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Roadway Powered Electric Vehicle Project Parametric Studies: Phase 3D Final Report

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Roadway Powered Electric Vehicle Project

Parametric Studies

Phase 3D

Final Report

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Table of Contents

List of Figures

4. Value Engineering of Roadway Cores

5. Economic Analysis of RPEV Technology

List of Tables

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This report has been prepared by the staff of SCT's Transportation Systems Engineering Department, who performed the work reported here. The SCT project team includes Daniel M. Empey, Edward H. Lechner, Gregory Wyess, Michael Vincent, Jon Garbarino, Robert Moore, Georginia J. Bailie, Jill V. Josselyn, Jeffrey Frenster, and Constance R. Klein, all under the direction of Steven E. Shladover and later Edward H. Lechner.

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Subcontracts were issued by SCT to Elma Engineering for $277,484 to cover the roadway cores for the test track. All other work was performed by SCT, with some very limited consultant assistance, and all other material purchases were accomplished on various purchase orders.

1. Scenario Definition

This task involved defining cases to be analyzed in subsequent tasks and in the Southern California Association of Governments (SCAG) regional impacts study. Support of the SCAG study on application of electrification and automation to freeways in the Los Angeles region, initially intended to be a small effort, became the major activity of this task.

As the methodology used in the Inductive Coupling System Design and System Synthesis tasks (Tasks 3 and 6, respectively) evolved, some of the study cases defined in this task diminished in significance. The design task evolved from doing single-point designs for approximately five cases to taking a much broader view where specific designs could be formed by interpolating between curves on more general plots. The more general approach allows overall trends to be clearly observed.

1.1 Driving Cycles

Driving cycles were defined to assist in the determination of both required power transfer levels and electrification patterns. Many cycles were defined, representing a broad range of total daily mileage and average velocity. These were patterned after driving cycles used in a hybrid vehicle research effort conducted by PATH. All the cycles were identical to the hybrid vehicle cycles except one, allowing results from the two studies to be easily compared. The driving cycles used in this study are shown in Table 1.1.

1.2 Selection of Vehicle Parameters

Five vehicles were chosen in the parametric studies analysis. Real vehicles were chosen where possible, while ensuring that a wide spectrum of vehicle sizes and performance levels was represented. These vehicles are the General Motors Impact, the Chrysler TE-Van, the General Motors EVDC G-Van, the PATH bus, and a hypothetical high-speed transit bus. For each vehicle, a set of EVSIM input parameters representing the desired vehicle performance was chosen. Characteristics such as gross vehicle weight and battery voltage and capacity were taken directly from actual vehicles (except the

Table 1 .1
Possible Scenarios for Parametric Studies

I. Driving Cycles	
A. Errand	15mi @45mph+5miofSAECcycle
B. Local delivery	40 mi @ 55 mph + 60 mi of SAE B cycle
C. City	30 mi @55 mph + 30 mi of SAE D cycle
D. Large city	120 mi @ 60 mph + 30 mi of SAE D cycle
E. Local bus	120 mi of SAE B cycle
II. Vehicle	
A. Four-passenger automobile	
B. Mini-van (TE-van)	
C. Delivery/service van (G-van)	
D. Transit bus (PATH electric bus)	
E. Fast bus	

Notes:

1. Driving cycle B corresponds to the "Small Delivery" cycle defined in the paper "Evaluation of Potential Hybrid Electric Vehicle Applications" by Gris and Shladover.
2. Driving cycle C corresponds to the "City" cycle of the above-mentioned paper.
3. Driving cycle D corresponds to the "Large Metropolis (A)" cycle of the above-mentioned paper.
4. Driving cycle E corresponds to the "Local Bus" cycle of the above-mentioned paper. Driving cycle E is also very similar to a proposed bus route in the city of Fresno.

hypothetical bus, which was based on the PATH bus with a more powerful drivetrain). Model outputs, such as acceleration times or energy consumption under specified driving conditions were compared with real data. Figure 1.1 shows simulated acceleration time histories for the five vehicles. When discrepancies were discovered, the input parameters were adjusted to drive the simulated vehicle performance closer to measured results. Energy consumption of the five study vehicles on the errand route is shown in Figure 1.2, while Figure 1.3 shows the energy consumption of the Impact on several driving cycles. These values are all net energy supplied by the battery. They are used to guide the later work, forming the basis for the approximate power requirements for a particular class of vehicle. For this reason, only moderate efforts were made to precisely match model performance to published data.

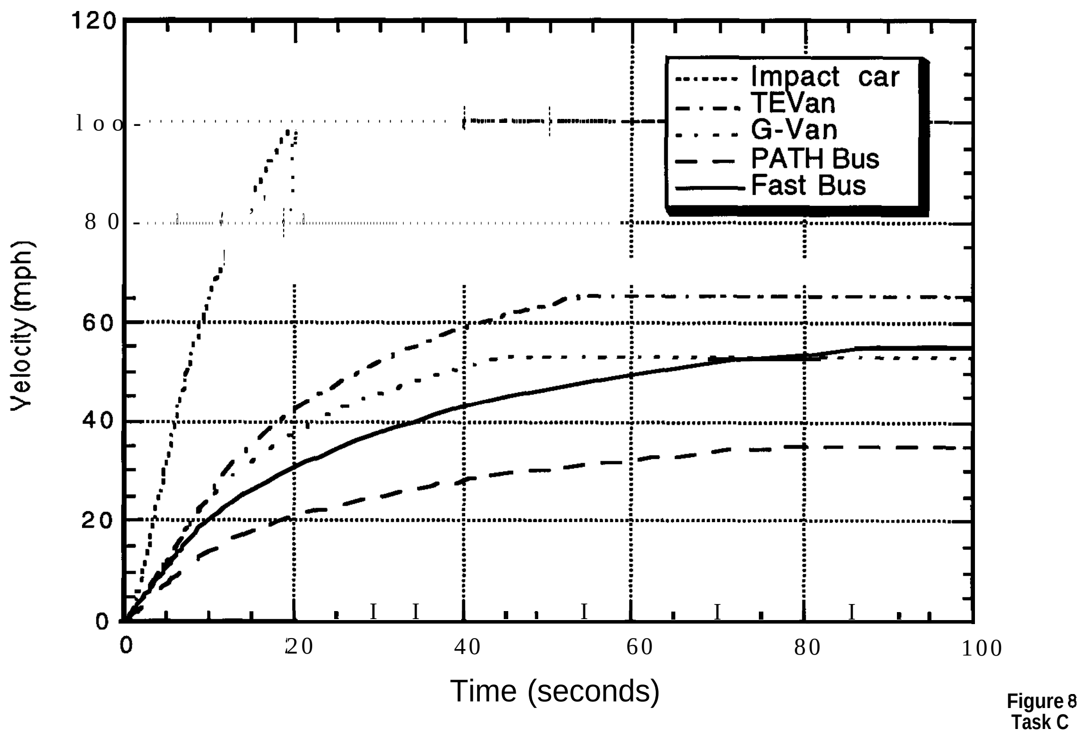


Figure 1.1 Simulated accelerations of the five study vehicles

1.3 Study Cases

The original approach was to design inductive coupling systems for each vehicle to allow that vehicle to operate satisfactorily on appropriate driving cycles. Pickup size, air gap, and required ICS output current were selected for each vehicle. Parameters that should

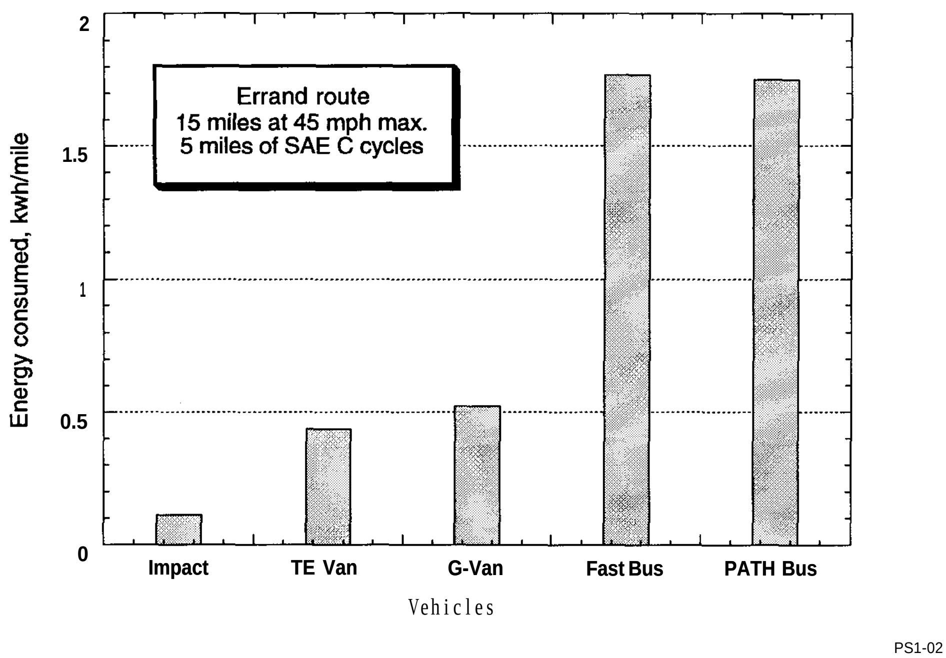


Figure 1.2 Simulated energy consumption of vehicles on errand route

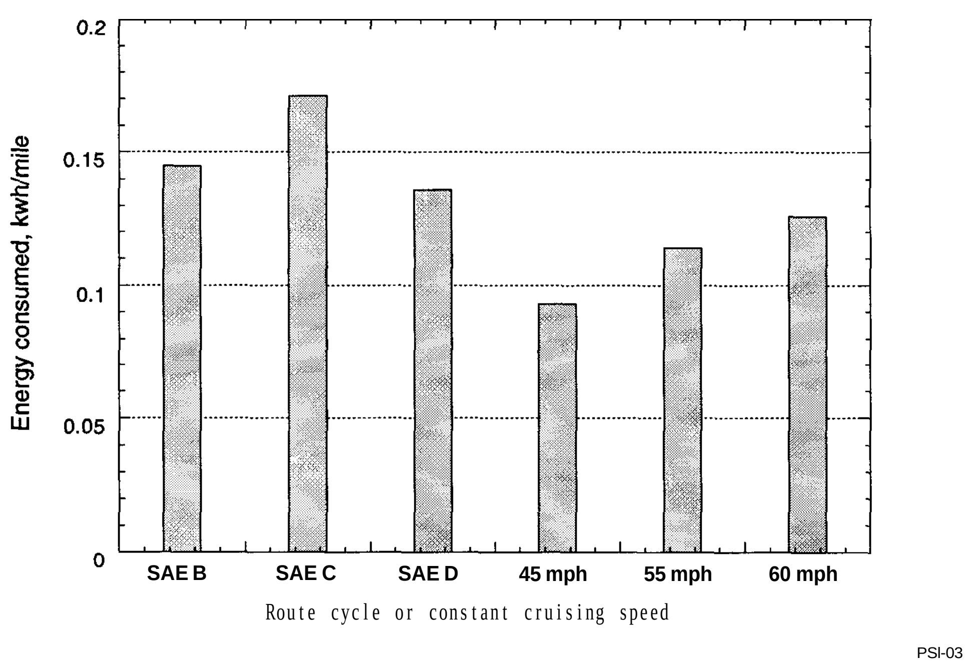


Figure 1.3 Simulated energy consumption of impact on various cycles

be common to all vehicles, such as roadway current and frequency, were selected for each vehicle, with the intent of determining a single value for these variables during System Synthesis (Task 6). The roadway excitation would be selected to allow each vehicle to operate satisfactorily, with the required output power and efficiency.

Approximately six months into the project, the approach to ICS design was changed. Reasonable ranges were chosen for key system parameters. The values were multiples of the lowest value anticipated for that particular variable. Table 1.2 shows the minimum, maximum, and baseline values of the key system parameters. The baseline values are near the middle of the range for each variable, and represent an approximation of a workable design for the G-Van or TE-Van. Frequency has the widest range of the parameters shown in Table 1.2. The extremely high and low values are used primarily to show the shape of curves (for instance that a curve levels out at higher frequencies) rather than being suggested operating points. Values of tuning capacitance were used to achieve the maximum output current for a given set of conditions, with values varying from 0.1 microfarad to approximately 10,000.

Table 1.2
Parameter Values for ICS Design Studies

	Minimum	Maximum	Baseline
Roadway current, amps	100	400	200
Frequency, Hz	125	64,000	4000
Battery voltage	100	400	200
Mutual inductance, µH	6	24	12
Leakage inductance, µH	3	12	6
Number of pickup turns	1	4	2
Tuning capacitance	as required to obtain maximum output current		

1.4 SCAG Study Support

SCT supported the Southern California Association of Governments (SCAG) Regional Impacts study. Results of the study, which addressed implementation of highway electrification and automation in the Greater Los Angeles region, can be obtained directly from SCAG.

2. Development and Enhancement of Analysis Tools

This task involved development of a set of economic analysis tools as well as enhancement of the three primary models used in the engineering analysis of the RPEV system. The economic analysis used three spreadsheets. The first examined a single mile of roadway operating in steady-state condition. The second examined the startup transient of a single mile, and the last model examined a regional system from start-up through steady state. The engineering models include the electric vehicle simulation (EVSIM), the Inductive Coupling System simulation (PHASE), and the magnetic model used to analyze the inductances of various core geometries (POISSON). The enhancements involved making the models more general, such as allowing the nominal battery voltage and motor rating point to be changed.

2.1 Economic Analysis Tools

The economic models are based on a commercial spreadsheet and involve similar assumptions, such as financing all capital costs through fixed-rate loans, and system users paying all system costs. The models increase in complexity from one to the next, allowing results from one model to be used to help validate subsequent models. Detailed descriptions of the models can be found in Chapter 5, Economic Analysis.

2.1.1 Steady-State Model

The first model involves operation of a single mile of roadway, operating at a steady-state volume of traffic. Within the Steady State Model (SSM), all costs are summed, including debt service on the construction loan, wholesale cost of energy, maintenance, and administrative costs. The total cost is divided by the total cost of energy sold to users, resulting in the breakeven retail energy charge to users. Daily volume of traffic, energy transferred to each vehicle, system efficiency, wholesale energy price, original construction cost, interest rate, term of loan, and administrative and maintenance costs can be varied.

2.1.2 Startup Transient Model

The Startup Transient Model (STM) examines one mile of roadway from initial construction, through a build up of user volume, to refurbishment of the roadway at the end of its assumed life. The system operates at a deficit until the number of users builds to a reasonable level. These early losses are included in the balance for which debt service costs are incurred. Once steady state has been achieved (number of users reaches steady state and early deficits are repaid), the annual costs match the steady-state costs from the previous model. The rate at which system usage builds up is the key difference between this model and the SSM.

2.1.3 Regional Economic Model

The Regional Economic Model (REM) examines a large regional system in which construction of the system is spread over many years. The total number of system lane-miles and the period of time allowed for construction represent added complexity compared to the Startup Transient Model.

2.2 Electric Vehicle Simulation

Modifications to the electric vehicle simulation program, EVSIM, were more extensive than to the other analysis tools. The specification of the driving profile was altered, allowing changes in the cruising velocity without bringing the vehicle to a complete stop. Jerk-limiting was removed from the model, improving run time but having virtually no effect on key model outputs, such as energy usage or the time required to complete a particular driving cycle. The changes in the route profile specification allowed trip profiles such as the SAE C-Cycle to be modeled. These changes allow simulation results to be compared to test results for real vehicles such as the G-Van.

The motor model was scaled so that it could represent a motor of any size and efficiency. The values for voltage, current, torque, and speed at the rated operating point are inputs, allowing the new motor model to adequately represent any dc motor. The motor's efficiency at the rated output is uniquely determined by these four inputs. This efficiency is used to scale the performance curves of the original motor up or down over the entire operating range.

The nominal battery voltage was changed from a fixed value to a variable. Along with the changes to the motor model, this allows EVSIM to approximate the operation of any electric vehicle. The modeling is most accurate near the motor's rated operating point but is reasonable elsewhere, especially considering the typical use of this analytic tool.

Several statistics were added to the post-processing of the simulation results, allowing model results to be interpreted more quickly and effectively. This also assisted in the comparison of model results with test results, such as those obtained with the PATH bus at the Richmond Field Station test track.

2.3 Inductive Coupling System Simulation

A number of enhancements were made to PHASE, the inductive coupling system simulation, all aimed at improving the simulation run time. Convergence criteria were added, stopping the simulation when steady state had been reached, rather than continuing the simulation run for a specified time interval. Initial conditions were added so that each simulation run uses the final value of the previous run as its initial conditions instead of always beginning with zero. Since conditions generally change only slightly from one run to the next (often the value of tuning capacitance is increased by one step), the system is relatively near steady-state. This results in the simulation reaching the convergence criteria more quickly, improving run time.

The changes to the PHASE model were validated by comparing simulation results with results from the RFS test facility.

2.4 Magnetic Analysis Model

A new operating system was installed on the SCT computer system before the start of this project. The POISSON magnetic analysis program, which had run properly before the change in operating systems, did not run successfully under the new operating system. Numerous changes were required to the command procedures to enable POISSON to be reactivated.

The time spent on these enhancements was worthwhile as it allowed the analysis to proceed more smoothly.

3. Inductive Coupling System Design

Many factors go into the design of an inductive coupling system. The most important are the output current and voltage ratings of the system, which must be adequate for the vehicle to operate on its driving cycle for the intended duration. When the rated output has been determined, the design of the ICS itself can proceed. Another issue, addressed in Chapter 6 (System Synthesis) is whether or not diverse types of vehicles (with widely varying output voltage, current, and power requirements) can be operated efficiently and effectively on the same roadway. The other important parameters associated with the ICS design are the roadway excitation (frequency and amplitude of the roadway current), the number of pickup turns, the mutual inductance of the pickup, and the onboard tuning capacitance. Each parameter plays an important role in determining the output current and overall efficiency of the ICS.

This chapter is divided into three sections. The first summarizes determination of the output current rating of the ICS for a particular application, which tends to couple with the design of the ICS itself only through the output current and voltage ratings. The second section discusses design trade-offs relating to a roadway powered G-Van, and the last section presents a generalized analysis of an inductive coupling system. The G-Van design focuses on variations in system variables where certain parameters (battery voltage, mutual inductance, and required output current) are fixed. In the generalized analysis, all key parameters are varied by at least a factor of four, and frequency is varied from 125 Hz to 64,000 Hz. The baseline operating point used for the generalized analysis is not intended to represent an optimum design, but was selected so that the parameter variations could be conducted without leaving the envelope of reasonable designs (such as driving the output current to zero or having absurdly high circulating currents onboard the vehicle).

3.1 Required Output Current

For typical driving cycles, electric vehicle energy consumption (net kwh / mile supplied by the battery) is only weakly dependent on velocity. Driving cycles with higher average velocities generally involve less acceleration / deceleration, but more aerodynamic drag. With regenerative braking, EVs lose less energy in stop and go driving than internal combustion engine vehicles. Energy consumption is lowest for constant-speed driving at about 30 mph, but this is not a realistic duty cycle. Since the net energy consumption (kwh/mile) is approximately independent of duty cycle (for any particular vehicle type), the total energy required is basically a function of total daily range. If the vehicle is to have infinite range, the average power transferred to the vehicle must equal or exceed the average power used by the vehicle. Both averages are taken over the entire duty cycle, which includes operation off of the powered roadway. An approximation for the power required by any vehicle on a particular duty cycle is the vehicle's energy consumption (kwh/mi) times the vehicle's average velocity, divided by the fraction of time the vehicle is over the powered roadway. ICS output power divided by the average voltage (nominal battery voltage can be used) gives the required output current.

3.2 ICS Design for a G-Van

Detailed design trade-offs for the Roadway Powered G-Van (RPG-Van) revealed some interesting trends about the design of an ICS system that were reconfirmed in the general studies. The roadway excitation and number of pickup turns were varied from one computer run to the next. The onboard tuning capacitance was adjusted as required to achieve the maximum output current with all other parameters held constant. The goal was to find multiple operating points providing the same output current. The various characteristics of these candidate operating points could then be compared, allowing intelligent selection of the operating point.

3.2.1 Maximum Inductive Coupling System Output Current

The first step in this analysis is determining the maximum ICS output current for a given roadway current at various frequencies. Figure 3.1 shows maximum output current as a function of frequency for a constant roadway current of 500 amps and a constant pickup mutual inductance (i.e., size and air gap) for both one and two pickup turns. For each frequency, internal parameters are chosen to maximize output current, without inducing excessive voltages onboard the vehicle. For any combination of roadway current and number of pickup turns, the output current increases with frequency up to a breakpoint, above which output current remains nearly constant. This breakpoint occurs at 500 Hz for two pickup turns and at 1750 Hz for one turn. The breakpoint is located at the intersection of asymptotes from the low frequency and high frequency portions of the curves, as seen in Figure 3.1 The location of this breakpoint is a complicated function of several variables, including the roadway current, battery voltage, number of pickup turns, and mutual inductance between the pickup and the roadway.

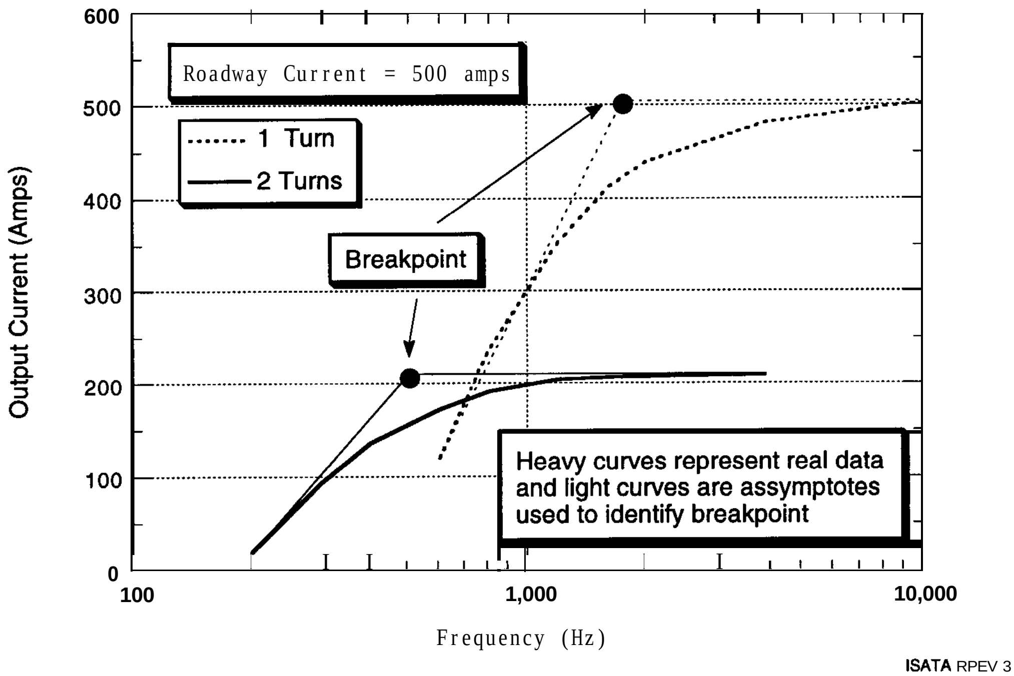


Figure 3.1 Sensitivity of G-Van ICS output current to number of turns and frequency

Below 800 Hz, two turns result in the maximum output current, while above 800 Hz a single turn couples more current. In general, increasing the number of pickup turns results in lower output current for the same roadway current in the higher frequency (flat) portion of the curve above the breakpoint. Minimizing the roadway current reduces open roadway losses and environmental impacts, such as stray magnetic fields and acoustic noise. This dictates that the number of pickup turns be chosen to minimize the roadway current while maintaining the desired output current at each frequency. For all analysis in this section, two turns are used for 200- 800 Hz and a single turn from 800 – 10,000 Hz. Data for both designs are presented at 800 Hz, which results in a step discontinuity in plots with frequency as the abscissa.

