that record the amount and time (peak or off-peak) of roadway-powered travel for billing purposes.

The gasoline fuel tax is earmarked for roadway maintenance and construction. It was assumed that RPEV users bear the full cost of electrifying existing roadways and the incremental roadway maintenance cost incurred because of electrification in addition to the equivalent ICEV gasoline tax. Because it would be difficult to distinguish between residential electricity used for battery charging and that used for other purposes, an annual RPEV user fee (perhaps based on annual RPEV mileage) would probably be assessed instead of a fuel tax. RPEV system installation and additional electric roadway maintenance costs were internalized in the analysis.

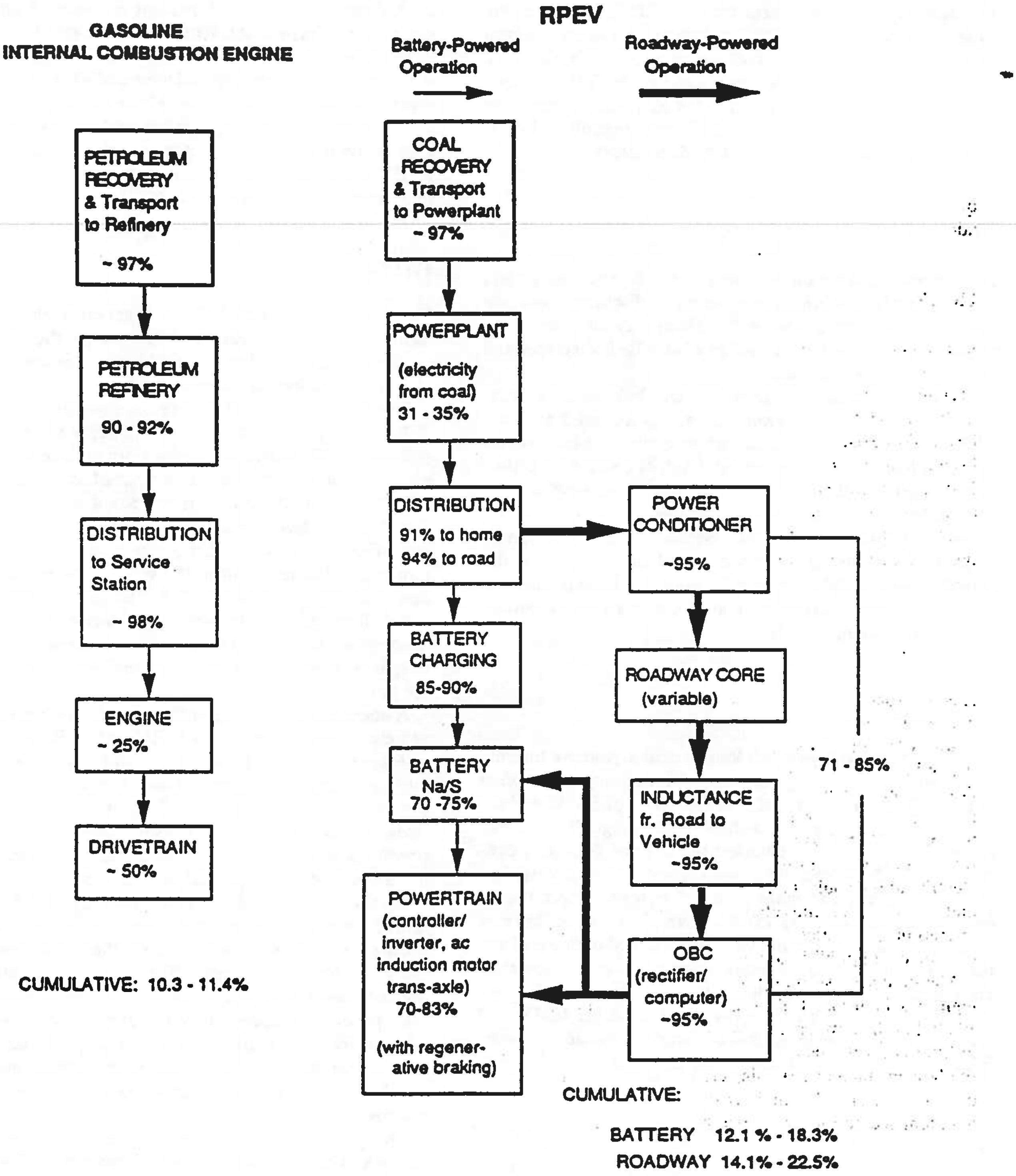

FIGURE 3 **Energy flow diagrams.**

Finally, it was assumed that the typical RPEV will accumulate 50 percent of its annual mileage by using energy from the road and that 50 percent of that energy will be during peak electricity periods. Changing the proportion of roadway power to battery power usage or the peak-period travel percentage does not have a profound effect on the total life-cycle cost results.

Other Operating Costs

The cost program estimated tire replacement cost, which is a function of vehicle weight, road conditions, and driving patterns. It was assumed that the only difference in the rate of tire wear between an ICEV and an RPEV is due to vehicle weight. Therefore, tire life for the RPEV is decreased in proportion to the total extra weight of an RPEV relative to a comparable ICEV.

Insurance costs are a function of many factors that may or may not be systematically different for RPEVs compared with ICEVs. The only difference that can be estimated with any degree of certainty is that component based on vehicle value. RPEVs, with their battery pack, OBC, and pickup inductor will initially cost more than a comparable ICEV. Consequently, insurance was increased in proportion to the additional cost of an RPEV relative to an ICEV.

Electric Roadway Cost

Installation Cost

Preliminary estimates for electric roadway installation are $1 million to $2 million/lane-mi for mass-produced components installed in existing roadways (*15*; Bechtel Civil, Inc., unpublished data, 1989; S. E. Shladover, unpublished data, 1989; J. Bolger, unpublished data, 1989). This estimate includes the cost of all the equipment and materials necessary to deliver electricity from the utility substation to an RPEV traveling on the electrified roadway and the labor required to install the system.

Electric Roadway Maintenance

