Roadway Electrification: Regional Impacts Assessment

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Roadway electrification has been proposed to address urban air pollution. The impacts on fossil fuel use and the electric utility industry are investigated, and the regional economic effects of this technology are assessed. The analysis initially involved the development of a roadway electrification network scenario selected from several alternatives on the basis of sensitivity analyses that allowed for variability in network location, network lane kilometers (miles), and market penetration of roadway-powered electric vehicles. A comparative analysis of emissions and fossil fuel usage between the roadway electrification scenario and a baseline (no roadway electrification) was performed. Emissions investigated were reactive organic gases, carbon monoxide, nitrogen oxides, sulfur oxides, and particulate matter. Petroleum and natural gas were the fossil fuels considered. Findings indicated that overall moderate reductions in emissions for all pollutants and petroleum usage may be obtained, but a sizable increase in natural gas consumption was likely. A small increase in generating capacity for the electric utilities was projected. The cost analysis of the system included construction and operating expenses of the electrified roadway and life cycle costs to facility users. The technology may offer economic advantage to users over the life of the vehicle if roadway infrastructure costs are subsidized like conventional nonpowered highway developments.

Urban traffic congestion and air pollution are issues in many metropolitan areas but are more acute in Southern California than in most other North American cities. The California Partners for Advanced Transit and Highways (PATH) Program at the Institute of Transportation Studies, University of California, Berkeley, and the Southern California Association of Governments (SCAG) have recently completed a 3-year investigation of the regional impacts that could result from implementation of advanced highway technologies in the Greater Los Angeles area (*1–3*). This paper summarizes the study's findings of a projected application of roadway electrification to portions of the SCAG region highway network (the nondesert portions of Los Angeles, Riverside and San Bernardino counties, and Orange and Ventura counties) for 2025. That year was chosen for the analysis to allow sufficient time for this technology to reach maturity and large-scale implementation.

Mitigation of mobile source emissions was expected to be the principal benefit derived from electrifying selected portions of the highway system. Reactive organic gases (ROG), carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) were assumed to decline as roadway-powered electric vehicles (RPEVs) replaced conventional vehicles. Fossil fuel usage and utility and regional economic impacts were also estimated.

Designing an electrified highway system for 2025 was the initial step in the roadway electrification assessment. The scenario development process included a sensitivity analysis that varied the location, number of lanes, and number of lane kilometers (miles) for the powered roadway. Additional network considerations, such as lane separation, access and egress opportunities, and lane capacity were investigated for electrified and mixed-flow facilities. The methodology that produced the electrified system configuration is documented elsewhere (*2*).

The impacts analysis contrasted 2025 baseline (no roadway electrification) emissions and fossil fuel and utility usage projections with comparable roadway electrification estimates. Baseline population, employment, transportation demand, and vehicle emissions were compiled using projected SCAG regional transportation and emission model updates. The 2025 regional transportation network consisted of the existing highway network, currently funded new highway construction, reconstruction specified in SCAG's Regional Mobility Plan for 2010, and long-range corridors identified to assist future transportation needs (*4*).

In addition to mobile source emissions, other environmental issues, such as electromagnetic fields produced by the powered lanes and acoustic noise in vehicles traveling on the powered roadway, should be addressed as part of a complete investigation of the technology's impacts. These issues are evaluated in another recently completed PATH project, conducted by Systems Control Technology, Inc. (SCT) (*5*), and summarized elsewhere (*3*).

ROADWAY ELECTRIFICATION SCENARIO DESCRIPTION

The objective of roadway electrification is to provide all-electric vehicles (EVs) that have the same characteristics as internal combustion engine vehicles (ICEVs), such as range, acceleration, and life cycle costs, by providing an external energy source for long trips augmenting the on-board battery. External energy can be transferred to RPEVs while they operate on powered roadways (e.g., freeways where long trips typically occur). This technology could increase the market penetration of EVs, especially with the proper incentives.

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Battery size for RPEVs can be considerably smaller than for pure battery EVs because energy is available from the powered roadway for long trips. The size reduction results in improved payload and acceleration and reduced battery costs. Short RPEV trips on battery power only were ignored in the analysis, resulting in conservative estimates for emissions reductions, user costs, and utility power demand profile.

To help select the 2025 roadway electrification scenario configuration, combinations of alternative electrified vehicle kilometers traveled (VKT) [vehicle miles traveled (VMT)] market penetration and network size were simulated with the SCAG transportation model for the a.m. peak period. Market penetrations of 5, 15, and 30 percent were each modeled on networks of 377, 694, and 1,058 center-lane km (234, 431, and 657 center-lane mi). This sensitivity analysis incorporated battery range and RPEV market potential considerations. A full description of the scenario development process is given elsewhere (*2*).