3.2.2 Roadway Current Required for Constant Output Current

The inductive coupling system for the G-Van is specified to deliver 200 amps to the vehicle (battery plus motor controller), so the next step is determining the minimum roadway current required (as a function of frequency) to accomplish this. The roadway current required to generate the desired output current varies with frequency, with larger roadway currents required at the lower frequencies, as would be expected from observing Figure 3.1 Similar plots can be created for other roadway currents, and interpolation determines many combinations of roadway current and frequency that couple the desired 200 amps to the vehicle (battery plus motor controller). Several such combinations are plotted in Figure 3.2 with two pickup turns used below 800 Hz and a single turn used above 800 Hz.

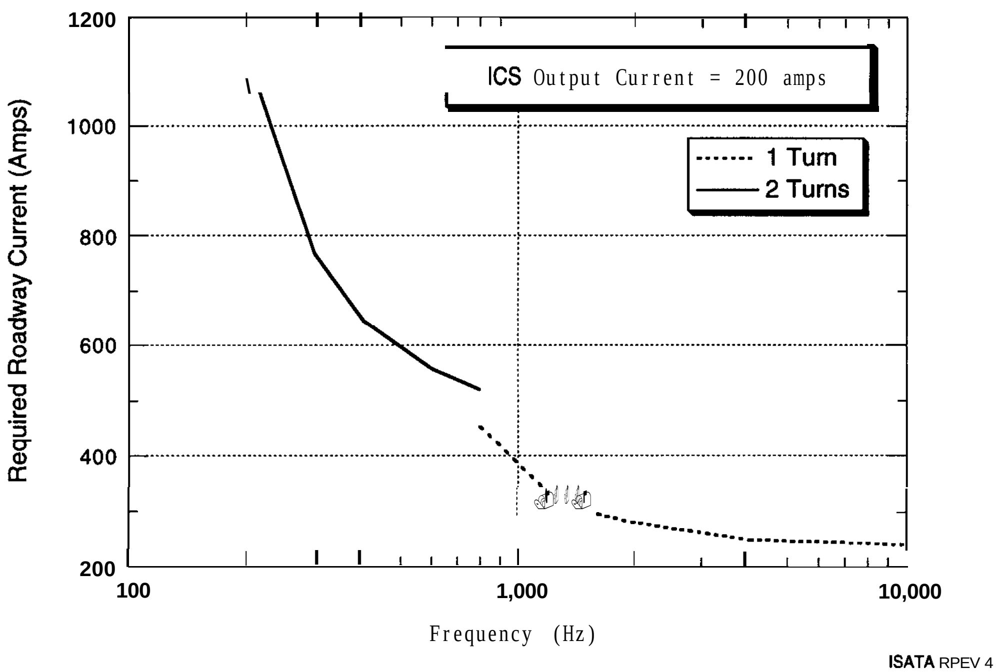


Figure 3.2 Required roadway current for G-Van design

As one would expect, the required roadway current drops with frequency up to 2000 Hz, approximately the breakpoint on Figure 3.1 Above the breakpoint, maximum output current is nearly independent of frequency, although other parameters, such as required compensation capacitance or pickup current, continue to change with frequency. Above 2000 Hz with a single turn, the output current is approximately equal to the roadway current, which can be seen in both Figures 3.1 and 3.2.

3.2.3 Losses

Analysis of system losses gives insight into a design. If losses are too high, larger components can be used, which increases the cost and weight of the components. If losses are extremely low, one may consider reducing the size of the components, saving cost and weight.

Losses are divided into four categories,:

1. roadway conductors
2. open (uncoupled) roadway cores
3. coupled cores (both roadway and pickup)
4. other onboard losses, including pickup windings and all onboard controller components

Losses for the baseline RPG-Van design (as described in Chapter 6 of the Testing report) were calculated for the range of frequencies being considered-200 Hz to 10,000 Hz. The trends noted are generally applicable to other designs. The project hardware was designed with a nominal operating frequency of 8500 Hz; however, it was selected to allow operation at 1000 – 2000 Hz as well. A design optimized for operation at 1000 Hz will have a better cost/loss performance at 1000 Hz than the 8500 Hz design (operated at 1000 Hz), but again, the loss trends are similar. For instance, at lower frequencies, currents (both roadway and onboard) increase, requiring larger conductors to keep resistive losses low at these operating points.

3.2.3.1 Roadway Inductor Losses-Uncoupled Condition

The most important factors in the design of the roadway inductor are ability to couple power, cost, losses, and mechanical integrity. The ability to couple power means providing adequate mutual inductance with the pickup inductor as well as the ability of the conductors to carry the required current without overheating and the ability of the cores to carry the required flux without saturating or overheating. The mutual inductance depends exclusively on geometry while the other two are generally satisfied by keeping losses to an acceptable level. Thus, the design becomes a trade-off between losses and cost.

For a given design, the losses change dramatically with frequency. Three terms contribute to the roadway inductor losses: resistive losses in the conductors, core losses in the uncoupled roadway, and core losses in the coupled portion of the road. The core losses per unit length are very different in the coupled and uncoupled cases, as the magnetic flux levels change by a factor between two and twenty depending on the operating point, and core losses scale with flux level squared. Total core losses in the uncoupled roadway cores and in the coupled roadway cores can be similar, as the length of uncoupled roadway is many times the length of the coupled section. The mechanical integrity of the roadway inductor (the ability to take tire loads for many years with minimal maintenance) is generally independent of operating frequency.

As a first-order approximation, conductor losses scale with the square of the current in the roadway, which indicates that for any conductor selection, losses decrease up to the 2000 Hz breakpoint and then level off. Cables adequate for carrying the required currents with acceptable losses are large enough that skin effect becomes significant at the higher frequencies. Skin effect, the tendency of current to flow near the surface of a conductor, increases with both conductor size and frequency. For a copper conductor of 1 centimeter diameter at 2000 Hz, the ac resistance is 1.73 times the dc resistance, while at 600 Hz it is only 1.13 times the dc resistance. Skin effect can be overcome by running several smaller conductors in parallel, as in the RPEV roadway inductor, although it increases installation cost. Roadway conductor losses increase slightly with frequency above 4000 Hz due to skin effect. Figure 3.3 illustrates these losses for the roadway inductor with the currents shown in Figure 3.2.

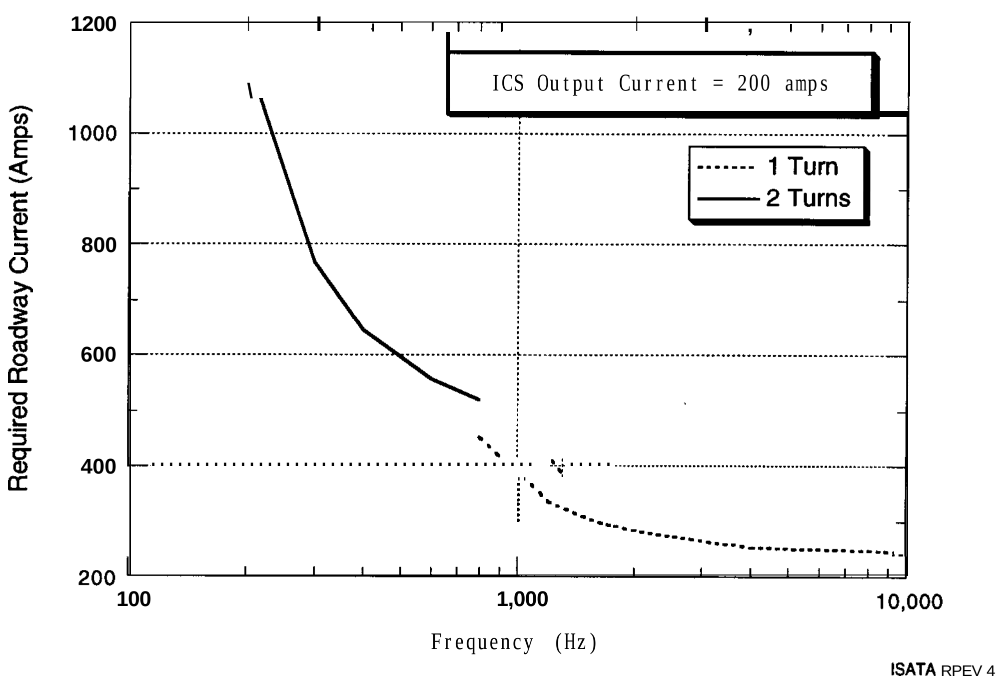


Figure 3.3 Roadway conductor losses for G-Van ICS

Energy is dissipated in the roadway cores due to both eddy current and hysteresis effects. These losses increase with both flux density and frequency. Total core losses are approximately proportional to flux density squared and to frequency raised to the power of 1.6. The flux density in the open roadway cores is linearly proportional to roadway current. Below 2000 Hz, roadway current decreases inversely with frequency (approximately), so that the core loss is nearly constant. Above 2000 Hz, where roadway current is essentially constant, open roadway core loss increases dramatically, approximately proportional to frequency raised to the power of 1.6. Figure 3.4 shows these losses.

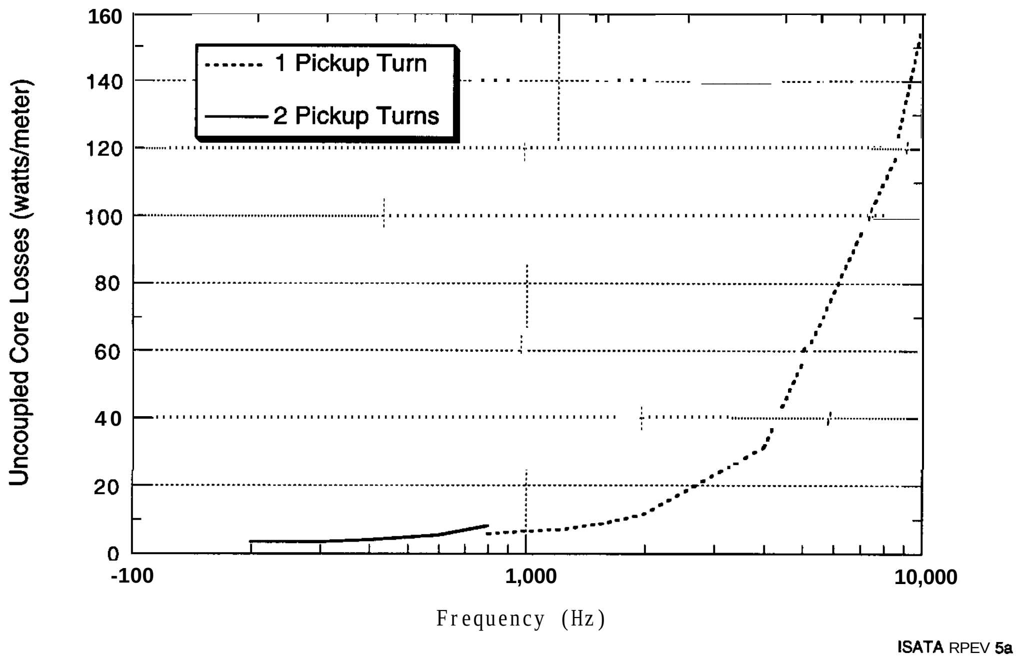


Figure 3.4 Uncoupled core losses for G-Van ICS

Conductor losses generally decrease with increasing frequency due to the lower currents. However open roadway core losses are exactly opposite with high values at high frequencies. Therefore, minimum roadway inductor losses occur at the middle frequencies (1000 – 2000 Hz), with higher losses at both extremes of the range investigated. If roadway segments are long, then it is desirable to operate at 1000 – 2000 Hz, as a segment length of up to about 1000 feet would still result in acceptable losses. The relative importance of the losses in the open roadway increases if segments are longer and decreases if multiple vehicles occupy the same segment.

3.2.3.2 Coupled Core Losses--Roadway and Pickup Inductors

Coupled core losses include both roadway and pickup core losses. As with the uncoupled roadway cores, the losses (watts/kilogram) increase with both frequency and flux density. Total flux in the coupled roadway and pickup cores is the same (except for leakage) but flux densities in the roadway and pickup cores are generally different because the pickup cores are thinner than the roadway cores (to minimize onboard weight). Pickup cores are made of a higher grade magnetic steel, which keeps the overall losses similar to the roadway core losses despite the higher flux densities.

Pickup voltage is proportional to the number of pickup turns, the frequency, and the total magnetic flux in the pickup cores. Regardless of the frequency or power transfer level, the pickup terminal voltage is similar to the battery voltage and, therefore, approximately constant for most designs. Thus, for a given set of design conditions (core design, number of turns, and battery voltage), the flux density is inversely proportional to frequency. The dotted curves in Figure 3.5 display this trend. Since core losses per kilogram increase less rapidly with frequency than with flux density, core losses (solid curves) decrease as frequency increases. At 800 Hz, where the number of pickup turns

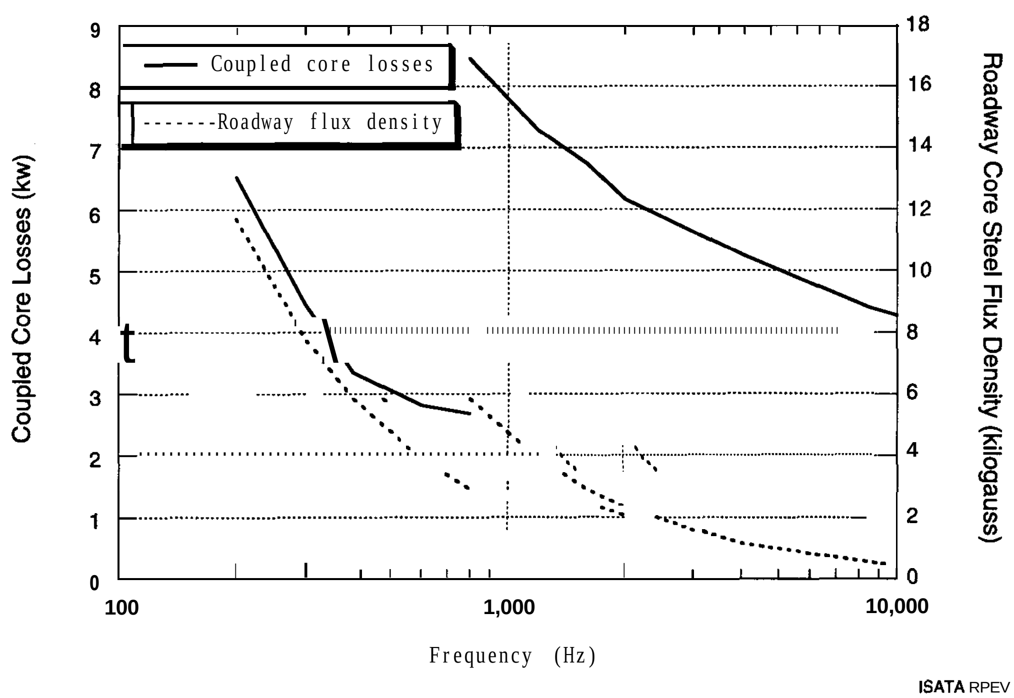


Figure 3.5 Coupled core losses and magnetic flux for G-Van ICS

changes from two to one, the flux densities in the cores double, increasing core losses by more than a factor of three.

The RPG-Van design pickup cores saturate at the 200 Hz operating point, so loss numbers are extrapolated. In reality, the pickup cores must be thicker or the number of pickup turns increased to reduce roadway core flux density below the saturation level of approximately 17 kilogauss.

3.2.3.3 Losses in Onboard Controller Components and Pickup Windings

Onboard losses, excluding those in the pickup cores, consist of losses in the pickup conductors and all OBC electronics (capacitors, inductors, switches, and rectifier). These losses increase with onboard currents, but are generally a weak function of frequency at any specific current. The sensitivity of these losses to frequency depends almost exclusively on how the onboard currents vary with frequency. Onboard currents drop sharply with frequency and the number of pickup turns. Figure 3.6 shows both pickup current and the losses of all onboard elements (other than pickup cores) as a function of frequency. The shape of the loss curve in Figure 3.6 is similar to the coupled core losses

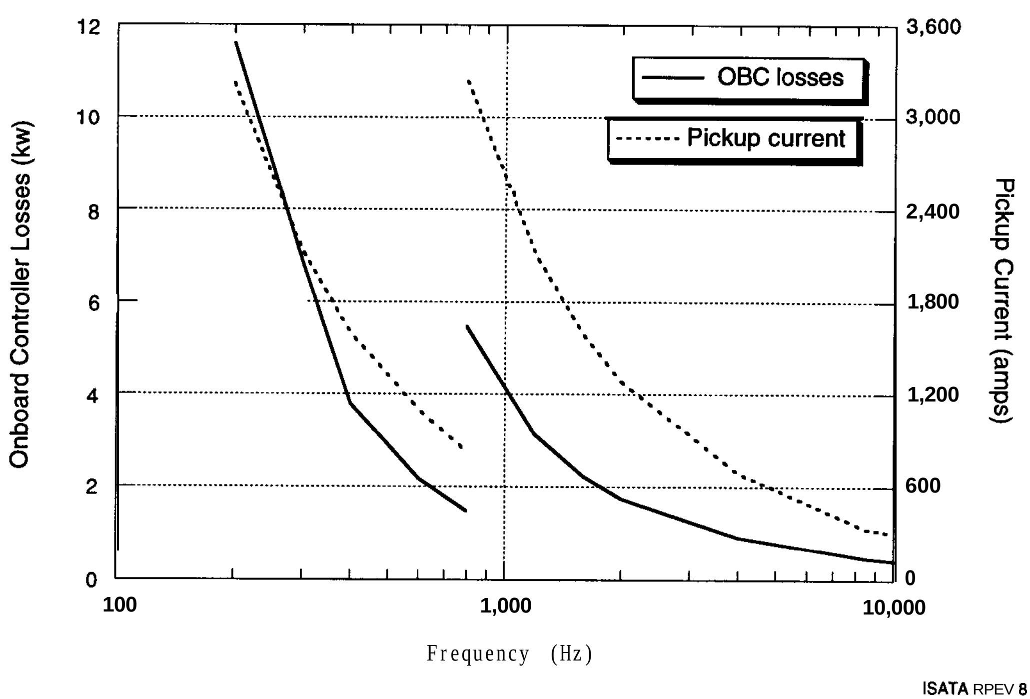


Figure 3.6 OBC losses and current for G-Van ICS

in Figure 3.5. Both drop sharply with frequency, but jump up when the number of pickup turns changes from two to one at 800 Hz.

3.2.3.4 Total System Losses

Losses from various sources can be summed to determine total system losses and overall system efficiency. Losses from Figures 3.3 through 3.6 are summed in Figure 3.7. The curves of Figure 3.7 are the cumulative losses with each curve being the sum of the losses on the lower curve and the loss term indicated. The roadway inductor segment length is assumed to be 35 meters or slightly over 100 feet. The minimum losses are about 6 kw and occur at 800 Hz with two turns, with most being contributed by the coupling of power (coupled cores and other onboard losses), not the open roadway. At this point, the losses are still decreasing with frequency, indicating that a design with two turns in the 1000 – 2000 Hz range should have the lowest possible losses, although the roadway current and environmental impact would be larger than for a single turn design at the same frequency.

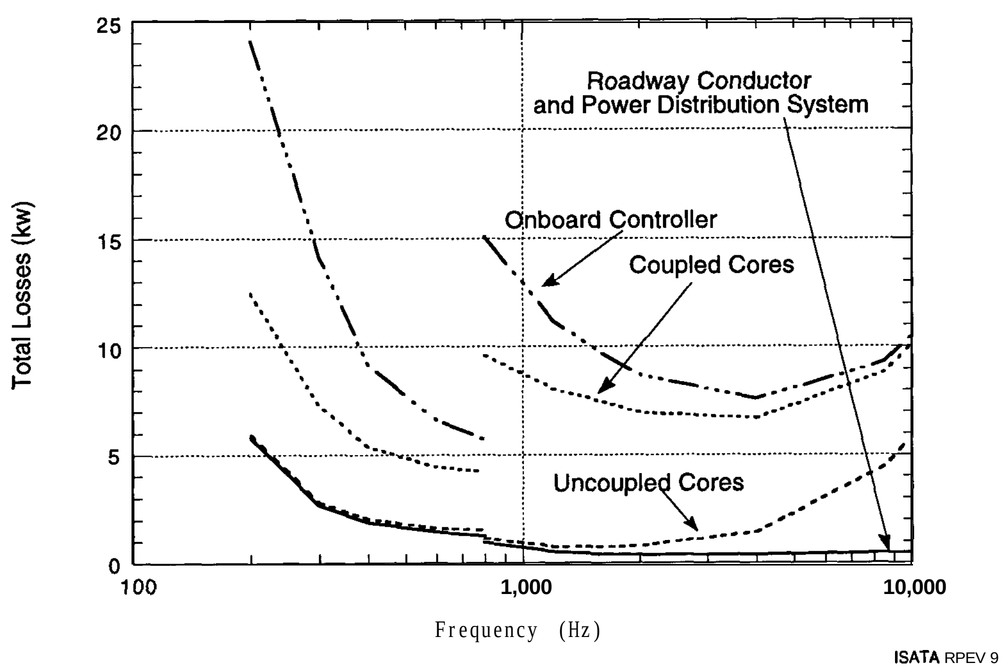


Figure 3.7 Total losses for G-Van ICS

For single-turn designs, total losses are below 10 kw between 2000 Hz and 8500 Hz and only weakly dependent on frequency. Ten kw is significant because that is the loss limit if 40 kw are to be delivered to the vehicle with 80% efficiency, both attractive goals for a G-Van design.

3.3 Generalized ICS Design and Sensitivities

The analysis techniques of the previous section can be expanded to cover variations in battery voltage, mutual inductance, leakage inductance, and rectifier input inductance, as well as roadway excitation and number of pickup turns. In the previous analysis, the required ICS output current was fixed and various losses were used as the measure of performance. In this analysis, the ICS output current is the primary figure of merit.