Electric roadways will probably require additional maintenance. At least part of this will involve keeping the electric roadway free of debris, cracks, and potholes that could obstruct the inductive coupling of the vehicle and roadway element. Power conditioners will also require routine maintenance. If the electrified roadway is not as durable as expected, maintenance could be extensive because most of the system hardware is embedded in the road. On the other hand, roadway electrification could benefit many cities if it is designed to melt snow and ice, thus eliminating the need for snow removal operations (a feasible option according to one RPEV expert) (J. Bolger, unpublished data, 1989).

Maintenance assumptions were based on data from major highways in urban California (Caltrans, unpublished data, 1989). For the low-cost case, a 50 percent increase was assumed in litter control plus a 25 percent increase in general routine roadway maintenance (sealing cracks, patching potholes, minor overlays, etc.). The high cost estimate increased general maintenance and litter control by 50 percent.

Electric Roadway Life

Because an electric roadway has yet to be built, there are no data on life expectancy under normal operating conditions. The entire roadway system, with the exception of the power conditioner, will be buried and therefore protected from the climate and externally inflicted damage. The power conditioner will be in a self-contained housing and, therefore, also protected. However, the elements embedded in the road could experience heavy loads and continuous loading and unloading cycles (especially if heavy-duty trucks are allowed to travel in the electrified lane). Such physical stress on electric roadway components could have adverse effects.

It was assumed that electric-roadway hardware will last at least as long as the typical urban highway (20 years) and, under the best circumstances, will last 25 years. It was assumed that there is no salvage value at the end of its useful life (even if the hardware is intact and functional after 20 to 25 years, new designs will probably render existing equipment obsolete).

Electric Roadway Utilization

It was assumed that the users of an electrified roadway bear the full cost of electric roadway installation and related maintenance. The cost to each RPEV user depends on how many other RPEVs use the system regardless of the extent of utilization by each individual. To determine the RPEV life-cycle cost, high- and low-utilization scenarios were assumed. If electrified lanes experience high-volume traffic flows typical of the busiest urban Interstates in California, they will carry approximately 25,000 RPEVs each day (electrified lanes can be used by other vehicle types, but if RPEVs become prominent, exclusive RPEV lanes will probably be implemented) (*51*). For the high cost estimate, it was assumed that the electrified lane carries 10,000 RPEVs per day.