A key consideration in the scenario development was an appropriate battery range for the RPEV. Since only unlinked vehicle trips were reported in the modeling process, derated autonomous battery ranges were studied. For example, a derated battery range of 64 km (40 mi) with a derating factor of 2 would correspond to a total battery range of 129 km (80 mi) without recharging. Derated battery ranges of 32, 48, 64, 81, and 97 km (20, 30, 40, 50, and 60 mi) were studied with respect to 2025 a.m. peak trip length distribution data for distance traveled on and off all three networks (*2*). This analysis estimated the number of trips [and VKT (VMT)] that could be performed by battery only, RPEV, and conventional vehicles, or market potential, and indicated a direct relationship among the market potential number of trips [and VKT (VMT)], battery range, and network size (*2*). The selection of a 64-km (40-mi) derated battery range enabled at least 97 percent of a.m. peak trips and more than 78 percent of a.m. peak VKT (VMT) to be completed by RPEVs.

Separation of RPEV and mixed-flow lanes was not required for the technology. Two roadway-powered systems were designed, however, to address practical implementation issues. A nonexclusive design permitted all vehicles to use the RPEV lanes. An exclusive system allowed only RPEV vehicles on the electrified lanes to ease collection of user costs and ensure accommodation of RPEVs requiring recharge. Exclusive access and egress facilities were not specified, thus requiring RPEVs to cross mixed-flow lanes to enter or leave the RPEV facility and use conventional on- and off-ramps. RPEV facility merge points were specified at 8-km (5-mi) intervals or less, depending on the number of ramp connectors, traffic volume, and modeling limitations. Modeling restrictions resulted in all vehicles experiencing some increased delay (*3*).

Lane capacity limitations were not required, although an RPEV network was designated with volume/capacity ratios representative of the baseline scenario.

An analysis of 2025 trip length distribution was performed next, which grouped the system's origin-destination travel pairs by on- and off-freeway network length, enabling comparison of total trip lengths with alternative battery ranges. The potential number of trips requiring the RPEV technology for trip completion was identified given the 64-km (40-mi) derated battery range selection for the impacts analysis. Of this set of trips, the number of RPEV trips designated for the RPEV scenario's trip assignment was based on a random selection of trips within the origin-destination pairs identified for RPEV use. In general, the longer the trip length, the greater the likelihood the trip would be chosen as an RPEV trip. For the RPEV scenario, 3.3 percent of the potential RPEV trips [or 15 percent of the VKT (VMT)] were selected. These trips were assigned first, since modeling restrictions precluded simultaneous loading of conventional and RPEV trips, and alternative model runs yielded negligible differences between the two trip assignment arrangements (*3*).

The roadway electrification scenario had the following characteristics: network size, 1666 lane-km (1,035 lane-mi); market penetration, 15 percent a.m. peak VKT (VMT) [10.6 million VKT (6.6 million VMT)] and 3.3 percent a.m. peak trips (170,000 trips); derated battery range of 64 km (40 mi); lane separation designated but not required; no special access or egress facilities required; and no lane-capacity restriction. Figure 1 shows the 2025 roadway electrification network.

Trip assignment results indicated that 4.7 million VKT (2.9 million VMT) was associated with RPEV travel on the RPEV facility, or 46.5 percent of all RPEV vehicle kilometers (miles) traveled. The impacts assessment of electricity demand, fossil fuel use, and powered-roadway operating costs required dividing VKT (VMT) into on and off powered-roadway components. The emissions impact was calculated for total RPEV VKT (VMT), since RPEVs are zero-emission vehicles. A comparison of the exclusive and nonexclusive RPEV system impacts produced negligible differences. Exclusive RPEV scenario impacts are reported in the following sections.

FOSSIL FUEL ENERGY CONSUMPTION

Comparisons of 2025 petroleum and natural gas usage for the RPEV and baseline scenarios were performed. Petroleum consumption was important due to this fuel's extensive use in the U.S. transportation sector and U.S. dependence on foreign oil. Natural gas consumption was significant since it was forecast to fuel approximately 81 percent of 2025 SCAG regional generated electricity (*3*).

The methodology used to estimate the fossil fuel energy consumption modified research by Wang et al. (*6*) for RPEV application and assessed each stage of the energy production process. All downstream energy sources were included to derive the primary energy consumption associated with the electricity-generating process, including trace amounts of nonfossil fuels such as biomass.

The impacts analyses were calculated for a.m. peak and daily time periods, light-duty automobile (LDA) and light-duty truck (LDT) vehicle types, and the extent of RPEV travel (*3*). LDAs and LDTs represented approximately 94 percent of the vehicle fleet in the SCAG region. Medium- and heavy-duty trucks and motorcycles, making up the remaining 6 percent of the fleet, were not included because of data limitations.