3.3.1 Baseline Operating Point

The baseline operating point is chosen so that all key parameters can be varied by at least a factor of two in either direction without driving the operating point outside the envelope of reasonable designs (zero output current or very high circulating currents for instance.) This baseline point was also selected to be near the breakpoint of the curve of peak output current versus frequency, as was observed in Figure 3.1. This allows the movement of the breakpoint with variations in the independent inputs to be observed.

The baseline operating point is similar to the G-Van design from the previous section, but uses two turns. The roadway excitation is 200 amps at 4000 Hz. The battery voltage is 200 volts, and, for ease of analysis, the internal resistance is virtually zero, so battery terminal voltage stays within one volt of 200 regardless of the ICS output. The mutual inductance is 12 microhenries and the pickup (secondary) leakage inductance is 6 microhenries. The rectifier input inductance and filter inductances are 16 and 32 microhenries, respectively.

Figure 3.8 shows the output current as a function of tuning capacitance for the baseline case. The current starts at zero with zero capacitance, rises approximately linearly with capacitance until the output current peaks at a tuning capacitance value of about 27 rnicrofarads, and then falls rapidly. The peak output current is 68 amps, somewhat less than the ideal transformer output of 100 amps (for an input current of 200 amps and a turns ratio of two). This reduction below the ideal output current is due primarily to the leakage inductance of the system. Additionally, there is a breakpoint in the plot of peak output current versus frequency (as seen in Figure 3.1), and this operating point falls below the break frequency. The fact that the operating point is not above the break frequency (the frequency at which peak output current no longer increases with frequency) by at least a factor of two also contributes to the reduction of actual output current below the ideal value.

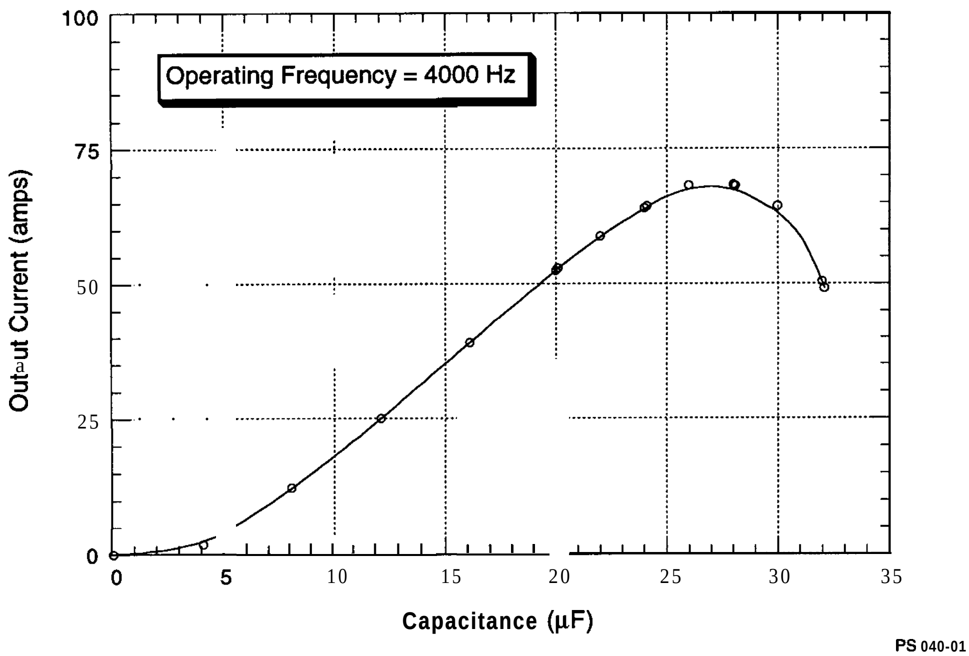


Figure 3.8 Tuning curve for baseline design

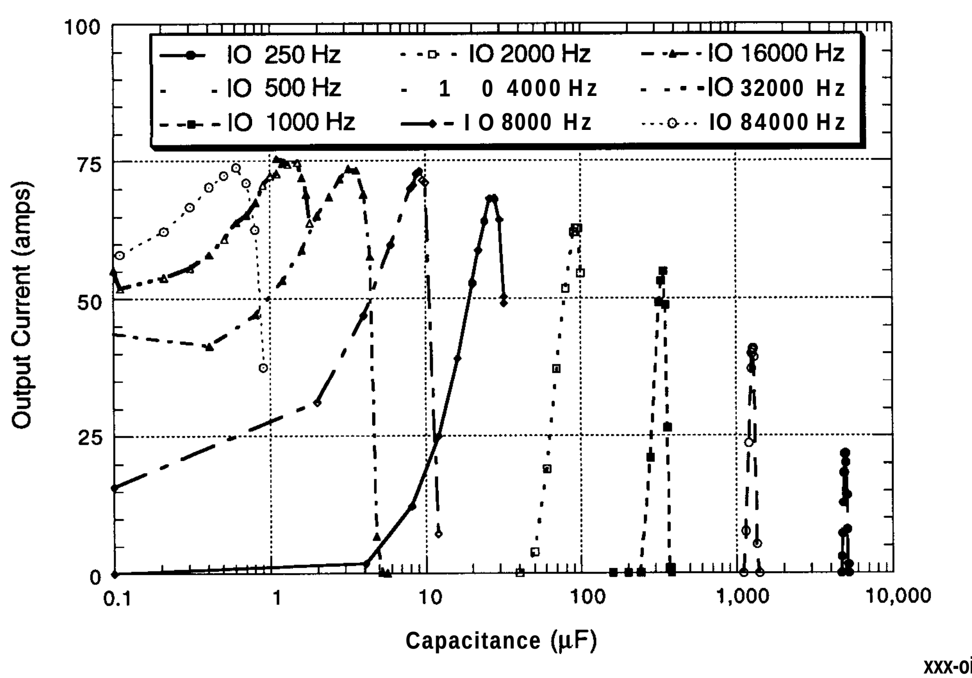


Figure 3.9 Tuning curves for several operating frequencies

3.3.2 Frequency Variation

Many parameters must be scaled with frequency to maintain an equivalent system. For instance, the tuning capacitance required to bring the system resonant frequency near the driven (roadway) frequency varies (approximately) inversely with the square of frequency. Figure 3.9 shows tuning curves for a wide range of frequencies including frequencies both higher and lower than would be considered for a practical RPEV system. This wide range is selected to demonstrate system performance trends.

The tuning capacitance required for peak output current changes by approximately four orders of magnitude as the frequency increases from 250 to 64,000 Hz. The rectifier input inductance, the filter inductance, and the filter capacitance must also be scaled with frequency. Certain resistances were also changed to accurately represent the system at these alternate frequencies.

The lower frequency curves in Figure 3.9 (those to the right of the figure) have very sharp peaks and small percentage changes in capacitance cause large changes in output current. The logarithmic scale used on the horizontal axis accentuates the effect but it is real and would make accurate control of output current difficult in low frequency cases, especially for a vehicle in motion, where the air gap between the roadway and pickup inductors would be continuously undergoing relatively small changes. This difficulty in controlling the output current at low frequencies (substantially below the break frequency, at which peak output current no longer increases with frequency) is inherent with the inductive coupling technology. It will occur at different frequencies, depending on the values of all other system parameters. For instance, the operating point used for testing the bus (1200 amps in the roadway at 400 Hz, with two pickup turns and a mutual inductance of about 15 microhenries) did not experience this difficulty in controlling output current, as that operating point is near the breakpoint rather than significantly below it. The higher values of roadway current and mutual inductance (factors of 6 and 1.25 respectively) would scale the 400 Hz used in the bus design to about 3000 Hz on Figure 3.9, a frequency at which the output current is easily controllable.

At high frequencies, the peaks are flat. In fact, the system couples significant power to the vehicle even with zero tuning capacitance, making it impossible to shut off the current from the ICS using capacitance control. This situation occurs when the open circuit voltage of the pickup with zero tuning capacitance is comparable to the battery voltage.

The shapes of these tuning curves can be made more clearly visible by factoring or normalizing. The data for each curve (both ordinate and abscissa) is divided by the value at the peak output current This forces the peak of each curve to go through the point (1,1) and the shapes of the curves become clearly visible, as seen in Figure 3.10.

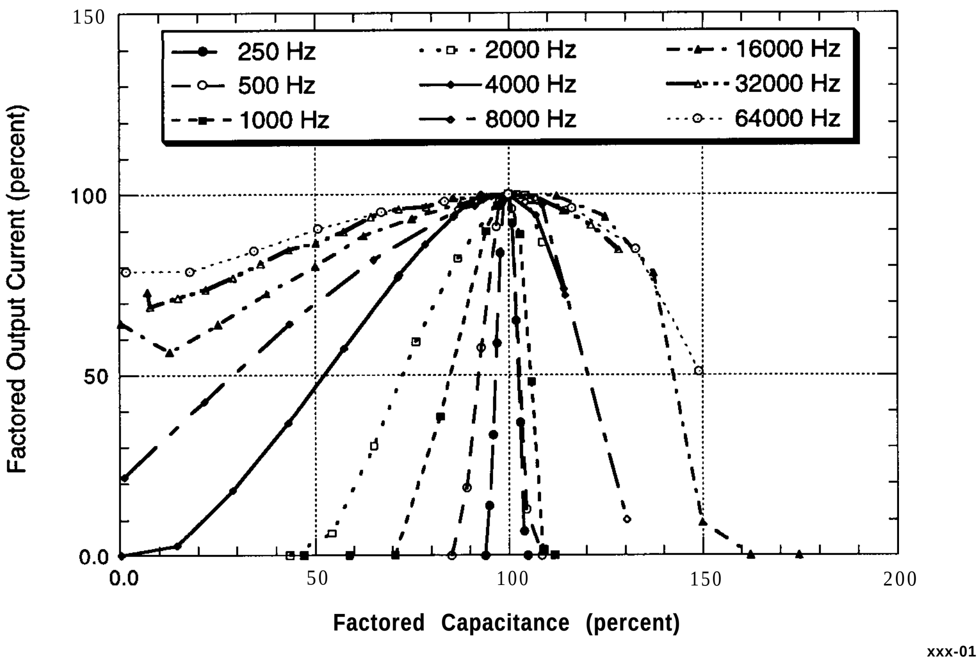


Figure 3.10 Factored tuning curves for various frequencies

Referring back to Figure 3.9, peak output current is approximately constant at 75 amps at the higher frequencies, starts decreasing at 4000 Hz, and reaches 0 at 125 Hz (not shown on plot). These peak output currents are plotted as a function of frequency in Figure 3.11. Due to the large range in frequencies, a logarithmic scale is used, with frequency as the abscissa. The curve in Figure 3.11 has the same shape as the curve in Figure 3.1, which is characteristic of the inductive coupling system.

Plots of this type are shown for all sensitivity analyses discussed in this section. The key features to note are

1. The level the output current approaches at high frequency
2. The location of the breakpoint (or knee in the curve)
3. Characteristics at low frequencies

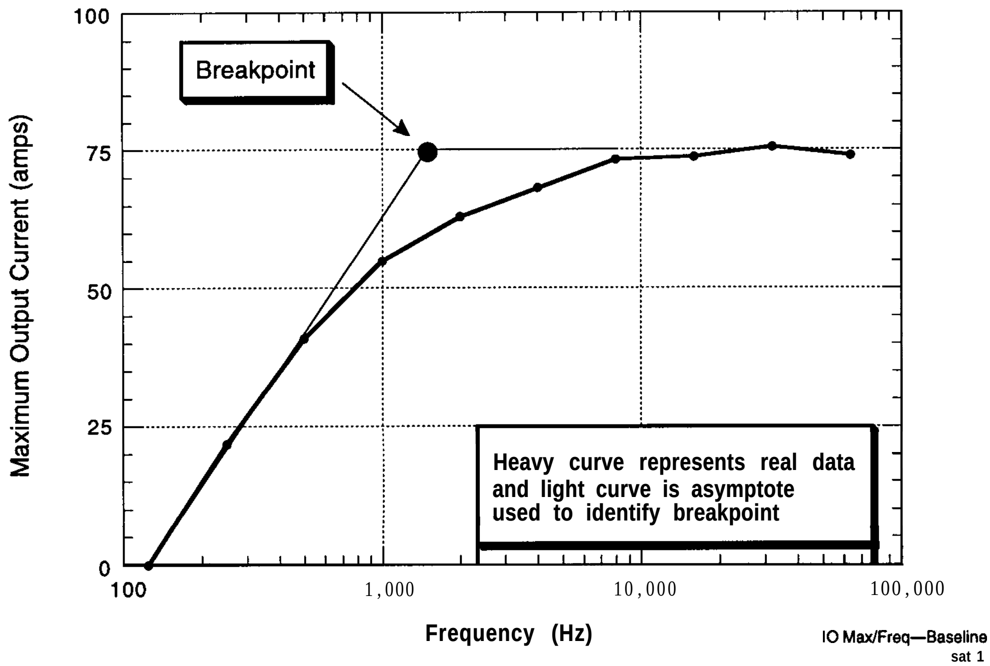


Figure 3.11 Maximum output current as a function of frequency

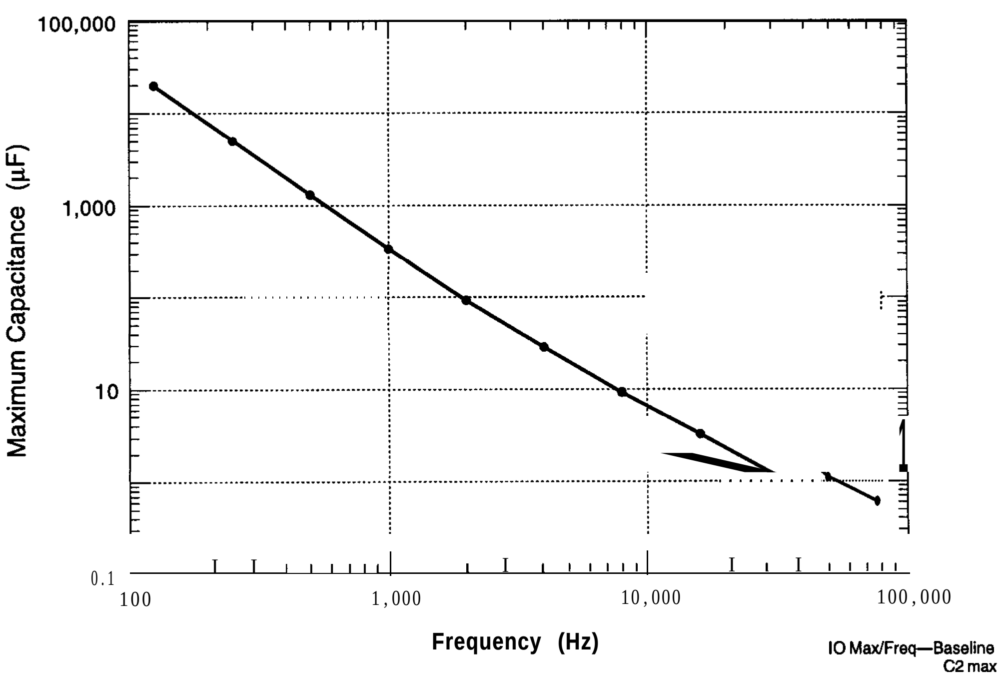


Figure 3.12 Required tuning capacitance as a function of frequency

In Figure 3.11 the high frequency current is 75 amps, the break frequency is 1500 Hz, and at low frequency, the output current increases 20 amps per factor of two in frequency. The break frequency is the frequency at which the asymptotes from the low and high frequency portions of the curve intersect. The output current at the break frequency is typically 20% smaller than the asymptotic value.

Figure 3.12 shows how the tuning capacitance required for peak output current varies with frequency. The data plots as nearly a straight line until the highest frequencies. The capacitance decreases 3.5 orders of magnitude for two orders of magnitude increase in frequency.

3.3.3 Battery Voltage Variation

Battery voltage is varied up from its nominal value by a factor of two in each direction. The tuning curves for these three battery voltages are shown in Figure 3.13. Reduced battery voltage increases the peak output current slightly, with a difference of about 20% between battery voltages of 100 and 400. The high battery voltage curve is more sharply peaked than the others, similar to the low frequency curves in Figure 3.9. This is reasonable, as the open-circuit voltage of the pickup represents a smaller fraction of the

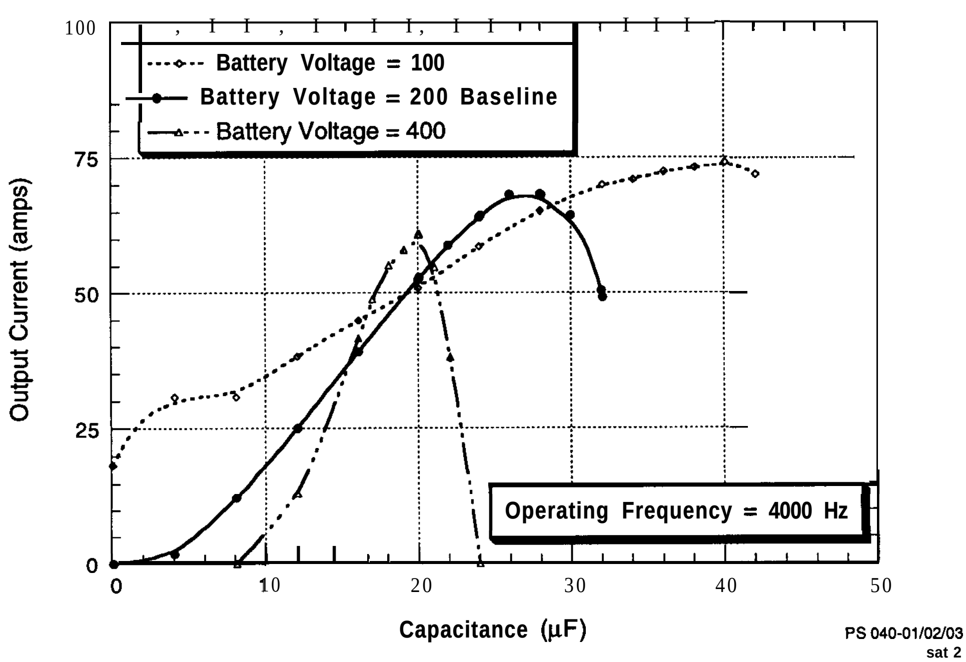


Figure 3.13 Tuning curves for various battery voltages

battery voltage for both of these cases. The capacitance required for peak output current decreases about 30% for a doubling of battery voltage.

Figure 3.14 shows the peak output current as a function of frequency for the three battery voltages. The three curves are nearly equal at the high frequency end. They are parallel and shifted laterally by approximately a factor of two at the low frequency end, with higher output currents at lower battery voltages. The break frequencies also display this trend.

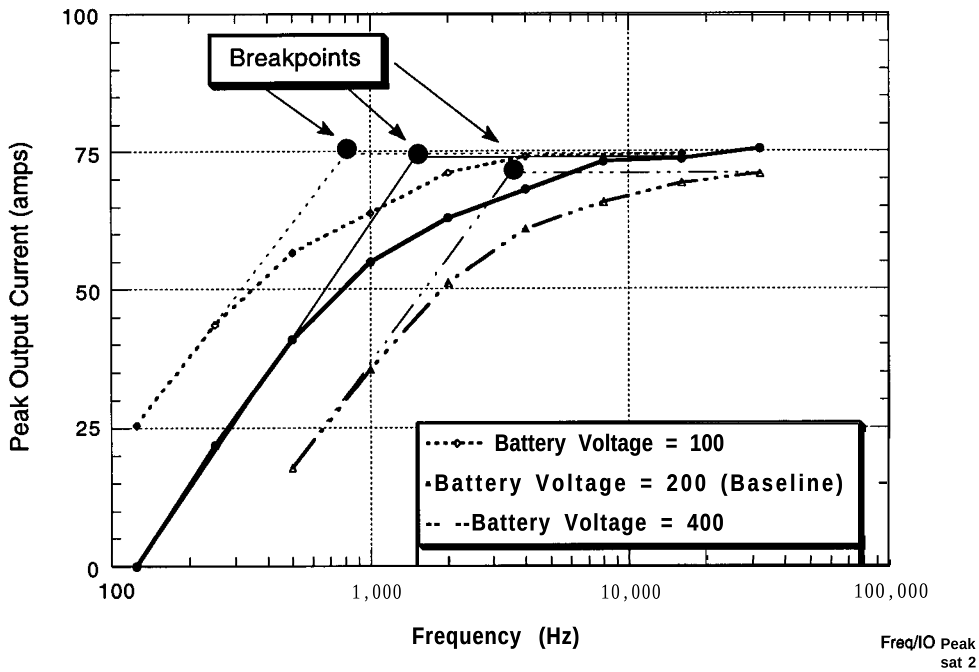


Figure 3.14 Peak output current for various battery voltages

The ratio between the open-circuit pickup voltage and the battery voltage is an important parameter in the design of inductive coupling systems. It is a dimensionless ratio, such as Mach number or Reynolds number in fluid dynamics. This is distinct from the factoring done in Figure 3.10, where the value to be used for scaling came from the curve being plotted itself. The data from Figure 3.14 is replotted in Figure 3.15, using open-circuit voltage (to battery voltage) ratio instead of frequency on the horizontal axis. The three curves have moved together. Each curve is within a few percent of its horizontal asymptote by the time the open-circuit voltage ratio (OCVR) is 1.0. The breakpoint or knee of the curve is located at an OCVR of about 0.25, although output current does not drop to zero amps until an order of magnitude lower than that value.