COST ANALYSIS RESULTS

On the basis of the input variables discussed above and given in Tables 1 and 2, the life-cycle cost of owning and operating an RPEV was calculated to be between $0.27 and $0.49 per mile, as indicated in Table 3. This brackets the baseline gasoline vehicle cost of $0.30 to $0.37 per mile, which is also indicated in Table 3. As can be seen, RPEVs may compete with ICEVs on the basis of economics alone if relatively optimistic assumptions prevail. Depending on the utilization of the electrified lane, the model indicates that roadway hardware and installation costs combined could account for as much as 12 percent or as little as 3 percent of the total per-mile life-cycle cost (if users bear the full cost of the facility).

The combined vehicle and total battery cost, amortized over the life of an RPEV, is almost equal to the cost of an ICEV. However, at the time of purchase the RPEV costs $2,950 to $6,884 more than the ICEV. The greater initial cost of an RPEV is amortized over the RPEV's longer life. This is important because consumers seldom perform a full life-cycle cost analysis when purchasing a vehicle and thus tend to use a higher implicit discount rate.

Battery technology may have implications far greater than what is reflected in the economic analysis. Although the battery in our RPEV cost analysis constitutes approximately 6 to 9 percent of the total life-cycle cost, advances in battery technology could lower these costs or extend driving range, or both. One of the main advantages of an RPEV is that it overcomes the range limitations of an EV; if batteries improve substantially or rapid recharge becomes feasible, the EV range problem may lose significance and RPEVs would become less compelling an option. On the basis of life-cycle cost, a battery-powered EV defined by the applicable assumptions in Table

TABLE 3 LIFE-CYCLE COST COMPARISON, CENTS PER MILE

High	Low	GASOLINE VEHICLE
5.71	2.57	Gasoline
14.76	11.93	Vehicle
7.84	6.91	Insurance
4.85	4.85	Maintenance
0.30	0.25	Oil
0.46	0.49	Replacement tires
1.27	1.27	Parking and tolls
0.25	0.25	Registration
0.25	0.25	Inspection and maintenance
0.86	0.57	Gasoline tax
0.19	0.19	Accessories
36.74	**29.53**	**Total Private Cost**

High	Low	ROADWAY-POWERED ELECTRIC VEHICLE
2.31	1.21	Total electricity cost for given operating mode
18.93	10.69	Initial vehicle cost
4.52	1.49	Batteries
9.48	7.35	Insurance
4.12	2.42	Maintenance
0.62	0.53	Replacement tires
1.27	1.27	Parking and tolls
0.34	0.28	Registration
0.86	0.57	Fuel tax
0.19	0.19	Accessories
0.049	0.016	Cost for additional electric roadway maintenance
6.00	0.78	Cost for electric roadway installation
48.69	**26.80**	**Total Private Cost**

2 could have a battery much larger than that of the RPEV in the cost analysis. However, vehicle range would still be limited not only by battery size but also by battery recharging time and the amount of vehicle capacity available for battery storage.

SENSITIVITY ANALYSIS

Each cost input parameter is subject to uncertainty, which is taken into account by using a range of possible values. The cumulative effect of uncertainty is reflected in the wide range of the resultant total cost projection. Because it is impossible to accurately determine the probability of each cost within this range, a sensitivity analysis was performed to determine the relative importance of the uncertainty associated with each variable used in the cost calculations. The effect of each variable on the total per-mile life-cycle cost is revealed by switching the low-cost and high-cost estimates for each variable, one at a time.

It was found that the uncertainty associated with any single variable did not have a profound effect on the total cost. The most significant variables were those that concerned RPEV batteries, vehicle maintenance and longevity, and roadway cost and utilization. However, changing three or more variables simultaneously did significantly change the total RPEV cost. For example, switching the high- and low-cost projections for roadway cost, roadway utilization, and RPEV maintenance increased the lower bound of the life-cycle cost 19 percent and decreased the upper bound by 15 percent.