Petroleum Consumption

The baseline scenario vehicle fleet was assumed to consist entirely of gasoline ICEVs. Their petroleum consumption was

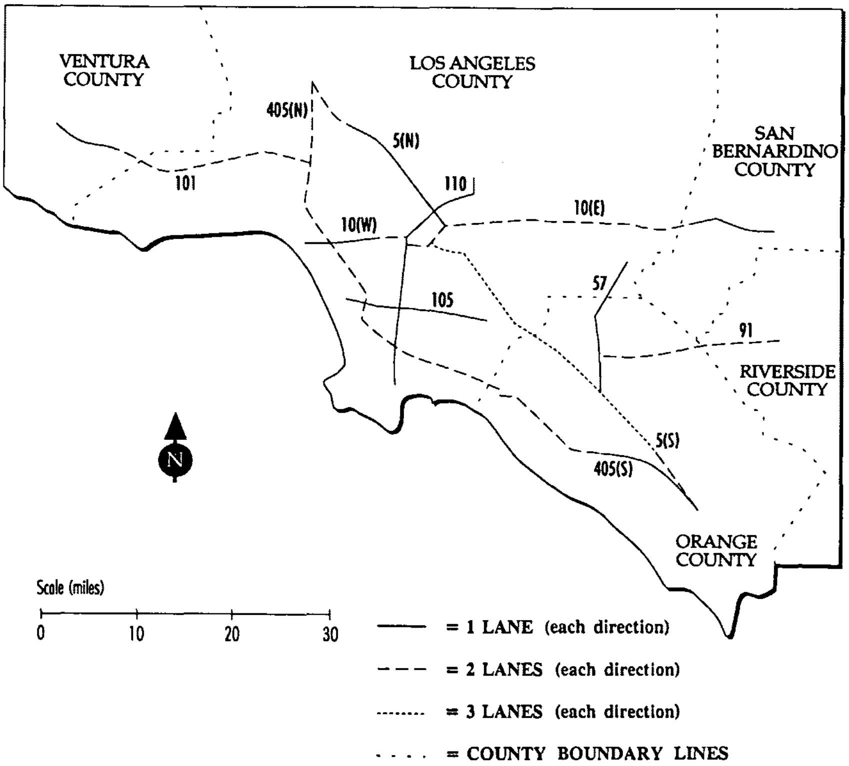

FIGURE 1 RPEV scenario, 2025 regional highway network.

derived from gasoline use and the use of petroleum-derived fuels in the initial phases of the gasoline production cycle. RPEV petroleum consumption was derived from petroleum use for electricity generation and processing other fuels such as natural gas.

The findings indicated a 15 percent daily petroleum consumption savings across vehicle types for both total and on-network RPEV travel as expected given the 15 percent decrease in ICEV vehicle kilometers (miles) traveled in the RPEV scenario. This savings meant a gasoline reduction of approximately 8.3 million L (2.2 million gal).

The percentage petroleum consumption reduction was derived relative to all LDAs, all LDTs, and their total. Relative to the fleet of vehicles replaced by RPEVs, the percentage petroleum consumption reduction ranged from 99 to 100 percent across all vehicle types.

Natural Gas Consumption

Total daily natural gas consumption for LDAs, LDTs, and the combination of the two was approximately 53.3, 18.8, and 72.4 thousand megawatt-hr (mwh) [0.182, 0.064, and 0.247 trillion Btu (tBtu)], respectively, in the baseline scenario. Corresponding estimates for the exclusive RPEV scenario were 80.3, 35.2, and 115.4 thousand mwh (0.274, 0.120, and 0.394 tBtu), representing increases in natural gas consumption of 50.5, 87.5, and 59.5 percent.

Large increases were expected since natural gas was projected to fuel 81 percent of electricity generated in 2025. Whereas the forecast petroleum consumption percentage decrease (15 percent) was considerably smaller than the natural gas percentage increase (59.5 percent), petroleum usage decreased approximately 81.5 thousand mwh (0.278 tBtu), whereas natural gas consumption increased approximately 43.1 thousand mwh (0.147 tBtu).

Baseline annual end use demand for natural gas in California was projected to be approximately 440 million mwh (1,500 tBtu) (*7*). Approximately half was expected for the SCAG region on the basis of population estimates, yielding an average daily amount of 602 thousand mwh (2.055 tBtu). The increase in daily natural gas consumption for the RPEV scenario for LDAs and LDTs relative to the baseline was estimated to be approximately 43.1 thousand mwh (0.147 tBtu), or a 7.2 percent increase.

The projected average daily percentage increase in natural gas demand for the SCAG region between 1990, 577 thousand mwh (1.97 tBtu) (*8*), and the 2025 baseline, 602 thousand mwh (2.055 tBtu), is 4.3 percent. Daily natural gas supply for the SCAG region in 2025 was forecast to be approximately 966 thousand mwh (3.297 tBtu). Thus, whereas the increase in natural gas usage for the RPEV scenario was significant relative to the period from 1990 to 2025, plentiful supplies of natural gas were projected for 2025.

EMISSIONS ANALYSIS

Emissions impacts of roadway electrification were derived and compared with 2025 baseline emissions. Daily results were compiled for ROG, CO, NOx, SOx, and PM for LDAs and LDTs and both vehicle types combined. Baseline mobile source emissions were composed of cold and hot start, evaporative, and running emissions and were derived from the California Air Resources Board's emissions impact rate models (EMFAC7E), SCAG's direct travel impact model, and Caltrans's travel data (*9*). Two stationary source emissions, refueling (evaporative emissions at fuel stations and bulk plants) and petroleum refinery emissions, also contributed to baseline emissions. The methodology used to estimate these stationary source emissions was based on research by Wang et al. (*10*).