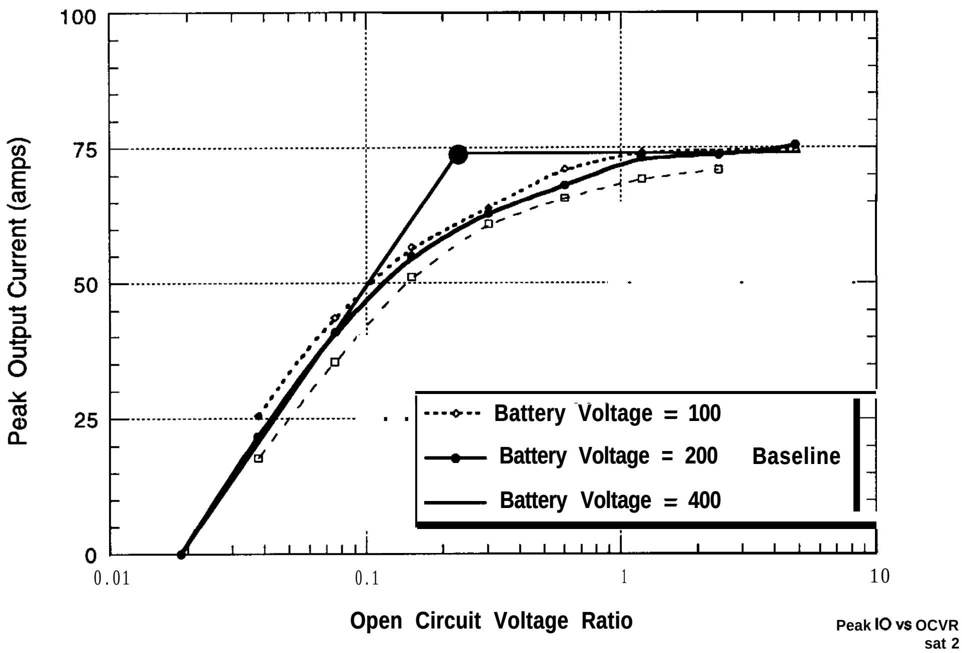


Figure 3.15 Peak output current (vs. OCVR) for various battery voltages

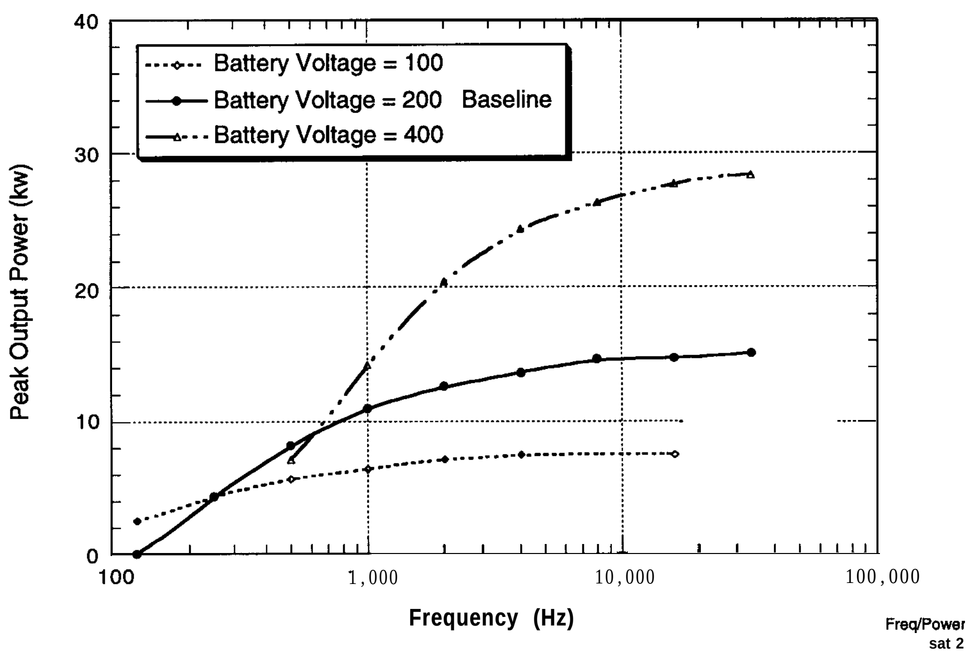


Figure 3.16 Peak output power for various battery voltages

The output currents have been multiplied by their respective battery voltages to form output power in Figure 3.16. Since the peak output currents are approximately equal for the higher frequencies, the output powers should increase proportionately with voltage in this frequency range, as the figure shows. The high-voltage case has the highest break frequency-approximately 3000 Hz. At 800 Hz, it passes through the 200 volt curve, and by 400 Hz has dropped below the 100 volt curve as well. At the lowest frequencies examined, the output power is zero for all curves except the 100 volt case, as the ICS cannot establish any substantial voltage.

3.3.4 Roadway Current Variation

The output current of a transformer increases monotonically with the input current. In an ideal transformer (which is a good approximation for a conventional transformer), this relationship is linear, with the turns ratio being the proportionality constant. Thus the output current of an ideal transformer equals the input current divided by the turns ratio. In the Inductive Coupling System, this relationship is not linear, due primarily to the non-linear characteristic of the battery. Figure 3.17 shows tuning curves for roadway current changes of a factor of two in both directions from baseline value. With larger roadway currents, the capacitance required for peak output current increases, and the tuning curves are less sharply peaked. For 4000 Hz, peak output current increases slightly more than a factor of two as roadway current is doubled. This is due to a reduction in the break frequency at higher roadway currents, as seen in Figure 3.18. The break frequency decreases at higher roadway currents, from 3000 Hz at 100 amps, to 1500 Hz at 200 amps, and 700 Hz at 400 amps. The peak output currents at high frequency scale linearly with roadway current, as do the slopes at lower frequencies.

The ICS output current can be scaled or normalized using the output current of an ideal transformer. Taking the baseline case for instance, with an input current of 200 amps and twice as many turns on the secondary as on the primary, the ideal output current would be 100 amps. The actual output current can be scaled by (divided by) this ideal output current to form a dimensionless ratio, analogous to the open-circuit voltage ratio. The data from Figure 3.18 has been replotted in Figure 3.19 after being rescaled vertically. For all curves the high frequency output current is approximately 0.75, or 75% of what would be expected from an ideal transformer (i.e. one with no losses and an infinitely large mutual inductance). The curves all have the same shape, but are displaced laterally. Changing the horizontal axis from frequency to the open-circuit voltage ratio results in Figure 3.20, in which the curves are nearly identical. At the lower

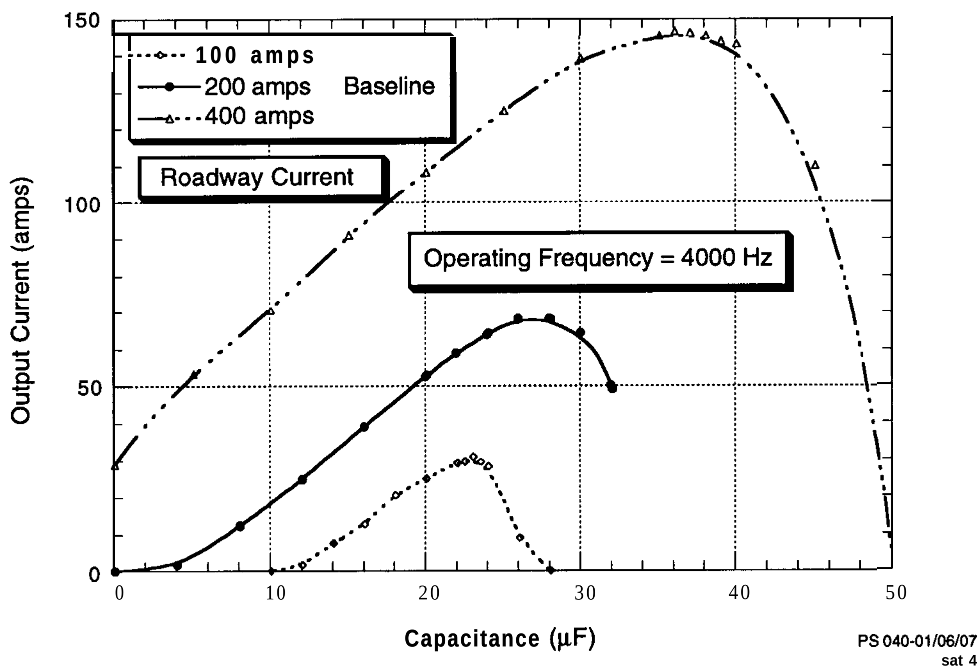


Figure 3.17 Tuning curves for several roadway currents

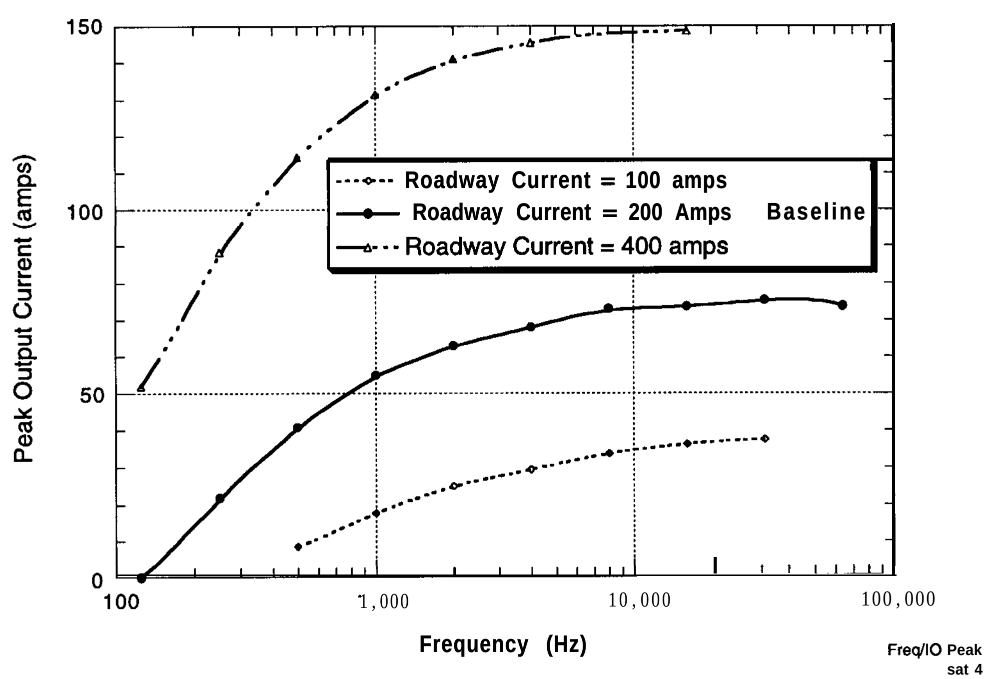


Figure 3.18 Peak output current for several roadway currents

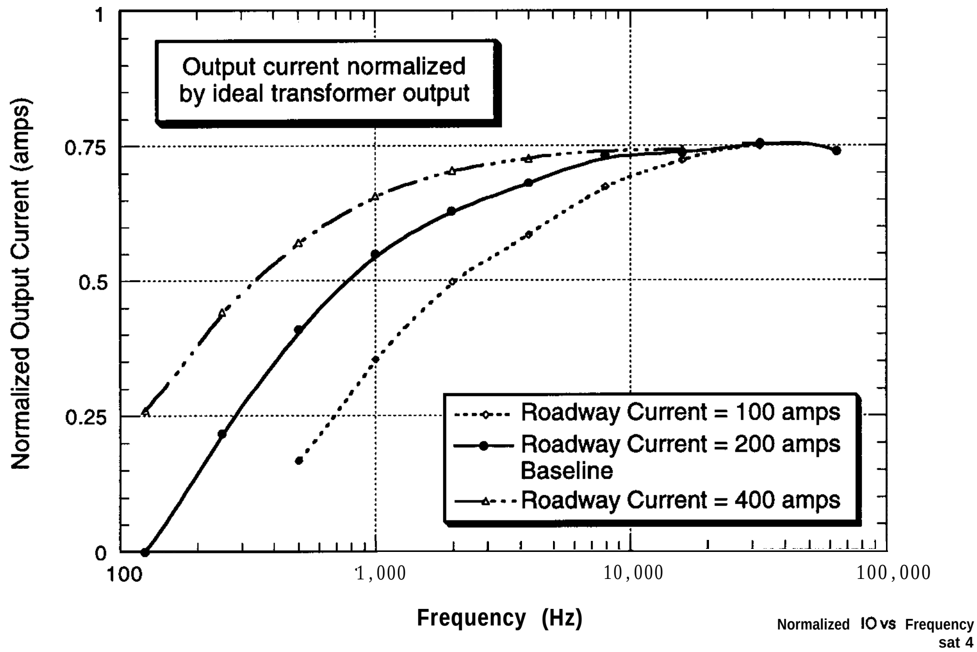


Figure 3.19 Normalized output current for several roadway currents

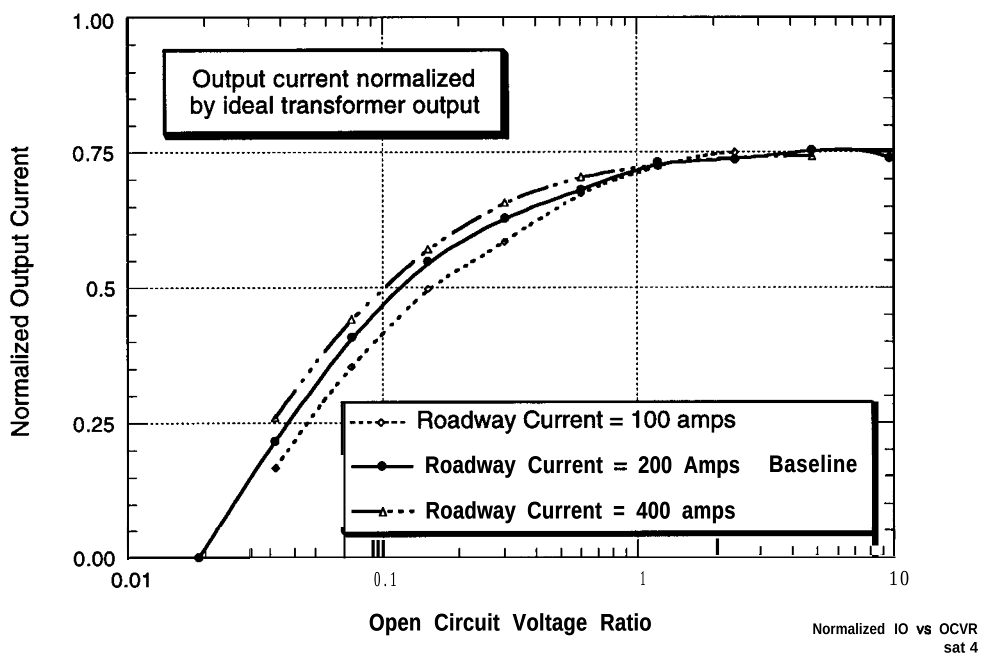


Figure 3.20 Normalized output current (vs. OCVR) for several roadway currents

frequencies (lower values of OCVR), the normalized output current is very slightly higher for the curves with higher roadway current. These differences disappear at the higher frequencies.

3.3.5 Pickup Turns Variation

In a conventional transformer, increasing the number of turns on the secondary winding increases the output voltage and decreases the output current. The analysis in Section 3.2 indicated that the ICS performs in a similar manner, although the amount of tuning capacitance required varies strongly with the number of turns. Figure 3.21 shows tuning curves for 1, 2, and 4 turns of the pickup winding. Required capacitance varies approximately inversely with the number of turns squared. (Decreasing the number of turns by a factor of two quadruples the capacitance required.) The tuning curves are sharper for lower number of turns, with the capacitance for half power equal to 70%, 60%, and 35% of the peak capacitance for 1, 2, and 4 turns, respectively. Decreasing the number of secondary turns from four to two roughly doubles the output current from 35 to 70 amps. The increase in output current from two turns to one is less than a factor of

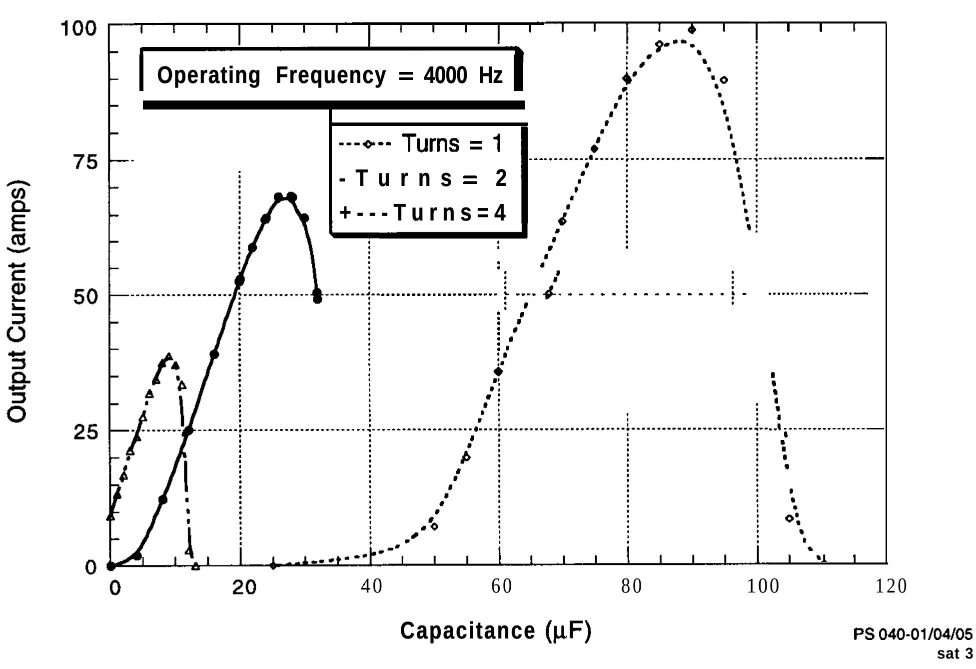


Figure 3.21 Tuning curves for several pickup turns values

two. The reason for this can be seen in Figure 3.22, which shows peak output current as a function of frequency for several values of pickup turns. At 4000 Hz, the curve for one turn has not yet reached the breakpoint, resulting in a lower output current than one would expect. In general, the high-frequency current increases inversely with the number of turns. The break frequency increases inversely with the number of turns squared from 1500 Hz with two turns to about 7000 Hz with a single turn.

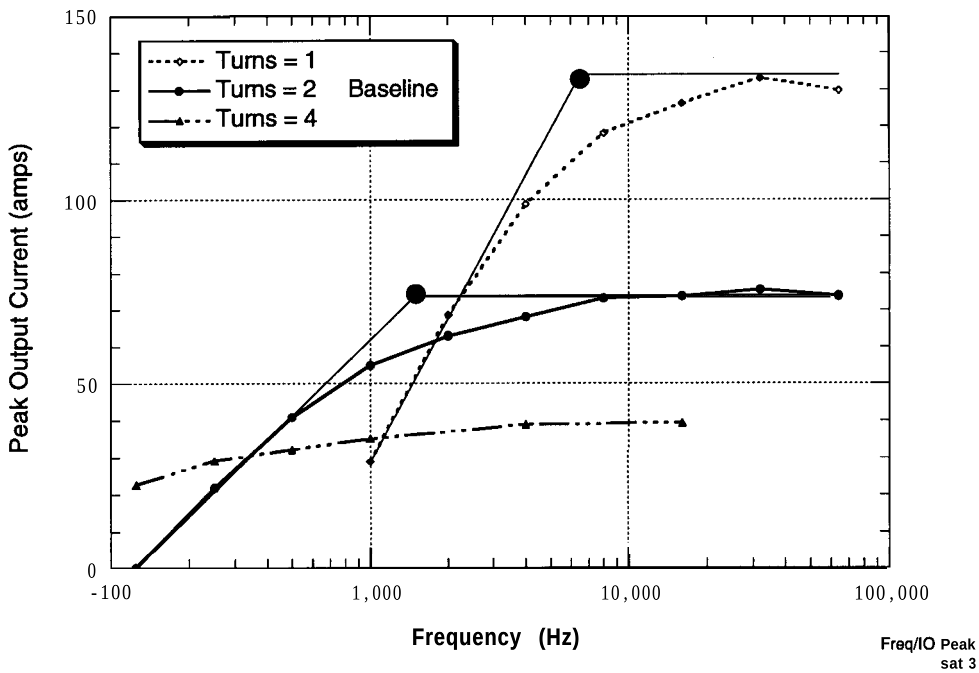


Figure 3.22 Peak output current for several pickup turns values

As previously mentioned, changing the number of pickup turns changes the output current of an ideal transformer. As was done in Section 3.3.4, the ICS output current can be scaled by the corresponding output current of an ideal transformer, forming the normalized output current. The data from Figure 3.22 has been replotted in Figure 3.23 after being rescaled both vertically (normalized output current) and horizontally (open-circuit voltage ratio). When this scaling was applied to variations in roadway current (Figure 3.20), all curves essentially plotted on top of each other, forming a generalized curve. This is not repeated for variations in the number or pickup turns. Although the high frequency currents are similar, they vary by at least 10%. The curves are also spaced laterally by approximately a factor of two or three.

3.3.6 Mutual Inductance Variation

Mutual inductance depends strictly on the geometry of the pickup and roadway inductors. In general, mutual inductance increases as the air gap height is decreased or the pickup size increased. For this sensitivity analysis, the pickup leakage to mutual inductance ratio has been kept constant. As the mutual inductance doubles from 12 to 24 microhenries (as might occur for a vehicle considerably larger than a G-Van), the secondary leakage inductance also doubles from 6 to 12 microhenries.