Several other considerations are worth mentioning. A lower interest rate or a higher initial ICEV cost makes the RPEV more competitive by making the RPEV's greater purchase cost less significant. In addition, anything that reduces the required battery size of an RPEV (e.g., increasing the efficiency of the baseline vehicle) will favor the RPEV compared with an ICEV. Finally, the ICEV life-cycle cost is more susceptible to fuel price fluctuations than that of the RPEV because ICEV fuel cost constitutes a greater percentage of the total life-cycle cost.

RPEV EMISSIONS ANALYSIS

Even if RPEVs are more expensive than comparable ICEVs, they still may be preferable from society's point of view because of their environmental benefits. In 1988 more than 100 U.S. cities exceeded the health-based national ambient air quality standard for ozone (*52*). In 1988 highway vehicles accounted for 31 percent of the national total emissions of nitrogen oxides (NO_x), 26 percent of all reactive volatile organic compounds (VOCs), and 56 percent of carbon monoxide (CO) (*53*). As will be seen, RPEVs essentially eliminate transportation-generated CO and VOCs (a primary ozone precursor) and have the potential to substantially reduce NO_x.

To determine the emission impacts of RPEVs it is necessary to determine average fleet emission rates of the ICEVs they replace and the emission rates of power plants for the same pollutants during RPEV electricity generation. The power plant emissions can then be allocated to the RPEV fleet for comparison. If this procedure is followed, an RPEV-ICEV emissions comparison is possible for any level of RPEV penetration. In the analysis RPEV and ICEV emissions were compared under two different scenarios. The first scenario represented the emissions impact from RPEV implementation under current conditions, whereas the second examined implications under circumstances of more stringent ICEV and power plant emission controls.

First, a calculation was made of what the emission rate of an RPEV defined by the cost model inputs would have been given total vehicle energy demand and power plant emission rates in 1988. This was compared with the actual average emission rate for gasoline automobiles during the same year. Emissions from petroleum recovery, refining, and transportation were not counted, but their exclusion did not significantly affect the total vehicle emission rate.

The second scenario compared gasoline automobiles that meet current 50,000-mi automobile emission control standards with RPEVs operating on electricity from a utility mix in which 50 percent of the power plants meet the federally regulated "new source performance standards" (NSPS) (*54*). Calculations were based on EIA's projected power plant fuel feedstock mix for 2000 (*49*). Power plants have about a 40-year life, whereas the national vehicle fleet turns over about every 10 years. Therefore, it was assumed that by the time the entire vehicle fleet meets current emission standards (about 10 years from now), 50 percent of all power plants subject to emission control standards will meet the new source emission standards implemented in 1978 (almost all electricity production in the United States is from power plants subject to the standards).

Particulate emissions from 1988 gasoline automobiles were based on data from the California Air Resources Board (CARB) emissions model—EMFAC7D—to distinguish between particulate emissions from tire wear and those from exhaust. Tire wear accounts for approximately 95 percent of gasoline particulate emissions. The analysis increased RPEV tire wear particulate emissions in accordance with the percent weight increase of an RPEV relative to an ICEV.

Sulfur oxide (SO_x) emissions from a gasoline vehicle, unlike other catalyzed emissions, are a function of the amount of fuel used. SO_x emissions were estimated on the basis of the fact that essentially all sulfur in gasoline is converted to SO_2 on combustion. SO_x emissions ~~for a~~ 1988 gasoline automobile were calculated in the above manner and then scaled up linearly for a 35-mpg ICEV for the 2000 scenario.

Because there are no gasoline vehicle standards for particulates and SO_x emissions and no power plant standards for VOC and CO emissions, it was assumed that these emission rates will remain at current levels (SO_x emissions were adjusted for fuel economy improvements as described above). Furthermore, current SO_x power plant emissions (essentially all SO_x emissions from power plants is SO_2) are less than the standard, so it was assumed that power plants will continue to emit at current levels.