Total emissions for the RPEV scenario consisted of mobile source emissions generated by ICEVs, stationary source emissions attributed to ICEVs, and power plant emissions produced during the electricity generation process. The ICEV mobile and stationary source emissions were derived by the methodology used to compute analogous baseline emissions. Total regional power plant emissions (grams per kilowatt-hour) were calculated by pollutant and power plant type. Data required for this derivation included (*a*) the percentage breakdown of fuel feedstock sources for regional electricity-generating power plants, (*b*) power plant mix by type for each fuel feedstock source, (*c*) future emission reduction technologies used in each power plant type coupled with the percentage emission reduction for each pollutant, and (*d*) the percentage of power plants by type using these emission reduction technologies (*1,3,11*).

Natural gas was the only regional fuel source used to derive power plant emissions. Gas power plants were further divided into steam, turbine, combined cycle, and advanced combined cycle types. Wind and solar fuel sources were excluded from the analysis because of negligible emissions. Oil-fired power plants were excluded given their negligible contribution to regional electricity production. Biomass-fired power plants were excluded given their small contribution to electricity production, lack of sufficient data to describe biomass emissions, and the assumption that biomass would not be part of the marginal power plant mix to produce electricity for RPEV usage (*12*). Coal-fired power plants were not projected for the region in 2025 and were excluded from the analysis since the study's focus was on regional air quality. Approximately 4 percent of the 2025 electricity supply was expected to be imported to the region from coal and hydroelectric power sources (*1*), with coal accounting for approximately two-thirds of the imports and all hydroelectric power imported from the Pacific Northwest. The data were insufficient to estimate the in- and out-of-state mix for coal imports. The entire amount of daily emissions from coal-fired power plants will range from approximately 9 kg (20 lb) for PM to 91 kg (200 lb) for SOx. These additional emissions increase the precoal power plant emission levels by at most 4 percent across all pollutants except SOx. Additional SOx emissions increased corresponding emission levels by 500 percent. However, precoal power plant emissions were sufficiently small that these added coal-generated emissions have no effect on the percentage change in emission levels from the baseline to the RPEV scenario for all pollutants. Thus excluding all coal-fired power plants from the analysis displaces a small amount of emissions attributed to usage in the SCAG region to other regions.

The power plant mix used in the analysis was representative of the average rather than the marginal fuel mix needed to satisfy incremental electricity demand created by RPEVs. No forecasts have been made of such fuel combinations for the SCAG region for 2025. Related research was done for the Southern California region for battery-powered EV use for 2010 (*12*) focusing on the Southern California Edison Company (one of two major regional electricity service providers) service area. This work showed that most energy needed for EVs (70 to 90 percent) will come from natural gas-fired power plants. This result agrees with the fuel mix used in our research, since natural gas was forecast to fuel 81 percent of 2025 generated electricity.

Power plant emissions (grams/kwh) were converted to grams per kilometer (mile) for each vehicle type after accounting for distribution losses between the power plant and the vehicle. Vehicle energy consumption for LDAs and LDTs was estimated to be 0.15 kwh/km (0.24 kwh/mi) and 0.34 kwh/km (0.55 kwh/mi) (*3,13*), respectively, representing averages over several driving cycles. Emissions were aggregated across power plant types, for each vehicle type, power source (electrified roadway or overnight battery recharging), and pollutant. For total RPEV travel, a weighted average of emissions was derived to reflect the on-network/off-network mix of RPEV usage. Total emissions were calculated by summing power plant and ICEV-related emissions.

Table 1 gives the emission reductions for RPEV travel relative to the baseline. Decreases varied between 7.1 and 14.9 percent, given the relatively modest market penetration for the roadway electrification scenario. The variation in emissions across pollutants for a given vehicle type was due to the strength of the relationship between pollutant and VKT (VMT). For example, SOx emissions depended primarily on distance driven, yielding a 15 percent emissions reduction for RPEVs. The number of daily trips rather than distance driven was the determining factor for CO emissions, thus producing an 8 percent emission decrease for RPEVs. Emission reductions ranged from 92 to 100 percent over all pollutants and vehicle types compared with the fleet of vehicles replaced by RPEVs. Substantial emission reductions occurred because of the small contribution of power plant emissions to total daily RPEV scenario emissions, which varied between 0.1 and 0.8 percent. The resulting trade-off between increased RPEV market penetration and associated power plant emissions and reduced ICEV emissions should be favorable for the RPEV technology, since the decrease in ICEV emissions should more than offset increased RPEV-related emissions.