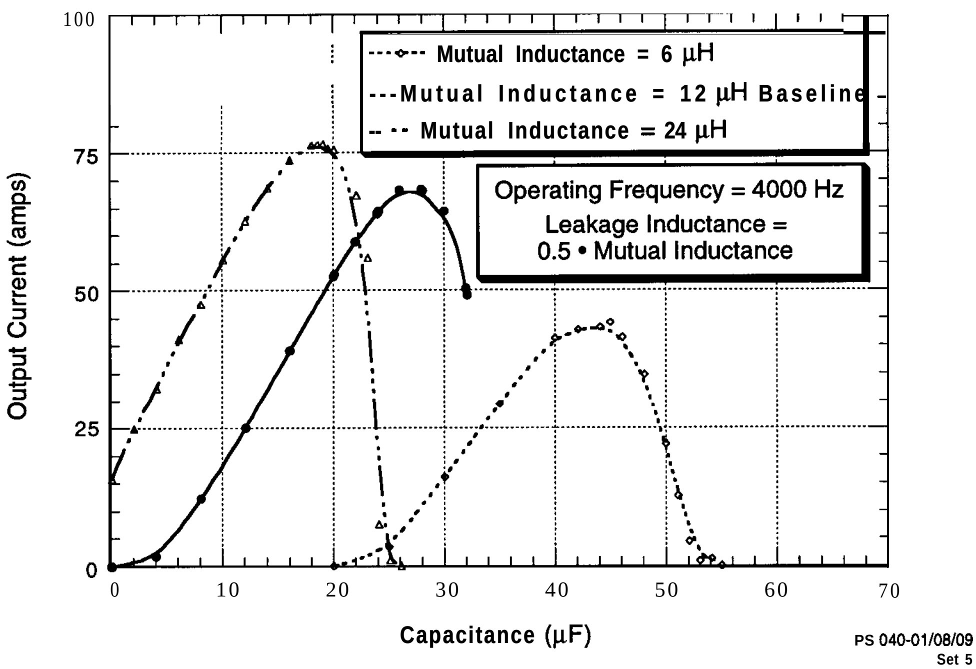


Figure 3.23 Normalized output current for several pickup turns values

Figure 3.24 shows tuning curves for three values of mutual and leakage inductance. Reducing the mutual inductance by a factor of two slightly decreases output current, nearly doubles the capacitance required to achieve the peak output current, and makes the tuning curve sharper. Most of the change in peak output current is due to a dramatic decrease in break frequency as mutual inductance is increased, as seen in Figure 3.25. This change appears to be a squared effect; a doubling of mutual inductance cuts the break frequency by approximately a factor of four. The data can be replotted using the open-circuit voltage ratio on the horizontal axis, as seen in Figure 3.26. The curves have shifted laterally and are closer together, but remain separated laterally by a factor of two

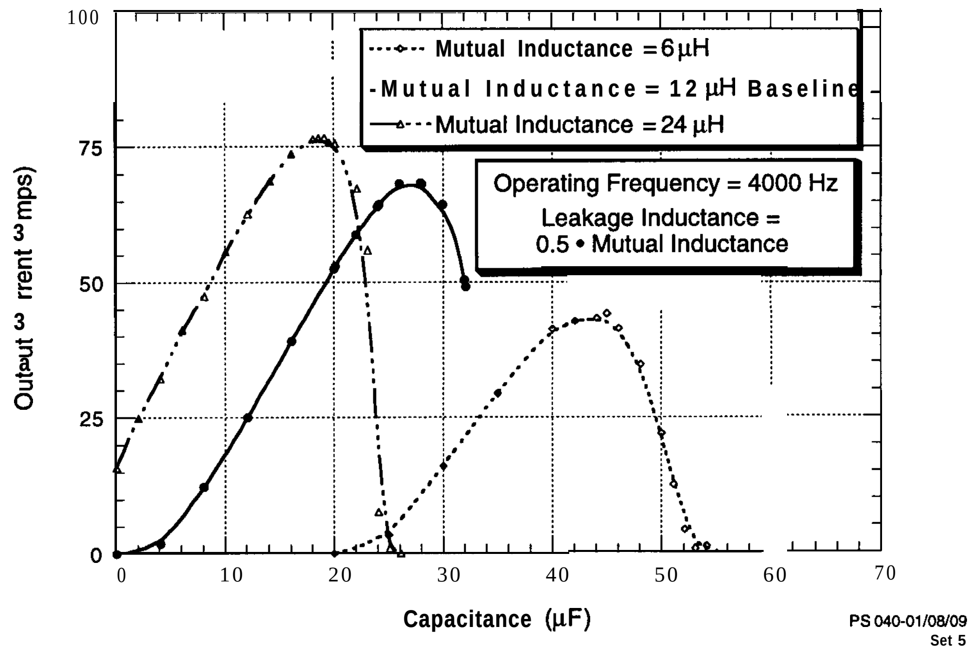


Figure 3.24 Tuning curves for several values of mutual inductance

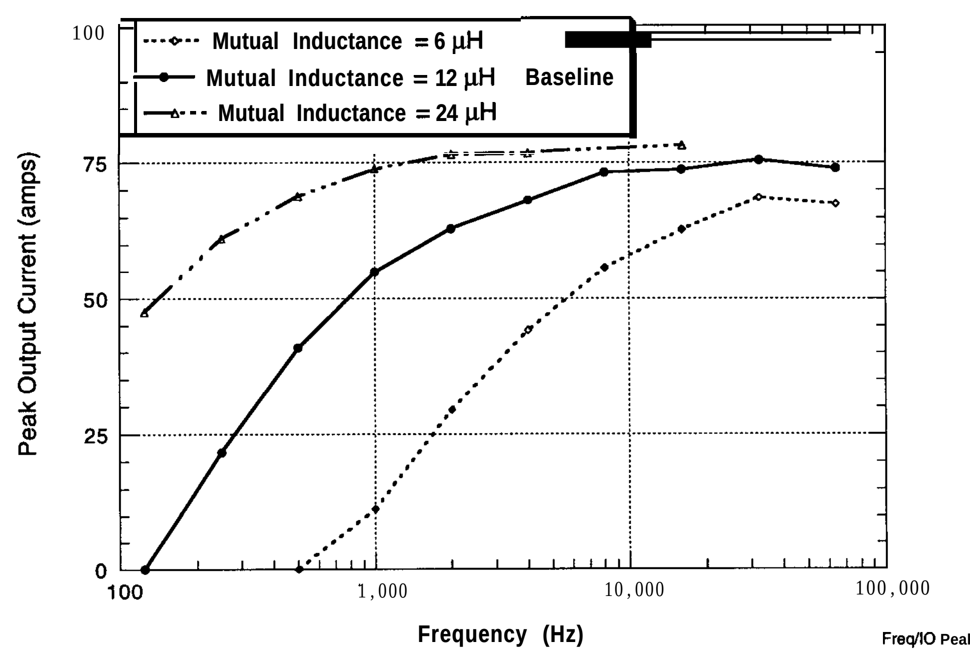


Figure 3.25 Peak output current for several values of mutual inductance

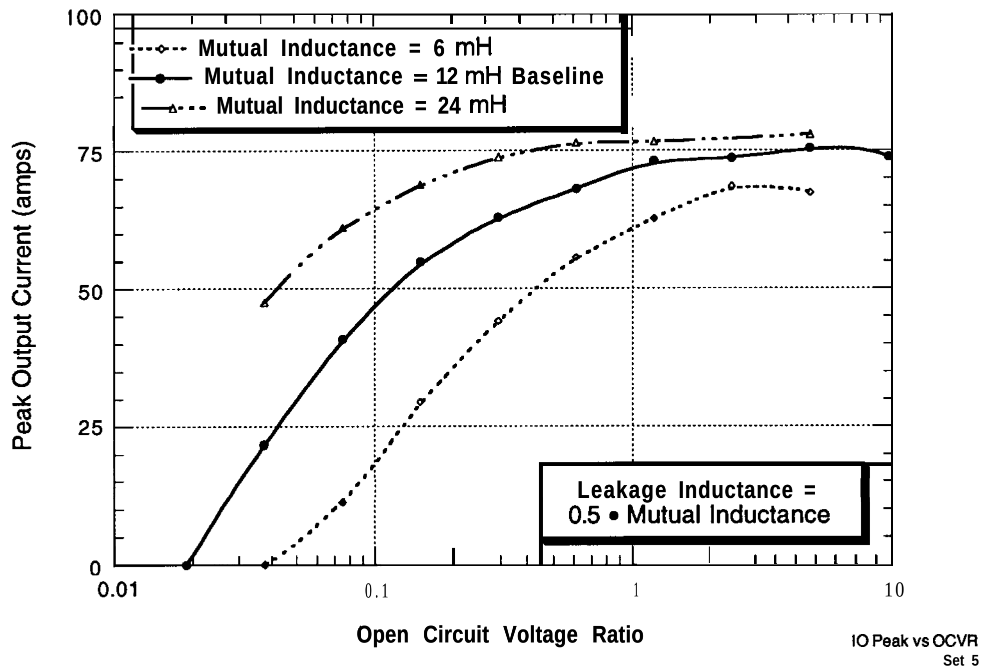


Figure 3.26 Peak output current (vs. OCVR) for several values of mutual inductance

as the pickup turns variation did. In the high-frequency regime, the peak output current is a weak function of mutual inductance, changing by no more than 10% with a doubling of both the mutual and the leakage inductance. An increase in the mutual inductance would however decrease the required tuning capacitance (as seen in Figure 3.24) and the onboard circulating currents. The low sensitivity of peak output current to mutual inductance at high frequencies implies that a larger pickup would increase the peak output current only slightly. A reduction in the air gap height would simultaneously increase mutual inductance and decrease leakage inductance. The increase in mutual inductance would have little effect on the peak output current. The effect of change in the leakage inductance is discussed in the following section.

The effects of a higher mutual inductance (larger pickup or lower air gap height) could be translated into a higher peak output power by changing other parameters, such as reducing the number of pickup turns or increasing onboard voltage. These changes would be an effective mechanism for increasing output power for any operating point that lies substantially to the right of the breakpoint of the plot of peak output current versus frequency.

3.3.7 Pickup Leakage Variation

In Section 3.3.6, the mutual and leakage inductances were both increased or decreased, but maintained a constant ratio. In this section, the mutual inductance is held constant, and the ratio between the two is varied. Tuning curves are shown in Figure 3.27. With a large leakage inductance, both the peak output current and the capacitance required to obtain this current decrease. The required tuning capacitance decreases because the mutual and leakage inductances are in series with respect to the tuning capacitor as seen in the equivalent circuit diagram (Figure 3.28). A smaller capacitance is required to obtain the same resonant frequency with a larger inductance, which is equivalent to observing that as energy stored by the capacitor is converted to energy stored in a magnetic field (as happens during every half cycle), both mutual and leakage lines of magnetic flux are available to absorb this energy. The required tuning capacitance varies inversely with the sum of the leakage and mutual inductances. The decrease in output current is a result of the fact that the roadway sees the leakage inductance as an additional voltage drop in series with the load. As the frequency increases, the magnitude of this voltage drop increases, so increased frequency does not counteract the

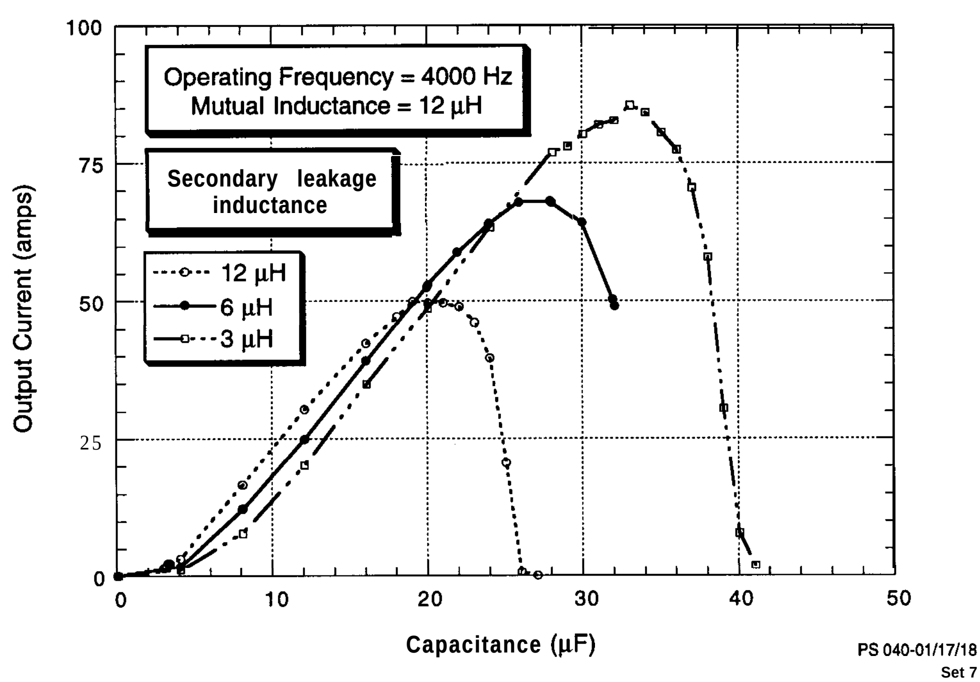


Figure 3.27 Tuning curves for several values of secondary leakage inductance

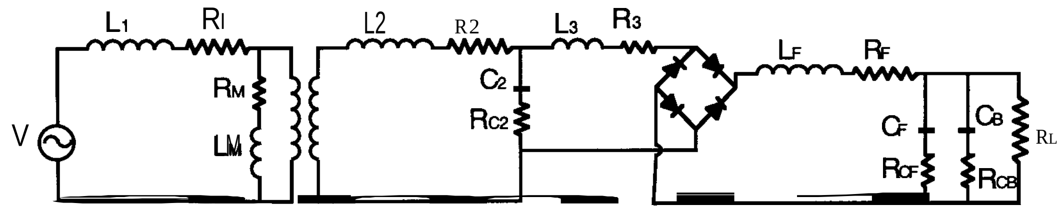


Figure 3.28 Equivalent circuit diagram

detrimental effects of a large secondary leakage inductance, which is clear in Figure 3.29, where the high-frequency values of output current scale approximately with the ratio of mutual inductance to the sum of the mutual and leakage inductances. The three curves are nearly identical at the lower frequencies. The frequency breakpoints scale linearly with the high frequency output current levels.

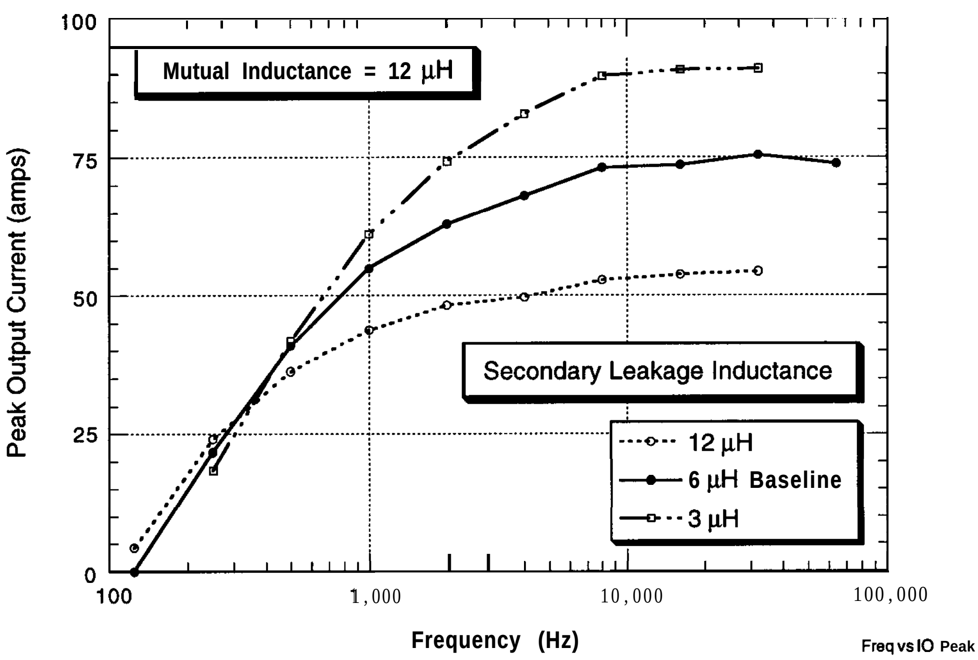


Figure 3.29 Peak output current for several values of leakage inductance

It was previously established that above the break frequency, the output current varies (approximately) proportionally with the roadway current (Section 3.3.5) and inversely with the number of turns (Section 3.3.4). Combining all these into a single equation yields

$$I_o = (I_1/N_2)*(L_m/(L_m + L_2))$$

where: I_o is output current,
I_1 is roadway current,
N_2 is the turns ratio,
L_m is the mutual inductance, and
L_2 is the secondary (pickup) leakage inductance

This formula yields estimated values of output current of 80, 67, and 50 amps compared to model results of 90, 75, and 55 amps. The model results are larger than the formula due in part to the effect of the rectifier input inductance (L_3), which is described in the next section.

3.3.8 Rectifier Input Inductance Variation

The effect of the rectifier input inductance is fundamentally different from any of the parameters previously discussed. It can change output current by changing the effective damping ratio of the resonant circuit. Increasing the value of the rectifier input inductance and filter inductance (rectifier output inductance) provides a degree of isolation between the resonant portion of the circuit and the load. By providing this isolation, the ratio of stored to transferred (or dissipated) energy is increased, lowering the damping ratio, and increasing the amplitude of the response. Dissipated energy refers to the useful energy transferred through the rectifier to the output terminals of the inductive coupling system. This term is chosen because this energy (which leaves the resonant portion of the circuit) corresponds to the energy lost in the resistive component of an LRC circuit.

The rectifier input inductance and filter inductance were changed together, maintaining a ratio of 1:2. Both of these inductances are scaled inversely with frequency to keep the voltage drop across the inductors approximately constant. A parameter called Rectifier Input Inductance Ratio (or RIIR) is used to control the rectifier input inductance and filter inductance simultaneously. The value of this parameter gives a rough approximation to the voltage across the rectifier input inductor expressed as a fraction of the battery voltage. The baseline value of this ratio is 0.2, meaning that the voltage across the rectifier input inductor is 0.2 or 20% of the battery terminal voltage. The calculation is based on an output current equal to the roadway current divided by the turns ratio. Since the output current is generally lower than this, the voltage across the inductor is generally smaller than the RIIR indicates. The rectifier input inductor voltage is 90 degrees out of phase from the current into the rectifier. The rectifier input voltage is approximately equal to the battery voltage and is approximately in phase with the current through the rectifier. Thus, for small values of the RIIR, the pickup voltage is only slightly higher than the battery voltage; however, when the RIIR approaches 1.0, the pickup voltage can rise considerably above the battery voltage. This effect is even more pronounced with high RIIR because the output current can become larger than the roadway current divided by the turns ratio.

Figure 3.30 illustrates tuning curves for several values of the rectifier input inductance ratio. With higher values, the tuning curve becomes higher and narrower, indicative of a lower damping ratio in the resonant circuit. The capacitance required for the peak output current is virtually independent of the RIIR. The peak output current doubles from the curve with baseline 0.2 RIIR to the curve with 1.6 RIIR.

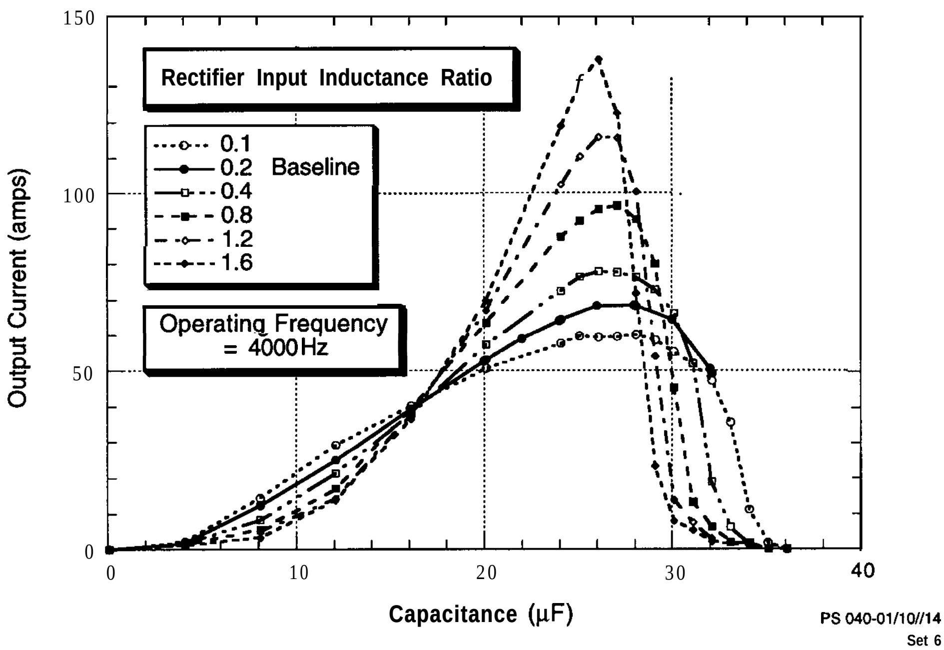


Figure 3.30 Tuning curves for several values of rectifier input inductance ratio

Figure 3.31 shows curves of peak output current as a function of frequency for various values of RIIR. At low frequencies, it has a relatively small effect, but at high frequencies, the effect is pronounced, with the peak output current approximately tripling as the value of the rectifier input inductance is increased from 0.1 to 1.6. The higher values of RIIR increase both the break frequency and the slope of the curves in the low-frequency range.

The data in Figure 3.31 is replotted in Figure 3.32, with lines of constant frequency and the rectifier input inductance ratio on the horizontal axis. At low frequencies, the RIIR has little effect, and may even decrease output current; however, at higher frequencies, the peak output current is increasing rapidly. For 8000 Hz and above, the curves are bending upward.

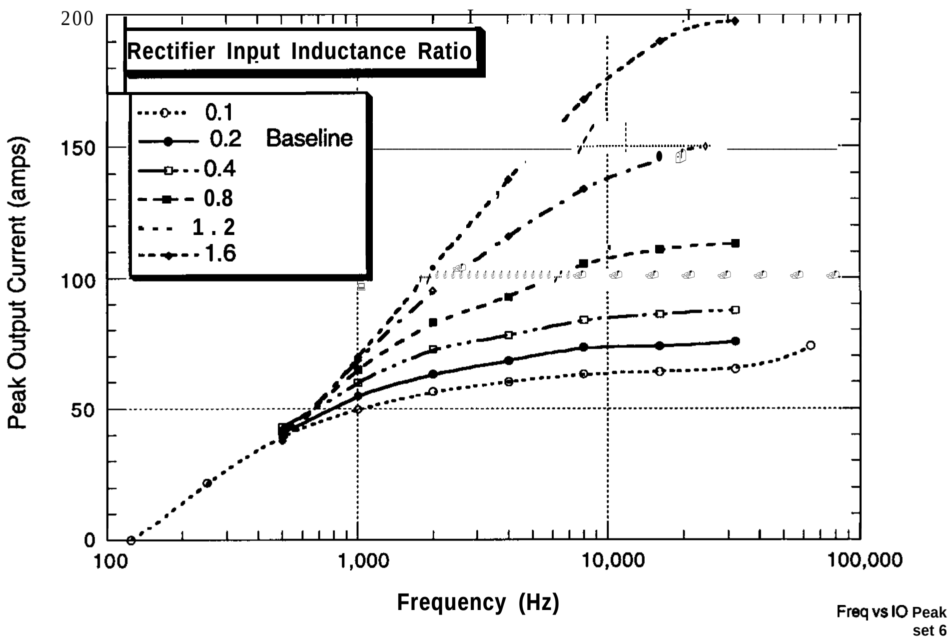


Figure 3.31 Peak output current for several values of rectifier input inductance ratio

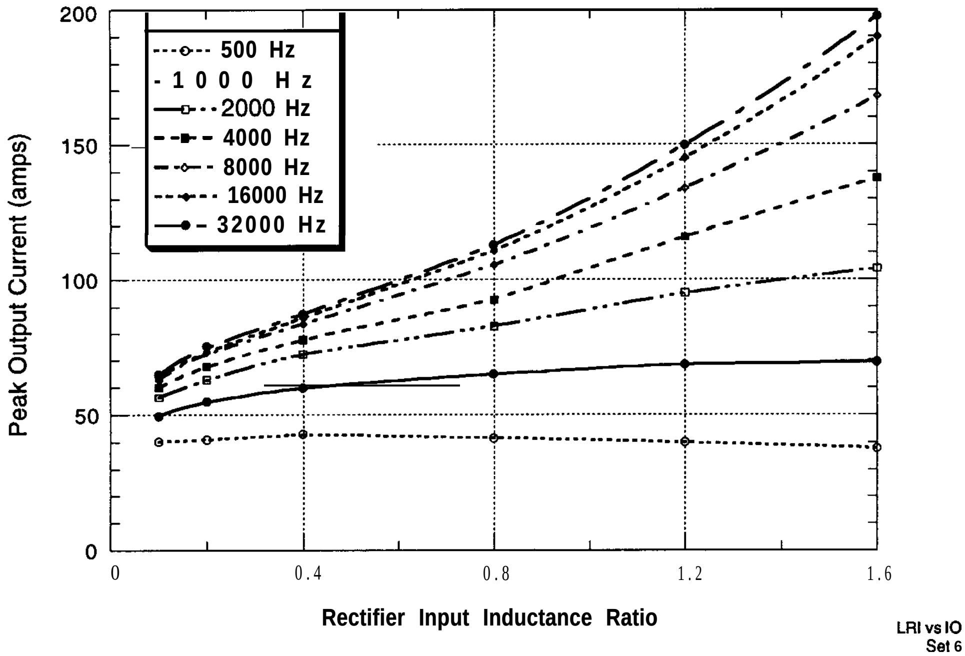


Figure 3.32 Peak output current (vs. rectifier input inductance ratio) for several frequencies

The data from Figure 3.31 is replotted again using the open-circuit voltage ratio on the horizontal axis in Figure 3.33. The curves have the same shape and relative position as in Figure 3.31, as the open-circuit voltage does not vary from one curve to another. It is interesting to note that the breakpoint moves to the right for higher values of the rectifier input inductance. The breakpoint on the RIIR=1.6 curve (dashed with filled diamonds) is at an open-circuit voltage ratio of about 2, considerably higher than any other case. This occurs because for high values of RIIR, the pickup voltage is considerably higher than battery voltage, a situation that arises only in this case.