Finally, two levels of RPEV efficiency were used in the analysis. Both high and low fuel economies are based on the RPEV defined by the assumptions given in Tables 1 and 2. The low-efficiency RPEV averages 2.8 mi/kW-hr overall, and the high-efficiency RPEV averages 4.4 mi/kW-hr. These efficiencies include all distribution and system losses and are based on a driving regime that draws 50 percent of all vehicle power from the roadway. The relative emission changes resulting from RPEV use are indicated in Table 4. Results are presented for automobiles only; the results for light-duty vans and trucks are similar.

TABLE 4 PERCENT CHANGE IN EMISSIONS PER MILE DUE TO REPLACING GASOLINE PASSENGER CARS WITH RPEVs

	RPEV Efficiency[1]	VOC	CO	NOx	SOx	Part.
1988 SCENARIO[2]	HIGH	-99.8	-99.8	-68.3	108	23.5
Actual vehicle and powerplant emission rates.	LOW	-99.7	-99.7	-50.6	222	53.3
YEAR 2000 SCENARIO[3]	HIGH	-99.9[4]	-99.2[5]	-65.7	---[6]	16.8[7]
All vehicles meet current emission standards and 50% of all electricity used for RPEVs is from powerplants that meet NSP emission standards.	LOW	-98.2	-98.8	-45.1	---	44.4

1. High RPEV efficiency is 4.4 miles/kwh (from utility station): low RPEV efficiency is 2.8 miles/kwh.
2. Actual gasoline vehicle emission rates based on total gasoline automobile emissions divided by total automobile gasoline consumption divided by calculated average fuel efficiency for gasoline automobiles. Assumed emission rate for gasoline automobiles is independent of fuel economy except for SOx emissions. Excludes emissions from petroleum extraction, refinery, and transport. RPEV emission rates based on powerplant emission rates divided by total powerplant electricity output divided by RPEV fuel economy from the powerplant.
3. Assumes half of all RPEV electricity is from powerplants that meet NSP emission standards (or remain at current levels whichever is less) and that all gasoline vehicles comply with current federal emission standards. Converts HC standard to equivalent VOC standard for comparison purposes by multiplying former by CARB conversion factor of 0.85. Powerplant emissions based on EIA's projected powerplant fuel mix for the year 2000.
4. No NSP standard -- assumes powerplant emission rate remains at 1988 level.
5. No NSP standard -- assumes powerplant emission rate remains at 1988 level.
6. 1988 emission rate lower than NSP standard -- assumes powerplant emission rate remains at 1988 level. No vehicle standard -- assumes vehicles emit at 1988 rate. Result is same as 1988 scenario.
7. No vehicle standard -- assumes vehicles emit at 1988 rate.

EMISSIONS SUMMARY

The emissions analysis indicates that VOC and CO emissions from automobiles will be virtually eliminated with RPEVs. NO_x emissions will also be substantially reduced. SO_x and particulate emissions from transportation are likely to increase with the implementation of RPEVs. However, automobiles are responsible for less than 3 percent of all SO_x emissions and about 16 percent of all particulate emissions in the United States (*53*). NO_x, SO_x, and particulate emissions are all sensitive to the amount of coal used to produce electricity for RPEVs. Reducing the amount of coal-fueled electricity generation will go a long way towards controlling these three emissions.

The percent changes in Table 4 probably understate the air quality benefits that RPEVs will bring about. First, reductions in VOC and NO_x will translate into reductions of anthropogenic ozone, the main constituent of smog. Ozone is formed through a chemical reaction between VOCs and NO_x in the presence of sunlight. Because of the complexity of its formation, a slight decrease in VOCs or NO_x does not guarantee a decrease in ozone formation. However, with VOC and NO_x decreases of the magnitude suggested here, a large decrease is likely.

Second, a number of other air quality and emission benefits are likely to accompany the introduction of RPEVs. It is easier to control and monitor emissions from a few stationary sources than from millions of vehicles. Emission control devices on vehicles are vulnerable to more rapid deterioration (because of more taxing conditions and design criteria), tampering, intentional or unintentional misfueling, and so forth. It is difficult to conduct vehicle emission inspections as frequently as power plant inspections, and surprise inspections of vehicles are more cumbersome and expensive. In addition, the burden and inconvenience of emission control upkeep now borne by millions of individuals would be transferred to a relatively few power plants.