TABLE 1 Roadway Electrification Total Daily Emissions, 2025 (Metric Tons)[a]

	Baseline		Exclusive RPEV			
Pollutant	LDA[b]	LDT[c]	LDA	(%)[d]	LDT	(%)[d]
ROG	199.8	55.8	185.6	(-7.1)	51.6	(-7.5)
CO	1,116.4	296.6	1,026.6	(-8.0)	272.6	(-8.1)
NOx	226.1	60.5	202.5	(-10.4)	54.3	(-10.2)
SOx	54.3	17.2	46.3	(-14.9)	14.7	(-14.7)
PM	70.2	18.6	60.5	(-13.8)	16.1	(-13.2)

[a] 1 Metric Ton = 1.1 short tons
[b] LDA = Light Duty Auto
[c] LDT = Light Duty Truck
[d] Numbers in parentheses represent percentage changes relative to the baseline for each vehicle type respectively

UTILITY DEMAND

The impact of roadway electrification on electricity use was derived for a.m. peak, p.m. peak, and daily time periods. Total energy use was calculated as the product of vehicle energy consumption per kilometer (mile) and RPEV vehicle kilometers (miles) traveled. Because vehicle energy consumption and VKT (VMT) differed by vehicle type, estimates were made for each vehicle type before aggregation. LDAs and LDTs are driven approximately the same average distance per vehicle type (*14*), and it is assumed for each time period that total VKT (VMT) is distributed uniformly across each vehicle by type. Thus, the VKT (VMT) percentage split of LDAs and LDTs mirrors their actual split (74.1 percent/19.6 percent) in the vehicle fleet. All distribution, vehicle, and roadway energy losses were included in the calculation of vehicle energy consumption. Results were derived for total and on-network RPEV travel.

Table 2 gives total electricity use for the RPEV scenarios. Electricity use for roadway power during a given time period refers to on-network travel. Overnight recharging in a particular time period is referred to as off-network travel. The time-of-day electricity demand profile was derived to provide a peak use day for analysis and planning purposes on the basis of historical daily use patterns. Travel distribution patterns were also required to develop an accurate impact assessment of roadway electrification on electricity service providers. The daily peak travel periods [a.m. peak (6 to 8 a.m.) and p.m. peak (3:30 to 6:30 p.m.)] overlap with electricity demand peaks in the late afternoon and seasonal peaks during the summer months (*15*).

TABLE 2 Roadway Electrification Electricity Demand, 2025 (mwh)

	RPEV Usage		
Time Period	Roadway Power	Overnight Charging	Total
AM-PEAK	866	1,015	1,881
PM-PEAK	2,595	5,374	5,633
DAILY	8,879	10,385	19,264

The SCAG region's 2025 baseline time-of-day electricity demand profile was projected from current usage estimates and the 2025 baseline peak hour demand estimate. The time-of-day electricity usage profile for on-RPEV network travel was derived from the daily on-RPEV network electricity demand (Table 2), the hourly traffic distribution on SCAG regional freeways, and the assumption that hourly energy demand for transportation was proportional to hourly traffic volume.

The time-of-day electricity usage profile for off-RPEV network travel was derived from data in Table 2, assuming that all battery recharging occurred overnight, all vehicles were fully recharged in the morning, and all roadway power was used to drive the vehicle rather than charge the battery. Whereas the first and third assumptions are rather strong and optimistic, they enable a time-of-day impact analysis to be derived. Overnight recharging was assumed to occur uniformly between 10 p.m. and 6 a.m., and all households were assigned the same average recharge over those 8 hr. Thus there was an average hourly demand for approximately 1,298 megawatts (mw) for overnight recharging (10 p.m. to 6 a.m.) (see Table 2) (*12*).

Total regional electricity demand by time of day was calculated as the sum of baseline and RPEV electricity use (see Figure 2). The time-of-day electricity demand profile was dominated by baseline use, since the additional amount of RPEV-demanded electricity was relatively small. Peak-hour demand shifted slightly from 2 to 3 p.m. to 3 to 4 p.m. Additional RPEV electricity demand represented an increase of 1 percent over the baseline peak. Although not entirely negligible, this increase must be compared with the 93 percent capacity increase the utilities must supply between the present and the baseline for 2025.

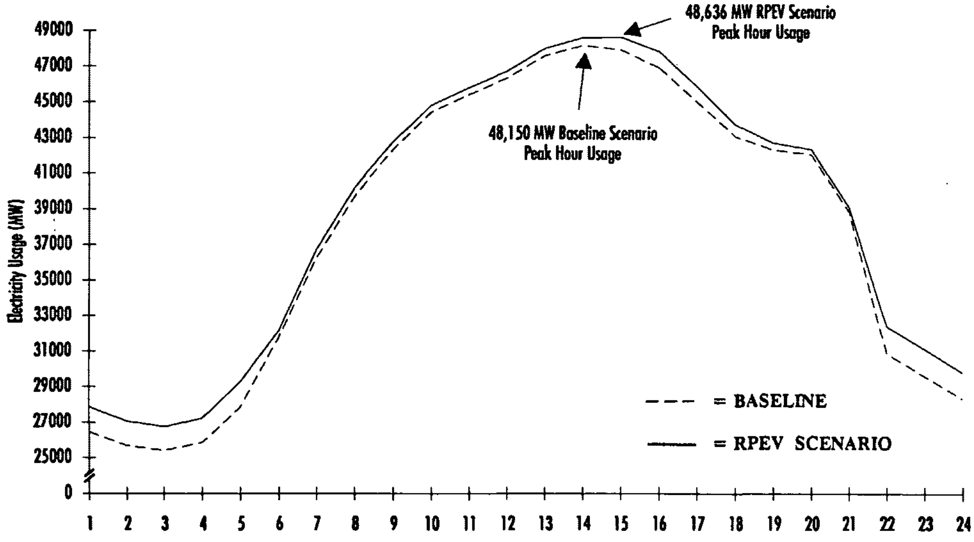

FIGURE 2 Electricity usage comparison, baseline versus RPEV scenario.