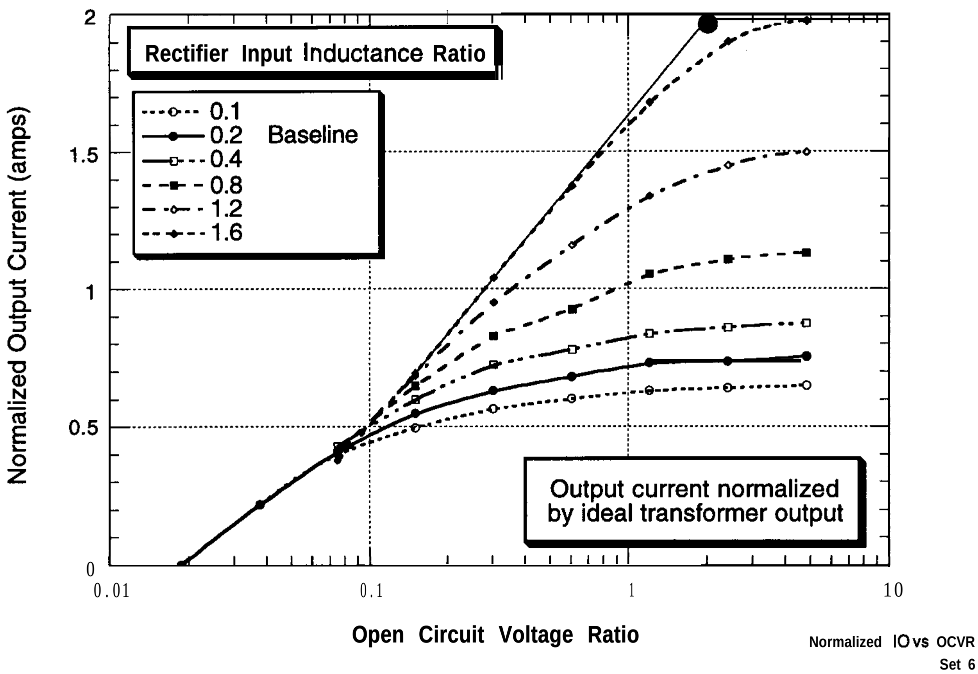


Figure 3.33 Peak output current (vs. OCVR) for several values of rectifier input inductance ratio

Increasing output current by increasing L3 decreases the resonant circuit's damping ratio, creating a high, sharp peak, with high voltages. As shown in Figure 3.34 the pickup voltage rises for higher values of the rectifier input inductance. This rise in pickup voltage is accompanied by increases in capacitor current, pickup current, and coupled core flux levels and losses. To take advantage of higher output currents, the onboard control equipment must be designed to accommodate high voltages and currents. It may be desirable to limit the pickup voltage to two or three times the battery voltage to keep losses and component size in the OBC within reasonable limits. Acoustic noise in the onboard components can be controlled by careful design of the components and use of acoustic isolation. Noise should not be a limiting factor for ICS design.

4. Value Engineering of Roadway Cores

The roadway inductors designed and built for the RPEV test track at the Richmond Field Station worked well and have proven to be quite durable; however, they were expensive to manufacture and install and thermal expansion of the cables caused localized buckling of the road surface. The objective of this task was to redesign the roadway inductor for less expensive manufacture and installation and to address the issue of thermal expansion of the conductors.

4.1 Conductor Thermal Expansion

Thermal expansion of the conductors was considered from the onset of the project. While designing the test track, we decided to build one segment of the track with each type of conductor to determine which-cables or busbars-had better mechanical properties, including load bearing and tolerance of thermal expansion. Due to the cables' spiral construction, thermal expansion appears as a change in both length and diameter of the cable. For very short segments, thermal expansion is not an issue, but as segment length increases the lengthwise expansion must be accommodated.

4.1.1 Experience with the RFS Roadway

The RFS installation has five busbar sections, each approximately 40 feet long and two cable sections nominally 80 and 120 feet long. Thermal expansion caused the conductors that make up the winding of the 120-foot section inductor to buckle through the slurry seal and sand-polyester potting mixture and become exposed at the road surface, as seen in Figure 4.1. To overcome this it is necessary to allow the conductors to expand and contract freely. The solution selected was to install the aluminum cables in PVC conduits that allowed the cables to slide into the connection vaults as they expanded.

4.1.2 Cable Replacement at RFS Test Track

The buckled conductors were removed in one of the conductor slots and replaced with smaller conductors inside conduits. The conduits were cast into the conductor slot in a manner similar to the original cables.

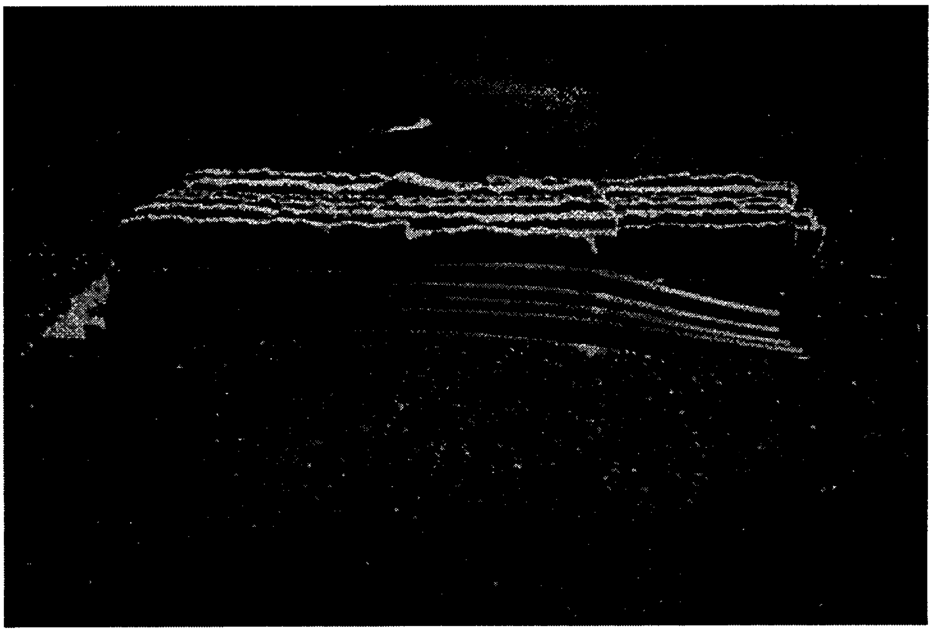


Figure 4.1 Buckling of roadway surface

A small forklift was used to pull the old conductors and potting material out of the slot. This was easier than anticipated and generally left the slot in good enough condition for installation of the new conductor system without any further preparation. Figure 4.2 shows removal of the cables. An old cable spool was used to improve the angle at which the cables were pulled from the slot. The other conductor slot is to the left of the one from which the cables are being removed. The buckled area of that slot is clearly visible to the left of the cable spool.

The chosen conduits were thin-wall PVC sprinkler pipe with a 0.75-inch inside diameter to allow the largest possible conductor to fit inside, while still fitting in the slot. Since the conductors are insulated and the conduits are potted in grout, the strength and insulation value of the conduit are not important. The replacement cables were 4/0 (212 MCM) aluminum conductors while the original were 350 MCM aluminum. Because the original conductors were designed to minimize losses, they had considerable excess

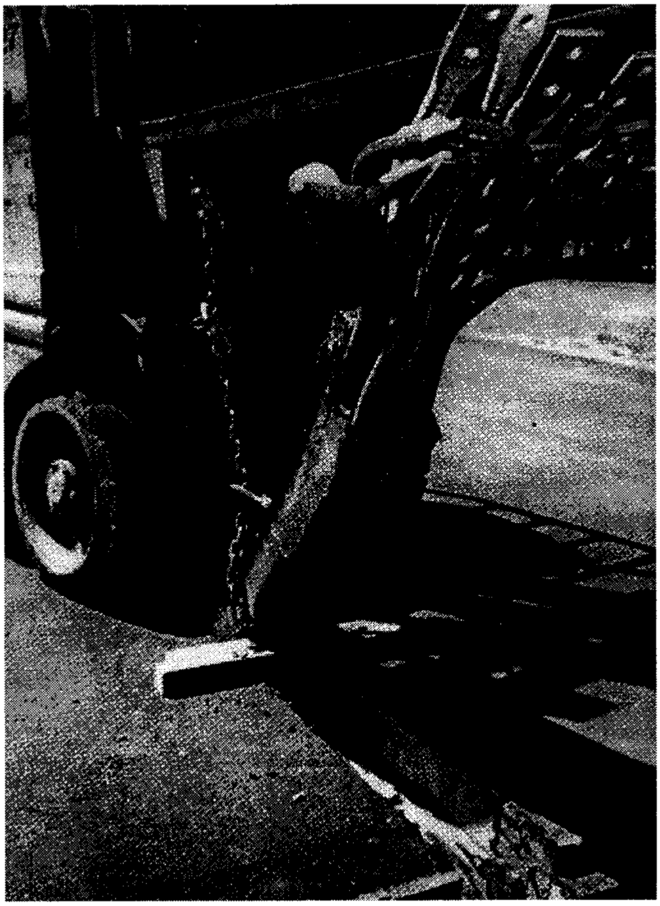


Figure 4.2 Removal of cables to repair thermal expansion buckling

current-carrying ability, and, while the 4/0 replacement cables have slightly higher losses, they still have excess current capability. Table 4.1 shows the diameter, resistance (ac and dc), current ratings, and losses of both sets of conductors.

Non-shrink grout was used to pot the conduits in place, which is less expensive and much easier to use than the polyester-sand mixture used during initial construction of the roadway. The 120-foot section was divided into lengths of 20, 40 and 60 feet, with an expansion joint placed between each of these three sections. The different lengths were used to test the thermal expansion characteristics of the conduit and grout. So far no buckling has occurred although some minor cracking of the grout has appeared.

Table 4.1
Comparison of Cables in RFS Roadway Inductors

	Original	Replacement
Type	350 MCM aluminum	4/0 aluminum (212 MCM)
Conductor Diameter, inches	0.592	0.460
dc Resistance, ohms per 1,000 feet	0.061	0.100
ac Resistance, ohms per 1,000 feet, 400 Hz	0.069	0.106
Skin effect, Rac/Rdc at 400 Hz	1.14	1.06
Total Conductor Area, square inches (15 cables)	5.46	3.29
Total Conductor Current Rating, amps (15 cables at 60 Hz)	3150	2250
Total Power Loss per 200-foot segment, kw (1200 amps at 400 Hz)	2.65	4.07

4.1.3 Long-Term Corrective Action

The long-term solution selected to deal with conductor thermal expansion involves the same approach as the repair described above, except that the conduits are cast into the roadway modules during their manufacture, rather than after the modules are placed in the roadway. This reduces the on-site labor required for installation of the roadway inductor.

4.2 Inductor Module Fabrication Methods

Elma Engineering, a manufacturer of precision coils and inductors for medical equipment and high energy physics labs, fabricated the original RFS core modules. The cores were encapsulated in a fiberglass-reinforced sand-epoxy mixture, vacuum cast in a high tolerance mold and oven-cured at high temperature. As a result the core modules, while well made, cost approximately $590 per foot of roadway-significantly more than anticipated. A cost reduction of a factor of three is needed to bring the cost of the RPEV system down to a cost-effective level.

4.2.1 SCT Internal Research and Development

SCT financed the research that demonstrated concrete could be used as the support material of roadway modules. The concrete modules required a less expensive mold, less expensive material, less fabrication time, and could be manufactured by less skilled laborers. SCT designed and had fabricated two concrete core modules and installed one in the RFS test track. This research led to the redesign of the roadway core modules discussed here.

A new roadway module was designed based on the experience of replacing the roadway conductors and the initial SCT IR&D concrete roadway module. In the new module, both sides of the inductor as well as the conduits for the conductors are cast as an integral unit. SCT built three core modules (with IR&D money). The first, shown in Figure 4.3, was a dummy module, with wood used to simulate the steel cores. The next two were operational modules using laminated steel cores. These modules were designed in concert with Southern California Edison-sponsored research to design, build, and test an RPEV version of a G-Van.

Figure 4.3 Casting dummy roadway module

4.2.2 Module Structure and Mechanical Integrity

The module structure has been designed to incorporate existing methods of pre-casting concrete to the maximum extent possible. Steel rebar is used to provide strength, while avoiding areas of the module with high magnetic flux levels. Small aggregate is used in the concrete to ease the flow of concrete between the core pieces. The conduits are accurately positioned at the ends of the module to assure proper alignment between modules for pulling the cables once the modules are installed in the roadway. There are provisions to allow for some mis-alignment between the modules, such as might occur on highways when one slab heaves.

Fiberglass-reinforced polyester is placed on the top and sides of the modules to prevent core corrosion. Various fiberglass materials can be used, although the one that seems most effective incorporates a mat with randomly-oriented fibers rather than woven fabrics.

4.2.3 Inductor Cores

The iron cores used to provide a low reluctance path for the magnetic flux are the heart of the inductor. The cores are difficult to manufacture because of their unique shape. For the RFS installation, a three-piece core was developed that used two easily manufactured component parts: tape wound C-cores and stacked “I” laminations. The

"I" laminations, used for the polefaces, were stacked loose in the Elma roadway modules and held in place by epoxy encapsulation. While this worked satisfactorily, it was labor intensive and expensive. Because concrete would not support and bind the loose laminations, pole pieces had to be fabricated in which the laminations were fixed to one another to form an easily handled unit. Several manufacturers made pole pieces under SCT IR&D. These poles were approximately 6 inches wide and 7.5 inches long. Some were simply impregnated with a resin or varnish while others were through-bolted with a non-magnetic stainless steel bolt before impregnation. Because the new module design has both conductor slots cast into one unit, it is possible to make the center pole piece twice as long and have it connect the two C-cores, reducing the part count and the cost of the module.

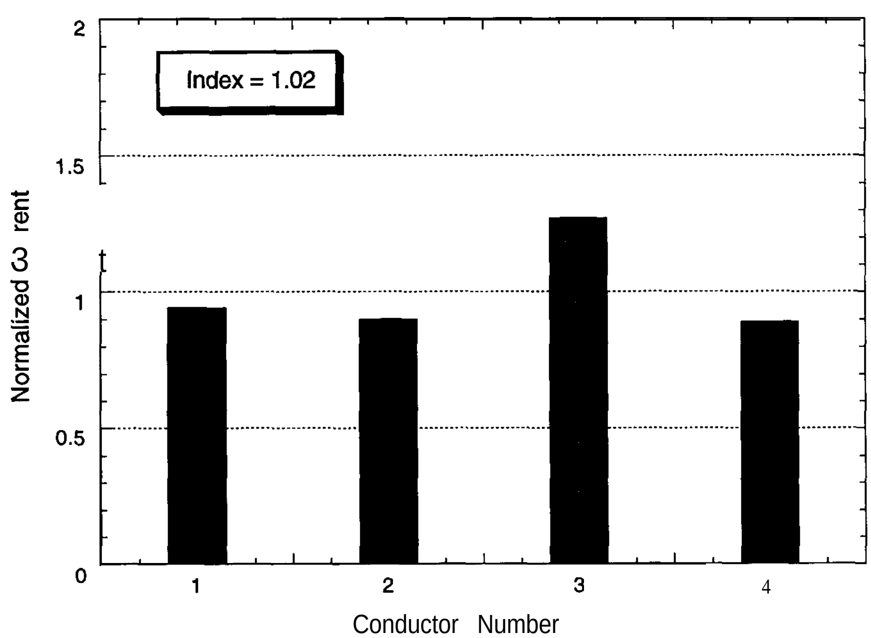
Inductor cores made by powder metallurgy have the potential to reduce the cost of the roadway significantly and have been used successfully in various small magnetic and electro-mechanical devices. When produced in large quantities, the labor costs are very low compared to laminated cores, where labor represents at least half of the core cost.

Powdered cores generally have low losses, but a permeability somewhat lower than laminated cores especially at lower frequencies. They are manufactured by compacting a powdered magnetic material (which has a very thin plastic or resin coating) under very high temperature and pressure. With current technology, the size of powder cores is limited to approximately six inches, which would require that the roadway inductor cores be assembled from several pieces designed to interlock.

Given the potential to dramatically reduce cost, the powdered core was given serious consideration. Several tests were performed with powdered iron cores. Losses were reasonable, but the permeability was too low. It should be pointed out that due to the large reluctance in the magnetic circuit caused by the air gap, permeability of the cores is not nearly so important for the inductive coupling system as for most other applications. While permeabilities of 500 to 20,000 are common for grain-oriented silicon steel laminations, powdered cores tend to have permeabilities of 50 to 500. A value of 200–400 would be adequate, but test results fell short of this range. The tests were performed with makeshift samples, and the results were close enough to the required values that powdered cores should be considered in future work.

4.2.4 Conductor Conduits

The roadway core modules that were built incorporating pre-cast conduits had eight per slot compared to 15 in the original design. After installing the new modules, we realized that fewer conduits would make installation easier. This is not as straightforward as it seems because equalization of the conductor currents must be considered. We believe that two conduits (or maybe just one) can be used per slot if a multi-conductor cable with spiraled conductors (most large multi-conductor cables have built-in spiral) is used. The spiral has the same effect as conductor transposition and should maintain equal current distribution. The modules fabricated for the G-Van testing were wired with a cable composed of four #4 AWG aluminum conductors. These cables were transposed through the 8 conduits of the IR&D modules, but also have the spiraling conductors mentioned above. Figure 4.4 shows the distribution of current within one of the cables and lists the index of the current equalization, which is very good compared to some of the original transpositions tried for the Electric Bus project, The index is the average of the squares of the current divided by the square of the average current.



RFS5-039

Figure 4.4 Current distribution of parallel conductors in spiraled cable

4.2.5 Field Cancellation Windings

One other innovation developed with the G-Van roadway cores-field cancellation windings-was incorporated into the module design. Figure 4.5 shows the location of the cancellation windings. The current flowing in these windings opposes the current in the conductor slot and cancels some of the magnetic field. Because of the geometry of the inductive coupling system, the cancellation effect is small in the air gap, causing about a 10 – 15% decrease in mutual inductance. The effect is larger 5 or 10 feet from the roadway centerline, decreasing measured magnetic fields up to 50%.

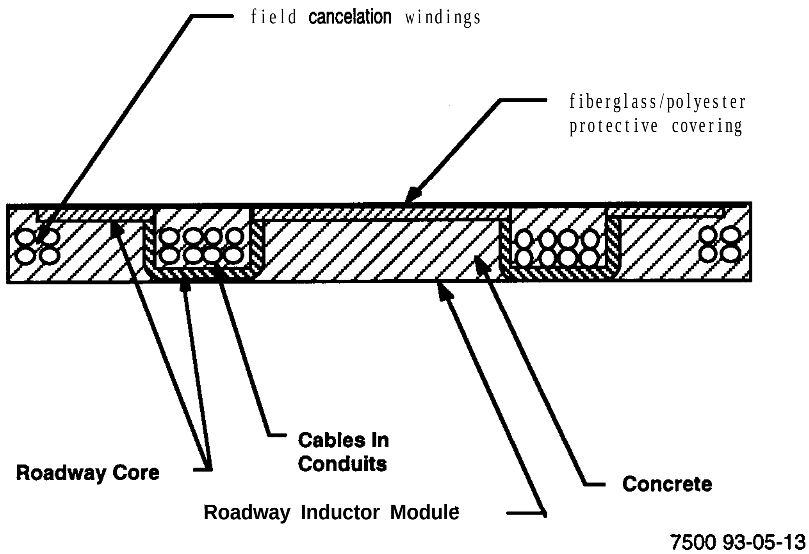


Figure 4.5 Field cancellation windings

4.3 Roadway Installation

Several areas for improvement suggested themselves during the construction of the RFS test track. Construction of the vaults for the roadway electrical connections was a time-consuming task, and simplification of this process should save money. Placing the modules was relatively easy but having fewer modules would speed up the job. Installing the conductors for the roadway was time consuming and labor intensive, and improvement in this area would simplify construction of the roadway.

The double-width roadway modules built under SCT IR&D were installed in the roadway at RFS to make a 20-foot section of roadway inductor for the SCE G-Van project. Because of the double width and pre-installed conduits, the installation of this short section went quickly. We used a precast vault of a standard size with a standard steel lid for the electrical connections. The vault was easy to install and modify for use with the roadway inductor. We were able to use a steel lid because the roadway current for this installation was only 240 amps compared to 1200 amps for the RFS roadway. Use of standard-size precast vaults should reduce the cost and simplify the installation of roadway inductors.

4.4 Summary

The replacement of the buckled conductors in the RFS roadway inductor went smoothly, and the replaced conductors are performing well. Some cracks have appeared in the grout that supports the conduits but no buckling or structural failure has appeared. Redesigning the roadway modules to be less expensive was a qualified success; the cost was reduced from $590/foot to $390/foot. It should be pointed out that 94 of the original roadway modules were made while only three of the new design were fabricated. While not quantified by this task, savings in the cost of the roadway inductor should also manifest themselves in less expensive construction due to simpler installation of conductors, the use of double width modules, and the use of standard precast vaults. There is also a possibility of even less expensive inductor cores if the permeability of the powered iron cores can be increased to an acceptable level. The direct cost savings for the redesigned roadway were significant but additional work in this area must be performed before large-scale production for the roadway is begun. This task showed that relatively simple changes can result in a significant cost savings and we believe that the cost of the roadway inductor can be reduced more in the future.

5. Economic Analysis of RPEV Technology

This report describes economic implications for the conceptual Roadway Powered Electric Vehicle (RPEV) system.