Another consideration is the time of day and location of emission releases. If the battery proves the primary source of power for RPEVs, most recharging and thus electricity generation will take place at night because of pricing incentives. Because sunlight is essential to ozone formation, nighttime charging will result in less ozone; in addition, fewer people will be subject to exposure during the night. More important, RPEVs can transfer emissions from the streets of urban areas where millions of people are subject to exposure to the top of smokestacks, which tend to be located in more remote and sparsely populated areas.

RPEV GREENHOUSE GAS EMISSIONS

It is estimated that transportation accounts for 30 percent of the global warming effect (*55*). In the United States, transportation accounts for approximately 27 percent of all fossil-fuel-generated carbon dioxide (CO_2)—the primary greenhouse gas (*4*). RPEVs offer potential for reducing emissions of greenhouse gases from the transportation sector. The actual benefits will depend primarily on the fuel used for electricity production, the efficiency of electricity production and distribution, and vehicle efficiency.

For this analysis a detailed model that calculates the difference between greenhouse gas emissions from an RPEV and an ICEV was used (*4*). The model calculates CO_2 emissions and CO_2-equivalent VOC, CH_4, N_2O, and CO emissions from ICEV and RPEV use on a per-mile basis. It considers all emissions from petroleum recovery (or feedstock recovery in the case of RPEVs) to end use. CO_2-equivalent emissions are based on the potential global warming effect of VOC, CH_4, N_2O, and CO. The results indicate that the impact of RPEVs on global warming depends strongly on the fuel mix used for generating electricity.

The results in Table 5 indicate the percent changes if all the electricity produced for RPEVs were to come from the indicated feedstock. For example, if the electricity for an RPEV were generated by using the 1988 power plant fuel mix, the vehicle would emit approximately 24 to 51 percent less of the specified greenhouse gases than a comparable ICEV. The high and low vehicle fuel economies are the same used in the emissions analysis—4.4 miles/kW-hr and 2.8 miles/kW-hr, respectively. With the exception of a coal-dominated power plant scenario used with low-efficiency RPEVs, RPEV use will reduce greenhouse gas emissions from transportation. The net reduction of transportation-generated greenhouse gases could be substantial if RPEVs supplant gasoline vehicles on a large scale and environmentally benign fuels are used to generate RPEV electricity.

ELECTRICITY DEMAND IMPLICATIONS—CASE STUDY

Wide-scale electrification of roadways will require increases in electricity production and electricity-generating capacity. Increased demand for electricity can have a positive or negative effect on electricity cost. If the increase occurs during off-peak hours, existing capacity will be more effectively utilized. In most areas, electricity demand peaks during afternoon hours, whereas traffic peaks in the early morning and late afternoon. If RPEVs do not rely heavily on storage batteries during peak electricity-generating periods, wide-scale use of RPEVs could require a significant increase in electricity-generating capacity. To increase generating capacity new facilities must be built. If the number of new facilities needed is large, average electricity costs could increase significantly because new sources of electricity are increasingly expensive (i.e., the marginal cost of production is greater than the average cost). The relationship between peak travel times and peak electricity-generating periods is the most important factor in determining RPEV electricity demand implications.

RPEV impacts on utilities were estimated under the most extreme scenario—the electrification of all highway lanes in California. It was assumed that all vehicles using California highways operate from electricity supplied through the electrified roadway. Traffic volumes and travel patterns were based on actual conditions in Los Angeles during 1985; non-RPEV electricity demand was based on production during 1985 from Southern California Edison, the largest utility in southern California (*56*).