With a larger RPEV market penetration, the demand for electricity will increase. The estimate for total daily RPEV vehicle kilometers (miles) traveled was approximately 103 million (64 million), representing 15 percent of total daily VKT (VMT). A sensitivity analysis of RPEV market penetration increases was performed and indicated changes in peak-hour electricity demand. A 5 percent increase in peak-hour demand, for example, would be required if RPEV market penetration grew to 55 percent of total daily VKT (VMT). On the basis of the RPEV scenario development analysis (*2*), a more likely conservative upper limit on market penetration would be about 40 percent, corresponding to a 3.4 percent increase in peak-hour electricity demand.

ECONOMIC ASSESSMENT OF ROADWAY ELECTRIFICATION

This section presents the RPEV economic model (REM) system development and operation costs results and an assessment of regional economic impacts. Construction and operating expenses of the electrified roadway were examined as well as life cycle costs to users. The complete RPEV economic analysis contained elsewhere (*3*) reviews supportive cost model analyses used to cross check the REM results (*16*) and life cycle expenses associated with owning and operating an RPEV and gasoline vehicle (*3,17*).

System Costs

The REM was developed by SCT with input from SCAG and PATH to portray the relationship between costs and revenues associated with powered-roadway operation (*3,16*). The analysis determined the cost to build and operate the electrified roadway with revenue derived from power purchased by system users. It used estimates of roadway construction, energy, and operation costs and calculated interest charges to offset deficits that accrued during the early stages of roadway development and use. The REM incorporated a market-penetration growth profile consistent with RPEV use, financing considerations for system development and use, and a construction schedule for network design. Table 3 summarizes the REM model inputs used for the baseline cost and revenue analysis.

The REM assumed that loans were used to finance roadway construction costs. Wholesale energy cost was calculated by multiplying the amount of energy sold by the wholesale energy rate and adding system distribution losses. Operating expenses were assumed to be related to construction activity and number of users.

TABLE 3 Regional Economic Model Inputs for Baseline Scenario

Parameter Values	Description (units)
Market Penetration:	
4,000	Number of RPEV users in the initial year of market growth
6,000	Number of additional users per year until market saturation
3	Start year
28,737	Volume limit (vehicles/lane/day or vehicle kilometers/lane-kilometer/day)
Revenue:	
0.294	Cumulative breakeven electricity rate[a] ($/kwh)
Cost:	
1.55 million	Cost per lane-kilometer[b] of roadway ($/lane-kilometer)
1.04 million	Replacement cost ($/lane-kilometer)
2.5	Administrative (% of debt + energy)
2.5	O & M (% of cumulative new roadway capital cost)
0.07	Wholesale cost of energy ($/kwh)
Vehicle:	
0.13	Energy consumption of vehicle (kwh/kilometers)
75	System efficiency (%)
53.8	Average vehicle-kilometers per day on the system per vehicle
Debt Service:	
3.3%	Interest rate (real %/year)
25	Life of loan and life of roadway (years)
Miscellaneous:	
25	Designated year for cumulative breakeven rate
9.95	Number of years for roadway construction
84	New system-kilometers constructed per year (168 lane-kilometers)

[a] Output of model

[b] 1 kilometer = 0.62 mile

The REM produced an estimate of the cumulative breakeven rate, or retail energy price, necessary to break even by Year 25. This cumulative cost and revenue analysis immersed the complete cost profile into electricity rate determination so that all previous roadway construction deficits would be zero by Year 25 and thereafter become cumulatively profitable. As indicated by the baseline results in Table 4 (see asterisk output values) and Figure 3, the cumulative breakeven of all system revenues and costs by Year 25 required a retail energy price of $0.294/kwh, or a 3.83 cents per km (6.17 cents per mi) user charge. At this rate, cumulative system revenues in Year 25 equaled costs of $7,552.8 million, including the full cost to build the 1666 lane-km (1,035 lane-mi) of roadway with a scenario specified market penetration of 28,737 vehicles per lane per day.

Important annual cost and revenue patterns embedded in the cumulative cost results were rapid annual cost increases during the 10 years of initial roadway construction; lower annual costs after Year 25 due to roadway replacement costs, assumed to be two-thirds of initial roadway construction expenses, and removal of the deficit interest charges associated with initial roadway construction; and increased annual revenue until market penetration was completed.