5.1 Background

The objective of the RPEV system is to provide an alternative to the internal combustion engine (ICE) passenger car by transferring energy to the vehicle via an inductive energy transfer system located in the roadway in combination with an electric battery. Society needs alternatives to the ICE because of the direct and indirect costs associated with air pollution from and petroleum of internal combustion engines. With the RPEV system, the power needed for passenger car transportation would not necessarily be generated in the same geographical area in which it is consumed, allowing the pollution source to be located remotely in less populated, non-urban areas. Additionally, the emissions from one power plant are much more easily controlled than those from thousands of automobiles.

With currently available technology, range estimates for battery-driven vehicles driven at 55 mph are typically 40 – 50 miles, depending on the specific vehicle. At slower speeds, the potential range increases. The range limitation of battery-driven vehicles is thought to be too restrictive to induce significant numbers of drivers to select battery-powered vehicles; however, battery performance enhanced by an inductive coupling system on the vehicle will effectively increase the potential range of the vehicle. The extent of this increase will depend, of course, on the extent of the roadway-powered system. Increasing the range of these hybrid vehicles will make such electric vehicles more appealing to drivers making car purchase decisions.

5.1.1 RPEV System and Users

For this analysis, a candidate RPEV system was selected for the Los Angeles Basin. The RPEV system consists of a network of roadway inductors installed in designated existing freeways that will provide power to a population of specially adapted electric vehicles, which will be battery equipped and able to be inductively powered by the roadway. The power network will consist of power conditioners, distribution lines, and inductors embedded in the roadway and will connect to the existing electric distribution grid. The peak power demand of the baseline system will be 500 megawatts, or 2% of the existing capacity, assuming 20% of the vehicle miles traveled (VMT) are on the powered roadway.

We assume that there will be a significant percentage of drivers who will purchase battery-equipped vehicles because the RPEV option will provide an attractive method of extending the vehicle's range. Some RPEV owners will use the powered network daily. Others will mainly use their vehicles in the battery-only mode and recharge their batteries at home during off-peak hours. These drivers will occasionally use the powered roadway during longer-than-average trips but generally will avoid roadway powering because the RPEV system energy will be priced at a higher kilowatt-hour rate than off-peak recharging. Even though these drivers rely on the powered roadway infrequently, they probably would not have made battery-only purchase decisions if the RPEV option not been available.

Although the split between the various modes was not analyzed during this study, the authors have prepared a possible (assumed) breakdown of VMT by mode for a large urban region. Figure 5.1 presents such a modal split. Total VMT per day is the sum of the daily VMT traveled in ICE vehicles, electric battery-only vehicles, RPEV vehicles using battery only, and two classes of users driving on the RPEV system-those who use the system every day and those who use the system occasionally.

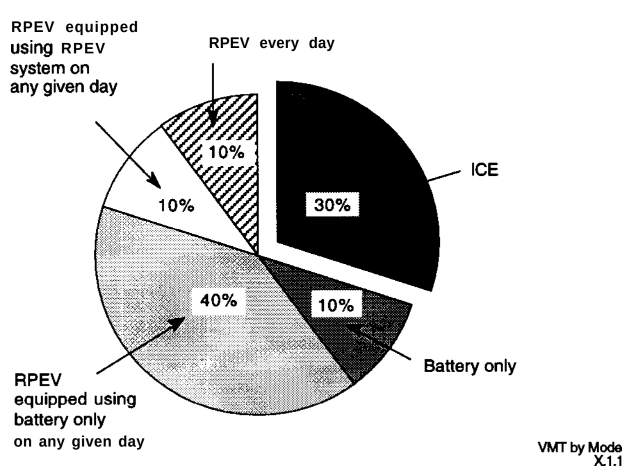


Figure 5.1 Total vehicle miles traveled (VMT)

The percentages are arbitrary estimates, but do represent several fundamental points. The first is that the battery-only EV is not likely to dominate the market, due to the fundamental limitations of batteries. Although battery and vehicle technology will undoubtedly improve during the coming decades and infrastructure support systems (such as mid-day or quick-charging stations) will appear, the battery-only vehicle's performance will never match the performance of ICE vehicles that people take for granted today. Battery-only vehicles are likely to be driven lower-than-average number of miles per day, so even 20% market penetration may result in only 10% of VMT.

The second important point is that not every RPEV-equipped vehicle will be driven on the RPEV system every day. Figure 5.1 shows that perhaps half of the VMT traveled on the RPEV system may be with vehicles that use the system on a daily basis. The other half (white sector in Figure 5.1) is by RPEV-equipped vehicles that use the system occasionally (perhaps 20% of their VMT), but happen to use the system on any given day. The other 80% of these vehicles' VMT (or 40% of the total regional VMT) consists of short trips that can be done on the battery alone. These trips and VMT would most likely be done in ICE vehicles if the RPEV system were not built. Even though these trips do not use the RPEV system, they contribute very substantially to the increase in ***electric*** VMT within the region and the associated reductions in air pollution. These battery-only trips by RPEV-equipped vehicles also have a substantial positive impact on the time-of-day demand profile placed on the utility by the RPEV equipment (sum of energy drawn by the powered roadway network and the battery charging done by RPEV-equipped vehicles).

The analysis in this report focuses on the life cycle costs of the RPEV system and the cost to the user (per kilowatt-hour or per mile) that would have to be charged for the system to break even in a specified year (cumulative revenue equal to cumulative costs).

The RPEV system costs are assumed to be incurred as if the system were privately owned with all costs borne by the users.

5.1.2 Analytical Approach

This analysis shows the basic relationships between the important system cost and revenue components. The major cost drivers are the

- Roadway initial construction and replacement costs per mile
- Number of miles constructed
- Debt financing (interest rate and loan life)
- Energy

Other costs for maintaining and administering the system.

Revenue from the system to offset costs is determined from

The number of users over time (market penetration profile)

Vehicle miles per user driven on the powered system

The energy consumption of the vehicle (kilowatt-hour per mile).

Initially, a simple, static cost model was developed. This cash-flow-based model, referred to as the Steady State Model (SSM), provides snapshot cost estimates for a one-mile portion of a fully deployed and populated system.

The Startup Transient Model (STM) addresses time-dependent costs and revenues for one mile of the system incorporating a market penetration profile over time.

The RPEV Economic Model (REM) is a model of a regional system including various market growth assumptions, construction schedule assumptions, and cost assumptions.

A baseline scenario was developed, and sensitivity analysis to the major cost assumptions was performed using these three models. The baseline break-even price escalates slightly from one model to the next because of slower market growth in later models. Each model is a carefully built-up extension of the previous model in which the differences were validated. Therefore, the results from the early sensitivity runs provide valid perturbations around the baseline even though the baseline retail break-even price is changed slightly.

5.1.3 Assumptions

Assumptions common to the three models are described in this section but assumptions unique to a scenario or model are defined in the applicable sections.

In our analysis, the total cost of the system is borne by those who are on the system. Revenue is assumed to be generated only through roadway-based energy sold. Other plausible income-generating or funding options such as an excise tax on RPEV vehicles sold, an RPEV tax on gasoline sold, government subsidy of capital costs, or including capital costs in the utility rate base are not included in this analysis. Substantial revenue will certainly be generated for the local utility through at-home battery charging, which does not enter into the cost analysis. In this respect, we are addressing the most stringent costing requirements because other income-generating avenues are ignored. Air quality benefits (or value of emissions reductions) are similarly ignored in the economic analysis.

The costs of home chargers and their associated energy are excluded from this analysis, as are the miles traveled by the vehicles using this energy. These miles and kilowatt-hours are associated with the market segment labeled “RPEV equipped using battery only on any given day” in figure 1. The energy cost for such miles would be considerably lower than for RPEV miles. This would bring down the average cost per mile down from the RPEV per-mile cost, depending on the split between RPEV and “battery-only” miles for any particular vehicle. Additionally, the energy transfer rate for vehicles traveling on the powered roadway is assumed 20% higher than the average energy used, allowing for recharging of the vehicles' batteries while operating in RPEV mode. The miles traveled on the energy used for recharging the battery “on the fly” are not counted, while the cost of energy is, making the calculated RPEV per-mile costs conservative (higher) compared to a real-life system.

5.1.3.1 System and Financing

Loans are used to pay for the capital costs of system construction, which means the interest rate and loan life are variable. This is an extremely conservative financing approach compared to methods generally used to finance transportation systems. In less conservative schemes, taxes or government funding could partially or completely offset the capital construction costs. Similarly, the capital costs could be added to the utility rate base (if the local utility owns the RPEV system) and the capital cost of the system could be borne by all users of electricity, not just users of the RPEV system, although such a scenario would require PUC approval, which may be unlikely.

The capital cost of the roadway is a per lane-mile estimate of the costs to retrofit the RPEV technology into an existing freeway lane. The marginal cost of installing RPEV technology into new construction will be lower.

The roadway has a variable useful life after which each lane-mile incurs a replacement cost to rebuild. These anticipated costs will be lower than the initial capital costs (in constant dollars). The useful life of the roadway and the replacement costs are both variables in the models. The replacement costs, like the original construction costs, are financed by debt, with the loan being paid off over the useful life of the improvements.

5.1.3.2 Demand

To ensure that average volume does not exceed saturation, the number of users is limited in several ways. Saturation means the maximum number of vehicles (per lane per day) that could reasonably be expected to use the system. This corresponds to total RPEV vehicle miles traveled (on the system) divided by the total system lane-miles. For the one-mile models, the number of users is limited by vehicle volume per lane-mile per day average flow on the system-typically 20,000 vehicles. For comparison, many freeways in the Los Angeles Basin handle volumes of 25,000 – 30,000 vehicles per lane per day averaged over their entire length. On their busier sections, daily volume per lane is often closer to 40,000. In actual use, some RPEV roadway sections may have a higher volume than saturation volume and some will have a lower volume.

The regional model replicates the market penetration profile of the one-mile model for roadway built in each year. An average trip length on the RPEV portion of the system is assumed because, unlike the one-mile models, all users will not drive the entire RPEV system each day. Therefore, the user population grows as specified until saturation based on the assumed average trip length on the RPEV portion of the system is reached. Each trip is composed of both battery-only and RPEV-powered sections but the off-system trip length is not a factor since at-home battery recharging utility revenue is not considered in the analysis.

5.1.3.3 Price

Costs are the sum of expenses for construction, debt, energy, administration, and operations and maintenance. The time-dependent models, the STM and REM, include a second interest calculation for the debt required to cover cumulative losses before the system's becoming profitable on a cumulative basis. Revenue is derived entirely from the retail sale of energy for use on the RPEV system. Use-dependent expenses and revenue assume a 365-day year. Results are measured in dollars, dollars per kilowatt-hour, and dollars per vehicle-mile traveled on the RPEV system. All costs are in constant 1992 dollars.

Profits are revenue minus expenses. Any tax consequences are dependent on ownership as well as other uncontrollable tax advantages. Therefore, profits as well as break-even rate calculations are based on pre-tax earnings and do not consider any possible tax implications.

Costs and revenue are tracked as components of a cash flow-based analysis. Therefore, depreciation is not included as an expense. Construction costs are debt financed. The model calculates the price at which retail energy must be sold for cumulative costs to equal cumulative revenue by a certain year. Typically, we look to break even by Year 25, which was selected because it was sufficiently far in the future to capture the predominant roadway costs. In addition, the user population has reached steady state by this time in both the STM and the REM and the roadway built in Year 1 has reached the end of its useful life and is ready for replacement.

The ***rate*** calculation is based on the cumulative total costs divided by the cumulative kilowatt-hours sold. There are four different rate calculations

- The SSM calculates a steady-state rate, which represents a fully saturated and deployed system. The SSM model does not consider accumulated costs before users are providing revenues, so early losses are not accounted for.
- ***Annual*** rate is the rate required for annual revenues (based on annual kilowatt-hours sold) to equal annual costs. The costs used for this rate include interest on deficits from early unprofitable years unless otherwise specified.
- ***Break-even rate*** is the rate in each year that will result in cumulative costs equaling cumulative revenue by that year. The break-even rate varies year by year because the calculation is intended to keep revenues aligned with cumulative costs. The break-even rate decreases with time because there is a larger user population over which to spread the costs.
- ***Effective rate*** is the value of the break-even rate for a designated year. It is applied for all years. At the designated break-even year, the effective rate results in a cumulative profit of zero. After the break-even year, the effective rate results in the system's turning cumulatively profitable. The years before the break-even year typically result in decreasing cumulative losses (beginning with the onset of user revenue), which decrease as the break-even year approaches. Cumulative total costs are calculated in a similar manner as in the SSM but also include the interest payment required to finance additional debt to cover the deficit in the unprofitable years.

5.1.3.4 Price Elasticity of Demand

Two major factors will affect the elasticity of demand with respect to price. The first is the life cycle-based capital equipment purchase decision that will be made when a user needs a new vehicle. Users will evaluate the anticipated costs and benefits of the various transportation modes (refer to Figure 5.1). Expected cost advantages between two transportation modes providing similar benefits, will certainly affect the capital purchase decision and result in proportional changes to the demand for gasoline or electricity. Such decisions on large capital purchases are not easily changed even if energy prices change. Thus, capital purchase decisions will strongly affect the type of energy demanded. Energy demand will therefore be fairly inelastic with respect to price to meet demand for basic transportation as the market can be expected to take several years to correct for the effect of relative energy price changes.

The second consideration is the option to reduce or extend usage of an energy type based on changes in the price. This type of use decision has been shown to be fairly elastic [1].

In the models, the energy demanded by the users is assumed to be perfectly inelastic to the price charged (i.e., rate changes do not induce proportional quantity changes). This means that the number of users and the extent of their system use will not be affected by the price they pay for energy. After a user is committed by a large capital purchase of either an ICE or RPEV vehicle, relative price inelasticity can be expected.

There is no data specific to the RPEV purchase decision as a result of the type of energy use decision. Modeling market penetration as a function of the break-even rate is beyond the scope of this project. The demand for energy is considered fairly inelastic because there are not readily available substitutions for the products supplied by the utility companies (gasoline, home heating fuel, residential electricity). People continue to drive and heat and light their homes [2], [3]. Therefore utility commissions are responsible for protecting the public from exploitation by the utility companies. The price elasticity of demand for transportation energy will certainly change when a substitute is in place. Presumably, the intelligent buyer's purchase decisions will be the result of life cycle cost estimates of each system.

The on-system cost of energy for RPEV vehicles will be higher than the residential price, which will encourage RPEV system users to recharge their batteries at night during off-peak hours. From the utility company's point of view, overnight charging will increase demand during the off-peak hours and minimize the extent users will be on-system unnecessarily during hours of higher electrical demand.

In urban areas, there are many more short trips than long trips. However, the long trips represent a significant fraction of the total VMT. It is believed that RPEV owners will choose whether or not to use the RPEV system for any particular trip will be a strong function of trip length, as well as the battery depth of discharge at the start of the trip. Factors such as additional trips planned during the day and availability of charging stations will also play a role. Some people who are more conservative may choose to use the RPEV system for all trips. Based on trip length distributions, it seems that there will be adequate demand for the RPEV system. The length of trips on the RPEV system will be much longer than average, contributing to a high vehicle-miles per day on the system for the vehicles which use the system on any particular day. This number can not be multiplied by 365 to get the overall fleet average usage per year. For instance, if a vehicle is driven on the system for 50 miles one day a week, the average distance traveled on the system, taken over only the days when the system is used would be 50.

However, the total yearly VMT on the system would be 2600 miles (50*52), not 18250 miles (50*365).

5.2 Baseline Scenario

Table 5.1 summarizes the variables and the values chosen for the baseline scenario used by the economic models. These values are intended to be realistic (although somewhat conservative) and provide the basis for the sensitivity analysis that follows.

The focus of this analysis was to provide an understanding of rough cost estimates and insight into the effect of changes to the primary cost drivers. The relationship between initial capital construction cost and future operations/maintenance costs is contained in Appendix A.

5.2.1 Market Penetration

Market penetration on the RPEV system is a consideration for the STM and REM. The SSM, because it is a steady-state model, does not consider startup effects. The SSM defines the number of users as a per lane per day volume.

The profile of the number of RPEV users over time can be described in two ways: a geometric growth rate or constant growth number per year. Both of these growth modes limit population growth by capping the total user population. In the baseline scenario, this limit has been set at 20,000 vehicles per lane-mile per day. From estimates contained in [4], freeway VMT is forecast to grow 50% – 60% over the next 35 years. Because freeway VMT will grow faster than freeway lane-miles, volume may be even higher than the 20,000 vehicles per lane per day used in the baseline scenario. To accommodate the additional vehicles, the rush-hour period will extend to more of the day and vehicles per lane per day will increase. These trends are already present in many California cities.

Table 5.1
Baseline Scenario Variables

Market Penetration	
1500	Number of RPEV users in the initial year of market growth
2250	Number of users escalation per year until market saturation or volume limit
3	Market penetration start year
20,000	Volume limit in vehicles per lane per day (or veh-miles/lane-mile/day)
Cost	
$1,500,000	Initial cost per lane-mile of roadway
$1 ,000,000	Replacement cost of roadway per lane-mile
1%	Administrative cost as a percentage of debt plus energy cost
1 %	O&M cost as percentage of cumulative new roadway capital cost (not including costs for replacement roadway)
25 years	Useful life of roadway before replacement
$.07	Wholesale cost of energy per kwh
$.1894	Retail price of energy per kwh (Used for some direct revenue calculations) REM output
Vehicle	
0.25	Energy consumption in kwh/mile
75%	System efficiency
50	Average vehicle-miles per day on the system
Debt	
3.3%	Real interest rate
25	Years to pay back loan
Miscellaneous	
25	Designated year for cumulative break-even effective rate calculations
11	Number of years for roadway construction
104	New lane-miles per year (52 system-miles)

The linear growth model is based on defining an initial number of new users beginning in a designated year, from which the population on any particular facility increases by a constant number of users each year. This method is linked to the construction schedule in the REM so that as each mile comes on-line, users populate it at the designated initial number and continue to grow until saturation is reached for that section. The advantage of this population growth profile is that it is tied to the construction schedule and each section is identically populated. Vehicles per lane-mile per day is a realistic way to control the number of users allowed to populate the RPEV system because it is sensitive to the construction schedule and roadway miles operational.

A geometric growth model is based on an initial number of users, beginning in a designated year, which increases at the growth rate specified (a certain percentage growth in the number of users). Growth is capped when volume reaches the specified saturation level.

5.2.1.1 Baseline Market Penetration Assumptions

The analyses in this report use the linear growth model. The baseline scenario has users beginning to populate the system in Year 3 with 1,500 users. In that year after two years of construction, there are 208 lane-miles of RPEV roadway available. The population grows by 2,250 on each section until saturation is reached at 20,000 vehicles per lane-mile per day.

Say for instance that in Year One, 52 system miles (104 lane-miles) of roadway were constructed, perhaps I-10 from downtown LA to San Bernadino. In Year Two no users are assumed. In Year Three, each lane-mile would have 1500 RPEV-users daily, which might represent about 2% of the total users of that particular freeway(counting all lanes). These users would drive a total of 157,500 vehicle miles (104*1500) daily. If each of the RPEV's that used the system drove 50 miles on the powered roadway (a 25 mile round trip), then these miles would be accounted for by 3150 RPEV's. Since most RPEV's would not use the system every day, the total number of RPEV's would be several times greater, perhaps closer to ten thousand. In Year Four, the number of users on each lane mile would be 3750 (1500 plus 2250), and all numbers would scale up proportionately.

In general, the RPEV's which don't use the system on any particular day are ignored. Since this modeling effort deals only with the RPEV's which use the system on any particular day, their average on-system miles are relatively high. Say for instance that only 25% of the RPEV's use the system on any given day. Further assume that the entire fleet of RPEV's <u>averages</u> 12.5 miles a day on the system. When this average is taken only across the vehicles which use the system on any particular day, the average would increase to 50 miles per day on the system as presented in Table 5.1.

5.2.2 cost

The capital cost of roadway construction is the marginal cost of the initial retrofitting of the RPEV equipment into existing freeway lanes. The system has a useful life (baseline value of 25 years) after which it is replaced. Replacement costs are anticipated to be lower than initial costs; therefore they are designated separately.

Operating costs include administration and operations and maintenance costs. Administrative costs are estimated as a percentage of the debt and energy costs. Operations and Maintenance (O&M) costs are a percentage of the roadway cumulative capital costs (not including replacement costs). By linking the administrative costs to the debt and energy, we are causing the program administration (billing, supervision) to be a function of both the construction activity and the number of users, which is a more significant cost factor later in the program when construction costs diminish. Debt service and energy account for the vast majority of system costs. Since the retail price of energy is set to cause revenue to equal costs (cumulatively in the specified break-even year), tying administrative costs to energy plus debt is equivalent to estimating administrative costs as a percentage of revenue. Linking the O&M costs to the cumulative new construction costs and construction profile recognizes the amount of roadway that will need servicing.

The wholesale cost of energy is a user-designated variable.

5.2.2.1 Baseline Cost Assumptions

Capital costs of $1,500,000 per lane-mile of initial roadway retrofitting and $1,000,000 for replacement have been used for our baseline scenario. The useful life of the system is 25 years, after which replacement costs are incurred. All capital costs are expensed according to the debt model parameters. Annual administrative costs are 1% of the debt and energy costs. O&M costs are 1% of the cumulative new roadway capital costs. The wholesale cost of energy is $0.07/kwh.

5.2.3 Vehicle Parameters

Total wholesale energy required is a function of the system efficiency, vehicle energy transfer rate, number of users, and average on-system miles traveled per day by each user.

System efficiency is defined as the DC energy delivered on-board the vehicle divided by the AC energy drawn from the utility grid. As traffic volume approaches saturation, system efficiency will increase because more than one car will be on any one segment at a particular time. For this analysis, system efficiency is designated for a single vehicle per segment, which is a conservative assumption.

Vehicle energy consumption is defined as the kilowatt-hours per rnile transferred to the vehicle (into the motor controller and into the battery for recharging). This is dependent on the terrain as well as the vehicle weight, velocity, aerodynamics, and the amount of battery charging. A compact vehicle on a flat highway could use as little as 0.10 kwh/mile for propulsion, while a van driving under less ideal conditions might require 0.40 kwh/mile. A large bus or truck at high speed may draw 1 – 2 kwh/mile. For example, the Impact, a compact electrical GM concept vehicle, requires 0.11 kwh/mile at 55 mph. It would generally draw energy for recharging its battery, which might average 25% of the energy required for propulsion, resulting in an average energy transfer rate (or energy consumption) of 0.14 kwh/mile. Vehicle energy consumption is assumed to include some net charging from the roadway, the extent of which is highly dependent on the battery state charge.

All users included in this model are assumed to use the RPEV system the user-specified (average) number of mile per day. Off-system driving and at-home recharging are not included in this model except that some on-system recharging is incorporated in the vehicle energy consumption assumptions.