The results indicate that in the unlikely event that *all* of California's highway traffic drew its entire energy supply from the electricity grid instead of from batteries, current production would increase approximately 62 percent and capacity by about 65 percent over 1985 output levels. This analysis is for illustrative purposes only. Complete RPEV penetration

TABLE 5 GREENHOUSE GAS EMISSIONS OF RPEVs RELATIVE TO ICEVs (AUTOMOBILES ONLY)

FEEDSTOCK	% CHANGE FROM ICEV CASE (CO_2-equivalent emissions)[1]	
	Low RPEV Efficiency[2]	High RPEV Efficiency
RPEV fuel from nonfossil electricity (excluding nuclear)	-100	-100
RPEV fuel from nuclear powerplants[3]	-95	-97
RPEV fuel from natural gas powerplants	-32	-56
RPEV fuel from 1988 feedstock mix	-24	-51
RPEV fuel from oil powerplants	-4	-38
RPEV fuel from coal powerplants	+11	-28

[1] CO_2- equivalent emissions include CO_2, VOC, CH_4, CO, and N_2O.
Assumes a national average powerplant efficiency of 33%.
Assumes 50% of all RPEV travel uses real-time electricity provided by the roadway.

[2] Low = RPEV efficiency of 2.8 miles/kwh (from the utility station): High = RPEV efficiency of 4.4. miles/kwh.

[3] Uses current electricity consumption of DOE gaseous diffusion plants; most of this electricity is from coal powerplants.

and highway electrification without on-board battery storage is highly unlikely; actual RPEV electricity demand during peak generating periods will undoubtedly be much lower. In fact, the best RPEV strategy may be to electrify only a modest share of urban Interstate systems because these highways represent just 0.3 percent of the entire U.S. roadway network but carry 12.7 percent of all traffic on the basis of vehicle miles traveled (*57*). In many urban areas the share of traffic on limited-access expressways is much higher—50 percent in Los Angeles (*58*).

POTENTIAL RPEV MARKETS

Applications

Although there have been no RPEV marketability studies, battery-powered EV market penetration studies on the basis of economic criteria and daily travel patterns indicate that electric vehicles could capture a significant share of the private and fleet vehicle markets. Perhaps the most revealing of these studies is one based on longitudinal travel data that examined individual travel patterns over an extended period (*59*).

The study indicated that an EV with a 55-mi range would suffice for 25 percent of the population surveyed on all but 37 days of the year and a vehicle with a 117-mi range would suffice for the same number of people for all but 1 week out of the year. Inability to use a vehicle for 37 days may prove unacceptable to many car owners; however, 7 days is less likely to be a major inconvenience or cost burden. This is even more likely if the 7 days are consecutive which, as the study points out, is usually the case (the 7-day period often represents vacation travel time). A multivehicle household could rely on a second vehicle to meet travel demand for those 7 days and a single-vehicle household could rent a vehicle with a longer range to meet an occasional long-distance travel need.

In addition, the study indicates that only 10 percent of the 2,286 people surveyed nationwide had daily travel patterns that exceeded 55 mi. These survey findings suggest that, although a range of about 55 mi is sufficient to meet the average daily travel demands of most people, a range of at least twice that distance would be needed to make the vehicle versatile enough to compete with longer-range vehicles. Therefore, a typical owner of a battery-powered EV would purchase and carry approximately twice as much battery as is needed on a daily basis. Battery size can be substantially decreased (and life-cycle cost reduced) if RPEV technology is strategically implemented.

Likewise, individuals who cannot recharge a battery overnight (e.g., those who do not have access to off-street parking or an electrical outlet) are excluded from battery-powered EV use. However, these prospective EV owners could recharge an RPEV battery through dynamic recharging or through inductor-equipped parking spaces. This could be an important consideration because approximately 43 percent of all urban dwellers rent apartments and are, therefore, unlikely to have access to an outlet for battery charging (*28*).

Given the above considerations, the largest market for RPEVs is probably as a commuter vehicle or as an around-town vehicle in a multivehicle household. At least one vehicle in every household will probably be capable of an ultralong trip, although this intermittent need could perhaps be met by a rented vehicle. Even as a "commute" vehicle, however, the RPEV would neither necessarily be a secondary vehicle nor accumulate less mileage annually than the long-distance vehicle.