The wholesale energy price was approximately one-third the retail energy price in the breakeven year, with debt service and cumulative interest on the cumulative deficit representing

TABLE 4 Regional Economic Model Output Results: Sensitivity Results

	Year 25		Year 40, $M		
Sensitivity Measures	Cumulative Breakeven Rate ($/kwh)	Cumulative Revenue & Costs ($M)	Cumulative Revenue	Cumulative Costs	Cumulative Profit
Roadway Cost ($M)					
0.0	0.156	3,998.0	9,326.4	8,317.3	1,009.1
1.5	0.241	6,182.1	14,421.5	11,518.6	2,842.9
2.5[a]	0.294	7,552.8	17,618.8	13,602.6	4,016.3
4.0	0.376	9,646.3	22,502.5	16,725.8	5,776.7
6.0	0.492	12,613.3	29,424.0	21,197.6	8,226.4
Wholesale Energy Cost ($)					
0.05	0.267	6,851.9	15,984.0	11,967.6	4,016.3
0.07[a]	0.294	7,552.8	17,618.8	13,602.6	4,016.3
0.09	0.322	8,253.7	19,254.0	15,237.6	4,016.3
Operating Expenses (%)					
1.0	0.256	6,573.0	15,333.2	11,966.3	3,366.8
2.5[a]	0.294	7,552.8	17,615.8	13,602.6	4,016.3
5.0	0.358	9,185.9	21,428.6	16,329.7	5,099.0
Interest Rate (%)					
3.3[a]	0.294	7,552.8	17,615.8	13,602.6	4,016.3
6.6	0.377	9,675.7	22,571.2	16,438.4	6,132.8
9.9	0.481	12,340.8	28,788.3	19,914.0	8,874.2
Energy Consumption (kwh/kilometer)					
0.10	0.357	6,968.7	16,256.4	12,240.1	4,016.3
0.13[a]	0.294	7,552.8	17,615.8	13,602.6	4,016.3
0.16	0.256	8,136.9	18,981.4	14,965.1	4,016.3
System Efficiency (%)					
65	0.309	7,930.2	18,499.3	14,483.0	4,016.3
75[a]	0.294	7,552.8	17,618.8	13,602.6	4,016.3
85	0.283	7,264.2	16,945.7	12,929.3	4,016.3
Average Vehicle-kilometers per day on system					
53.8[a]	0.294	7,552.8	17,619.8	13,602.6	4,016.3
64.4	0.262	8,037.6	18,749.8	14,733.4	4,016.3
80.51	0.229	8,772.0	20,463.0	16,446.7	4,016.3

[a] Baseline values

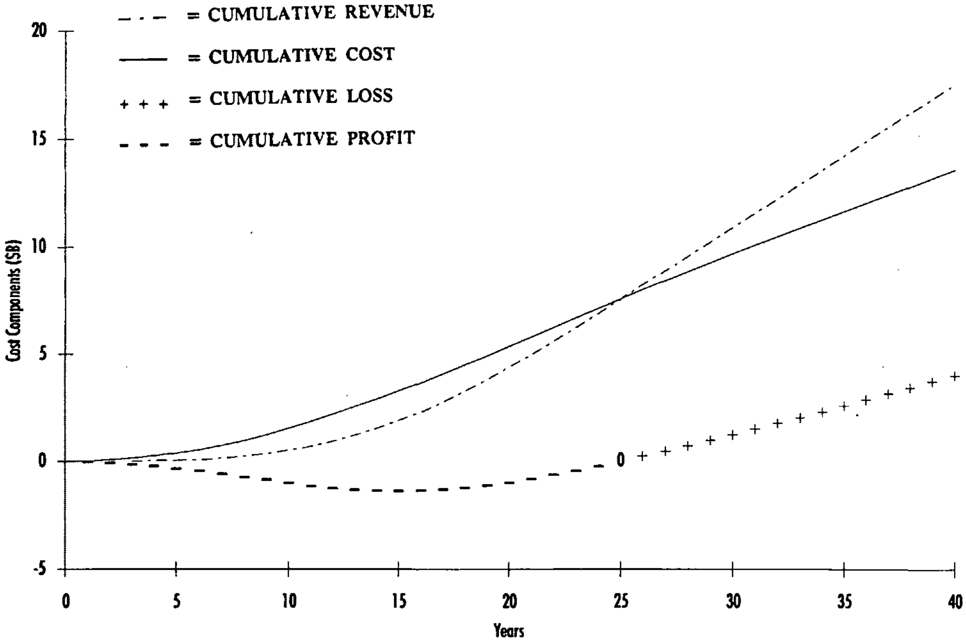

FIGURE 3 RPEV economic model cumulative revenues and costs.

nearly half the retail energy price. The wholesale energy cost represented an increasing proportion of the retail energy price over time, whereas all other cost components' percentage contributions declined since all system costs other than energy were spread over more users with time.

Sensitivity analyses were completed with respect to changes in roadway capital cost, wholesale energy cost, operating expenses, interest rates, energy consumption, system efficiency, and average vehicle-kilometers (vehicle-miles) per day on the system. The results, presented in Table 4, were based on the requirement that cumulative costs and revenues balance in Year 25 and demonstrate that the cumulative breakeven retail electricity rate generally increased with expense category sensitivity values and decreased as system performance and usage sensitivity measures improved. Greater system efficiency, however, reduced cumulative costs. Cumulative costs, revenues, and profits were found to be especially sensitive to alternative roadway costs and interest rate measures.