In addition to privately owned commute vehicles, certain job-specific vehicles also provide a good application for RPEVs. Small-to-medium delivery vehicles, certain fleet vehicles (such as utility fleets), taxis, and buses are all prime candidates for RPEV use. Two extensive surveys of fleet managers—the North American Van Market Survey (*60*) and the EPRI/Detroit Edison survey (*61*)—found that electric vans with a 60-mi range could replace almost 200,000 vans in the 31 largest van fleets alone (including government vans) or approximately 3.5 million fleet vehicles nationwide. More important, both surveys indicate that these levels of EV penetration could be increased substantially with relatively minor range increase. Because many fleet vehicles routinely travel over the same roadway and are centrally refueled, they would be good candidates for RPEV replacement. In addition, many fleet vehicles in the surveys required considerable cargo capacity. Thus, the RPEV with its smaller battery may prove a better option than a battery-powered EV.

Location

High-volume urban roadways provide the best location for roadway electrification because the infrastructure cost can be distributed among more users. Approximately 60 percent of all travel in the United States takes place on urban roadways, and 65 percent of all urban interstate travel occurs under congested conditions that imply reduced travel speeds (*57*). This favors roadway electrification because the longer a vehicle is on the powered roadway the more battery charge it can receive and, unlike an ICEV, an RPEV does not waste fuel or pollute while it is immobile.

Roadway electrification would also be plausible on urban streets frequented by the same vehicles. Bus routes present an ideal opportunity for RPEV technology because they often go through heavily populated pedestrian areas that are sensitive to pollution (diesel buses are heavy emitters of highly visible harmful particulate matter). Other environmentally sensitive areas where pollution has more noticeable impacts, such as national parks, would also provide good applications for RPEV technology.

Roadway electrification could be used for intercity trips of moderate length. Long sections of roadway between reasonably close metropolitan areas would be electrified. The electrified lanes would be long enough to allow an RPEV to reach a neighboring city either by charging the battery en route or by replacing battery energy with roadway energy for part of the trip. However, the electrification of long stretches of rural highways is an expensive proposition because the cost would be allocated among fewer vehicles than would the cost of urban roadway electrification.

CONCLUSIONS

The RPEV may be a workable alternative to the petroleum combustion engine and an option for overcoming the main drawbacks of battery-powered EVs. Although there is a great deal of uncertainty regarding the cost of an RPEV, the air quality benefits are conclusive. In addition, an RPEV transportation system could help mitigate global warming.

The initial analysis of RPEV life-cycle costs described here indicates that RPEVs may be less expensive to own and operate than conventional petroleum vehicles even if RPEV users bear the full cost of electric roadway installation and maintenance. Furthermore, RPEV operating costs are less vulnerable to fuel-cost fluctuations and fuel-supply disruptions than are those of a comparable ICEV. RPEV implementation is well justified on the basis of air quality criteria. Wide-scale use of RPEVs would essentially eliminate transportation-generated VOC and CO emissions and substantially reduce NO_x emissions. RPEVs allow air quality benefits far greater than what is feasible with advanced-technology petroleum ICEVs. RPEVs would probably reduce greenhouse gas emissions considerably in addition to reducing regulated emissions. On the basis of the 1988 national fuel feedstock mix for electricity power plants, RPEVs would reduce automobile greenhouse gas emissions by 24 to 51 percent from 1988 gasoline automobile levels.

Battery-powered EVs are already finding their way into the fleet vehicle market and are being promoted as one solution to the air quality problem in southern California. However, even if optimistic expectations of battery technology materialize, EV markets will still be relatively small because of vehicle range limitations. Roadway electrification is a relatively new technology that offers important advantages over battery-powered EVs. A flexible RPEV system that offers a variety of battery sizes to accommodate various driving demands is capable of capturing a significant share of the commuter vehicle and fleet vehicle markets.

Although RPEV technology has been demonstrated and tested, a number of system design considerations must be addressed before the technology can be implemented. Once fundamental system objectives are determined, the technology can be tailored to best meet those objectives. Financing mechanisms also need to be established in the early developmental stages. The potential of RPEVs can only be realized if the uncertainties surrounding the concept are adequately addressed through expanded research and development. Because RPEV technology is in its infancy, there is reason to expect substantial efficiency gains and cost reductions in the near future.

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