Regional Economic Impacts

Air quality improvement associated with reduced mobile source emissions is the most significant regional economic impact of roadway electrification. Its quantification requires calculating the associated primary health benefits (*3,18,19*). In addition to health benefits, increased crop yields for produce sensitive to ozone damage, visibility improvements and the associated increased property values, reduced damage to livestock, and decreased material deterioration would be further regional air quality improvements (*18*). Benefits associated with improved air quality may also exist in the labor market, since areas that provide amenities are often migration attractors (*20,21*).

Attempts to measure benefits associated with reduced emissions are often imperfect. The California Energy Commission (CEC) calculated dollar values per metric ton for yearly residual emissions in the South Coast Air Basin (*22*). Using its estimates to quantify emissions changes relative to the 2025 baseline and RPEV scenarios produced the following annual benefits: $424 million from daily CO decreases of 113.4 metric tons (125 tons), $177 million to $318 million for daily NOx reductions of 2.7 metric tons (3 tons), $37 million to $87 million from decreased daily SOx of 10.9 metric tons (12 tons), and $3 million to $138 million for daily ROG reductions. CEC did not report a residual emission value for PM emissions. Thus, this partial emissions assessment indicates annual benefits of $641 million to $967 million for the study's application of roadway electrification.

The benefit of reduced reliance on petroleum consumption to fuel the transportation system would be another primary economic impact of RPEV technology (*23*). Decreased production of greenhouse gases associated with petroleum-fueled vehicles could also be experienced globally. At the regional level, it is likely that reduced petroleum consumption could provide secondary environmental quality gains through decreased water pollution. Losses to regional economic sectors providing petroleum would occur.

Roadway electrification-related electricity demand would increase utilities' revenues. The utility sector would experience income and job growth, although there would probably be corresponding job and income losses in gasoline production and distribution.

Employment and income changes in the construction, maintenance, and vehicle service sectors are unclear. Although maintenance and vehicle servicing are expected to be substantially reduced by the RPEV technology, workers may gain skills necessary to provide assistance to RPEV users and acquire different positions as part of a newly created RPEV industry.

Another potential benefit would be associated with successful efforts to manufacture and commercialize RPEVs [and

EVs (*24*)] in the SCAG region. Such developments would necessitate provision of complete production systems to integrate local industries, service centers, and training and research facilities toward building an industrial base for this technology. Localization economies could be fostered by clustering firms regionally within the RPEV industry to capture scale economies in the production of intermediate inputs, labor market economies, and communication economies. Regional RPEV production and service could generate local multiplied impacts for the regional economy if market demand spread to other areas.

The ability of the Southern California region to attract federal funding and private capital for RPEV system development would play an important role in capturing many of the significant regional income and employment impacts and fostering regional economic growth. The ability to fashion proper incentives to stimulate increased RPEV (and EV) market penetration, to provide supportive public and industrial policies to assist technology development, and to build an integrated support structure for maintaining and servicing these technologies is important in the overall determination of regional economic impacts.

Implementing an RPEV system requires coordinated planning and management efforts addressing market penetration, continued technology development, and support service dimensions of system implementation simultaneously to capture maximum regional benefits. Mobilization of local industry, government, universities, and other institutional participants should be a first step toward system development.

CONCLUSIONS

Roadway electrification was modeled and evaluated on a portion of the Greater Los Angeles area highway system with respect to motor vehicle emissions, fossil fuel use, electricity demand, system costs, and other regional economic impacts. Results demonstrated the potential for air quality improvement and reduced petroleum use. Emission decreases varied between 7 and 15 percent, depending on pollutant and vehicle type. Reduction in petroleum consumption resulted in savings of approximately 8.3 million L (2.2 million gal) of gasoline. Natural gas consumption for transportation use was estimated to increase by 50 to 85 percent, yet forecast 2025 regional natural gas supplies would be plentiful. Increased RPEV electricity demand was 1 percent higher than peak-hour baseline usage and could be fulfilled by planned power plant capacity.

An economic model examined the magnitude and pattern of costs and revenues corresponding to electrified roadway development and use. The model incorporated a market-penetration growth profile, financing considerations, a construction schedule, and sensitivity to alternative model inputs. All revenues were derived from power purchases, and costs included roadway construction, energy, operation, and interest on development loans.

The cumulative breakeven of all system revenues and costs specified for Year 25 required a retail energy price of $0.294/kwh for system users. The cumulative breakeven rate generally increased with roadway expenses and decreased as system performance and usage increased. Increased system efficiency, however, reduced cumulative costs. Cumulative costs, revenues, and profits were found to be most sensitive to alternative roadway cost and interest rate measures.

Health benefits corresponding to emission decreases and reduced reliance on petroleum consumption were expected to be the most significant regional economic benefits. Additional RPEV-related electricity demand provided increased revenues to the utilities. Employment and income changes in the construction, maintenance, and vehicle servicing sectors are unclear. A potential benefit for roadway electrification exists with successful efforts in regional manufacturing and commercializing of RPEVs and EVs.

Implementing a powered roadway system requires coordinated planning and management addressing market penetration, continued technological progress, and support services for system implementation to capture maximum regional benefits. Mobilization of local industry, government, universities, and other institutional participants should be a first step toward system development.

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