5.2.3.1 Baseline Vehicle and System Assumptions

We assumed 75% system efficiency. Vehicle energy consumption is based on a vehicle traveling at 60 mph requiring 15 kwh/h. Such a vehicle will draw 0.25 kwh per mile from the RPEV system. Of this, perhaps 0.15 to 0.20 kwh will go to the motor controller and 0.05 to 0.10 kwh will go to charging the battery. Daily system vehicle-miles traveled is 50 miles per vehicle per day on the RPEV system. As pointed out previously, this average is taken across only the vehicles which use the RPEV system on any particular day. If the average were taken across all RPEV's, it would be quite a bit lower, perhaps 10 and 20 miles per day.

5.2.4 Debt

Standard interest-bearing loans are used to finance the capital costs of roadway construction and the subsequent replacement at the end of its useful life. This is a conservative assumption compared to the financing of other transportation infrastructures, as the population of RPEV system users bears the entire cost of constructing as well as operating and maintaining the system. All cost terms used in this analysis are in constant 1992 dollars.

Annual costs are initially higher than revenue due to the large debt service payments. As the user population grows, revenue grows much faster than costs.

5.2.4.1 Baseline Financing Assumptions

A 25-year payback period was used to service the loan. This is realistic and spreads the debt service evenly across the useful life so that costs for replacement were not incurred while original construction was still being serviced.

The interest rate used to calculate annual debt servicing was based on the historical real interest rate of 3.3% [1].

5.2.5 Miscellaneous

The effective rate calculation requires specification of a year by which the cumulative revenue equals the cumulative costs. In this report, the effective rate is defined as the 25-year cumulative breakeven rate. The shorter the allocated period, the higher the effective rate. Annual breakeven price can be expected to decrease as debt servicing is reduced. The contribution of debt service to the annual breakeven price of energy sold decreases with time for two reasons. First, the debt service costs for any particular facility remain constant, but the user populationand VMT and kilowatt-hours sold-increase over time, reducing the dollars/kilowatt-hour required to cover construction loans. Second, when the roadway is rebuilt (25 years after the original construction) the replacement cost and debt service costs are lower than the original construction costs, reducing the annual breakeven price for all years after replacement. Annual revenue flattens out, but does not decline, as the population reaches saturation. Thus, years following the breakeven year are increasingly profitable.

Construction of the RPEV system is described by two variables: the number of years for construction and the number of lane-miles per year retrofitted. Construction is assumed to span the entire year, and the roadway does not become available to users until the following year. The baseline market penetration profiles do not assume any users until one year after the roadway is opened (Year 3).

5.2.5.1 Baseline Assumptions

For the baseline scenario, we have assumed that construction lasts for eleven years and that 104 lane-miles per year are retrofitted (52 miles in each direction or one system-mile per week). A 25-year breakeven period was chosen to spread costs over a large enough quantity of kilowatt-hours sold to bring the costs down to a realistic level. The user population has reached steady state for both time-dependent models with the baseline market penetration profile by Year 25. A longer period to breakeven has some effect on lowering the cost to the user. An earlier breakeven year will raise the costs. Figures later in this report demonstrate this effect.

Roadway construction begins in Year 1. Market penetration in the baseline scenario begins in Year 3. Costs are accumulated for the first two years, but there is no revenue until Year 3.

5.3 Steady State Model (SSM)

The Steady State Model (SSM) represents a one-mile section of a fully deployed RPEV system. All users are assumed to drive the road each day. This model provides a snapshot of a fully saturated system in steady state. Measures of effective rate are not applicable to this restrictive scenario because the system is assumed to be uniformly saturated. The model does not consider startup transients or time dependency, so a steady-state rate at which energy must be sold to breakeven is calculated.

5.3.1 Description

The input variables used by this model are:

- Energy consumption of vehicle (kilowatt-hours transferred to the vehicle per mile)
- System efficiency
- Incremental cost of RPEV roadway (dollars/lane-mile)
- Loan interest rate
- Life of loan
- Number of vehicles (volume/lane/day)
- Wholesale cost of energy (dollars/kilowatt-hour)

The model calculates the breakeven rate as the price at which energy must be sold for revenue to cover all costs. Expenses included in total cost are

- Debt service (interest and principal payment on conventional loan) on construction of roadway
- Energy purchases to service users and to account for system losses
- O&M and Administrative expenses

Energy sold is a function of the number of vehicles and the energy consumption of the vehicle. The wholesale energy required equals energy sold plus losses, with losses depending solely on system efficiency and energy sold. Annual debt servicing is based on the capital cost of the roadway, interest rate, and loan life. Operating costs include administrative and O&M costs. Administration costs are a function of the debt and energy costs. O&M costs are a percentage of the capital cost. The model input format is shown in Table 5.2 and the results output format is shown in Table 5.3.

5.3.2 Results and Analysis

Using the Steady State Model, we have performed a number of trade-off studies involving anticipated costs, financing options, and technological assumptions.

5.3.2.1 Baseline Scenario Cost Results

The cost breakdown for the expenses in the baseline scenario is shown in Figure 5.2. The predominant costs are energy and debt servicing. The wholesale cost of energy is split into the cost of energy sold to system users and the cost of energy lost The cost of energy sold is 46% of total costs, indicating that in steady state, with high utilization of the RPEV system, energy will be sold retail through the RPEV system at approximately twice the wholesale energy cost.

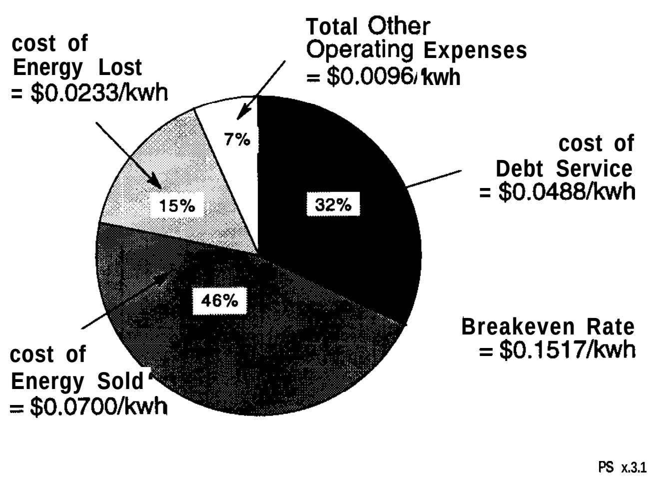


Figure 5.2 Cost breakdown for the expenses in the baseline scenario

Table 5.2
Steady State Model Input Data Format

Steady State One-Mile Model		**Scenario**	________ ______ _____
	INPUT		
Market		**cost**	
________	Volume (vehicles per lane per day)	________	Incremental cost of RPEV ($/lane-mile)
		________	Administration (% of Debt + Energy)
		________	0 & M (% of cumulative new roadway capital cost)
		________	Cost of energy (wholesale $/kwh)
Vehicle Parameters			
________	Energy Consumption of vehicle (kwh/mile)	**Debt Service**	
________	System efficiency (%)	________	Interest rate (real % per year)
		________	Life of loan and life of roadway (years)

Table 5.3
Steady State Model Results Format

Steady State One-Mile Model-Yearly **Scenario** ____________________

Energy Summary	**kwh**		
Total (wholesale) energy			
Energy sold			
Energy lost			
Expense Summary	**$**	**Effective $/kwh Rate**	**%**
Debt service			
Total energy (wholesale price)			
Cost of energy sold (wholesale price)			
Cost of energy lost (wholesale price)			
Operating Expenses			
Administrative			
O & M			
Total cost			
Revenue Summary			
Energy sold (retail price)			

5.3.2.2 Sensitivity with Respect to Interest Rates

The sensitivity of total annual cost to changes in interest rate is shown in Figure 5.3. For example, raising the interest rate from 3.3% to 9.9%, results in an annual increase in total cost of more than 20%.

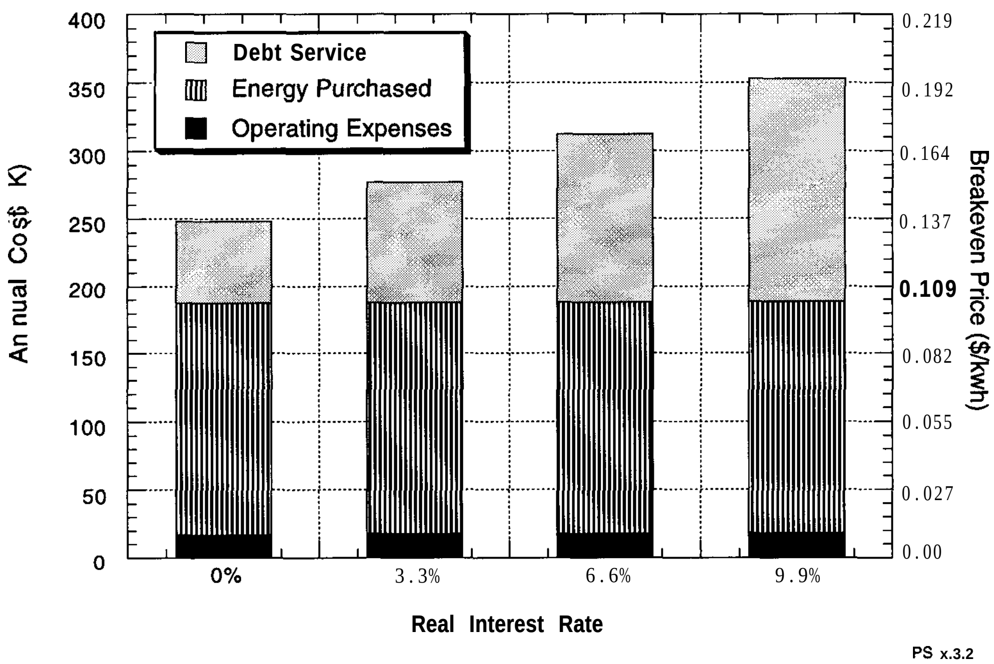


Figure 5.3 The sensitivity of total annual cost to changes in interest rate

Lowering the interest rate from 3.3% to 0% results in a cost reduction from baseline. As can be seen from Figure 5.3, the other components of total annual cost remain virtually constant. Administrative costs, which are a function of debt service, increase by an insignificant amount as the interest rate varies.

For our baseline scenario, a 3.3% interest rate was selected, which represents the real interest rate since the analysis methodology does not consider inflation. Historically, the real interest rate in the United States has remained very close to 3.3%.

5.3.2.3 Sensitivity with Respect to Capital Cost and Wholesale Cost of Energy

The roadway capital cost and the wholesale cost of energy purchased are the two major cost contributors to the total system cost. The rate charged users to make revenue equal costs is called the breakeven rate. For the Steady State Model, the costs and revenues do not vary with time, so all rates-annual, cumulative, effectiveare equal. In the time-varying models (Startup Transient Model and RPEV Economic Model), breakeven is determined by making cumulative revenues equal the cumulative costs by the breakeven year (baseline value is Year 25). For the time-varying models, this cumulative breakeven rate is also called the effective rate. Figure 5.4 shows the range that this rate spans as a result of varying the cost per lane-mile and the wholesale cost of energy.

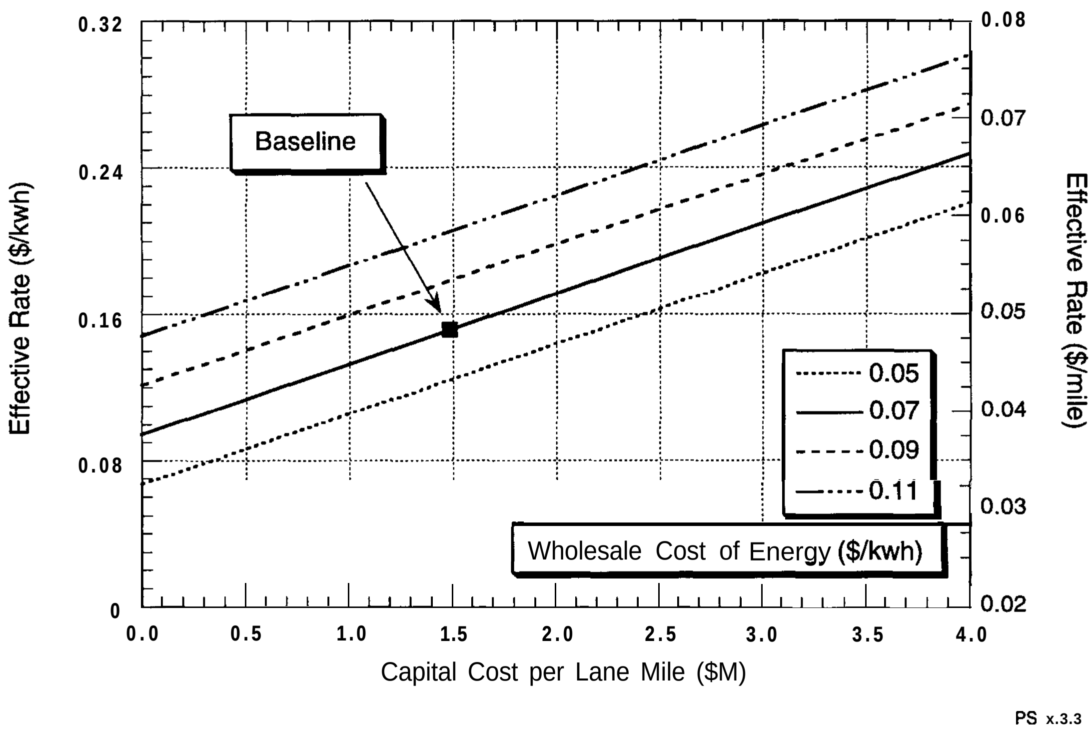


Figure 5.4 Results of varying the cost per lane-mile and the wholesale cost of energy

The baseline scenario assumes capital roadway costs of $1,500,000 per lane-mile and $0.07/kwh for the wholesale cost of energy. The effective rate for the baseline steady state case is $0.1517/kwh, or approximately double the wholesale rate. In cost to the users per vehicle-mile of operation, the rate corresponds to $0.038 per mile. Current energy costs of operating a gasoline-powered vehicle ($1.20/gallon, 25 miles per gallon), are approximately $0.048 per mile. If state and federal gas taxes (about $0.31 per gallon) are deducted from the price per gallon, reducing it to $0.89 per gallon, the resulting energy cost per mile is $0.036, very close to the steady-state rate charged for the RPEV.

The strong effect that wholesale energy cost and roadway capital cost have on the effective rate is demonstrated in Figure 5.4. In the case of the wholesale cost of energy, a decrease from $0.11 to $0.05 results in a retail rate change of approximately $0.08/kwh. Increasing the capital costs of construction from $1,500,000 to $4,000,000 per lane-mile will raise the effective rate by almost $0.10/kwh.

5.3.2.4 Sensitivity with Respect to System Efficiency and Energy Consumption per Vehicle

The less efficient the RPEV system and the more energy required per vehicle per mile, the more energy will be required at the wholesale level. Figure 5.5 shows how these two variables contribute to the total energy requirements. The baseline scenario uses 0.25 kwh/mile for the vehicle energy consumption. The baseline system efficiency is 75%.

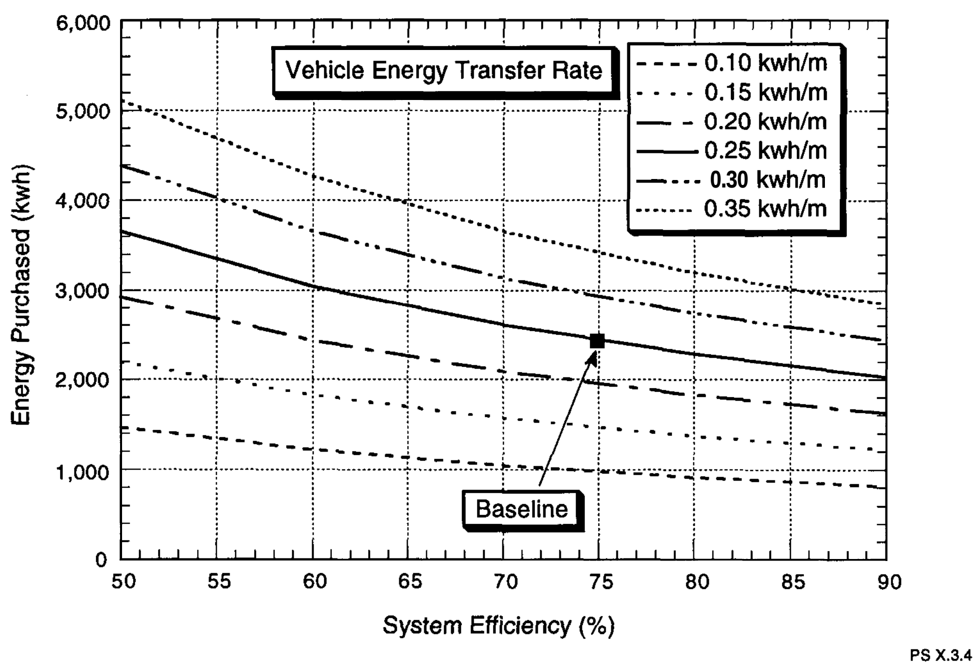


Figure 5.5 Contribution of system efficiency and energy consumption per vehicle to the total energy requirements.

A performance improvement in terms of an increased system efficiency contributes to a lower effective rate because fewer kilowatt-hours are lost. A performance improvement in terms of a decrease in the vehicle energy consumption raises the effective rate because the fewer kilowatt-hours that are required by the users, the higher the price because the debt service costs are distributed over fewer kilowatt-hours. As the users are purchasing fewer kilowatt-hours per mile, the cost to the user in dollars / mile decreases even though the cost in dollars / kilowatt-hour increases. This example demonstrates that care must be used in interpreting results as some trends are counter to one's impulse reaction. In this report we have used both dollar / kilowatt-hour and dollar / mile when discussing rates because users can easily relate to both measures. It should be noted that the energy consumption estimates include a significant amount of battery charging while on the RPEV system, which increases the user cost per mile.

5.4 Startup Transient Model (STM)

The Startup Transient Model (STM) examines the life cycle of one lane-mile of RPEV roadway. The major structural change from the SSM was expansion from a steady-state system that was based on assumptions of high utilization, full deployment, and volume saturation. The STM is a time-dependent model extending 40 years from initial construction. As a result of these enhancements the STM is sensitive to market penetration.

5.4.1 Description

The most significant changes to steady-state conditions from the addition of time dependency into the analysis are reflected in the profile over time of the number of users on the one lane-mile of roadway. The analysis period extends forty years from the year of initial construction. All costs are in constant 1992 dollars.

The market penetration profile is governed by a number of variables that specify population characteristics and limit rates of change. As described in Table 5.1, market penetration is based on an initial number of users in the market start year, which is Year 3 for the baseline. The population on that section increases by a specified number of users each year until saturation is reached. It is assumed that an RPEV vehicle that retires is replaced by another.

Volume on the roadway is limited to a specified number of vehicles per lane per day. The baseline value for the STM is 20,000, which is approximately 80% of the current average vehicles per lane per day on the facilities designated for the RPEV network.

The STM also can regulate the growth rate of new users and the upper limits to new users, both annually and in total. In the scenarios run to support these sensitivity studies, these variables were set high enough so that their limits never affected the number of users.

Revenue resulting from energy sold to users is calculated based on the rate required to break even in the designated year. When cumulative losses exceed cumulative revenue, the deficit must be financed. This is a factor in the early years where significant (albeit decreasing) losses appear. The model finances the debt as an additional interest-only expense at the designated interest rate. When cumulative revenues exceed cumulative costs, it could be argued that the profits should be invested, and the additional revenue recognized. The model, however, makes no attempt to invest cumulative profits. In that sense, by financing the deficit and incurring additional interest expense, but not investing potential cumulative profits, a fiscally conservative bias is applied to the cost results. This is equivalent to assuming that when the system is profitable on a cumulative basis, profits are removed as they are generated.

The input data format for this model is shown in Table 5.4. The output categories are shown in Table 5.5. In addition to a market penetration profile, the STM carries analysis beyond the conservative 25-year life of the roadway. The infrastructure is replaced (at a cost estimated to be one-third less than the original construction costs in constant 1992 dollars). The replacement costs are financed through a loan paid over the useful life of the replaced roadway.

5.4.2 Results and Analysis

Using the Startup Transient Model, we have performed a number of trade-off studies that demonstrate the effects on annual and cumulative costs over time. Cost sensitivities have been evaluated by changing market penetration assumptions, financing options, and wholesale cost of energy.

5.4.2.1 Baseline Scenario Cost Results

Figure 5.6 illustrates the behavior of the important baseline scenario parameters profiled across time. The population can be seen to rise, beginning in Year 3 and growing through Year 11 when vehicle volume on that one mile reaches saturation. Population and energy curves level off at this point. Costs rise until Year 12, and then decrease slowly through Year 25. The cost curve would be flat during this period if interest expense due to cumulative losses were not included. Costs drop very sharply in Year 26 when the original construction loan is completely repaid.

Table 5.4
Startup Transient Model Input Data Format

Startup Transient One-Mile Model **Scenario** ______________________

INPUT

Market Penetration		**Cost**	
________	Market start year	________	Incremental cost of RPEV ($/mile)
________	Initial number of users (per day)	________	Replacement cost ($/mile)
________	Growth each year (Number of new users per day per segment)	________	Administration (% of Debt + Energy)
________	Saturation cap in average vehicle/lane/day	________	0 & M (% of cumulative new roadway capital cost
		________	Cost of energy (wholesale $/kwh)
Vehicle Parameters			
________	Energy Consumption of vehicle ($/kwh)		
________	System efficiency (%)	________	Interest rate (real % per year)
________	Average miles per vehicle per day	________	Life of loan and life of roadway (years)
Miscellaneous			
________	Designated year for cumulative breakeven effective rate calculations	____*____	Breakeven Price ($/kwh)

*Output by Model

Table 5.5
Startup Transient Model Results Format

Year

Population Summary

New vehicles this year
Cumulative live vehicles
Cumulative number including cap
Volume (vehicles/day)
Volume (vehicles/year)

Annual Expenses

Debt service
Wholesale cost of energy
Administrative (1% of debt + energy costs)
0 & M (1% of capital costs)
Operating expenses
Interest on cumulative deficit
Total cost

Annual Cost Components

Debt service
Wholesale cost of energy
Administrative (1% of debt + energy costs)
0 & M (1% of capital costs)
Operating expenses
Interest on cumulative deficit
Total cost

Annual Summary

Energy sold (kwh/year)
Total wholesale energy (kwh/year)
Wholesale cost of energy (total)
Wholesale cost of energy (losses)
Wholesale cost of energy (sold)
Annual profit using specified price
Annual profit at effective rate

Cumulative Summary

Cumulative profit based on specified price
Cumulative profit based on effective rate
Cumulative total cost
Cumulative energy sold
Cumulative interest payment on cumulative loss
Breakeven rate

The difference in total cost between Year 25 and Year 26 reflects the change from original construction to replacement. Total cost reduction is almost exclusively due to the lower loan balance, as both the interest rate and term of the loan are unchanged from the original construction loan.

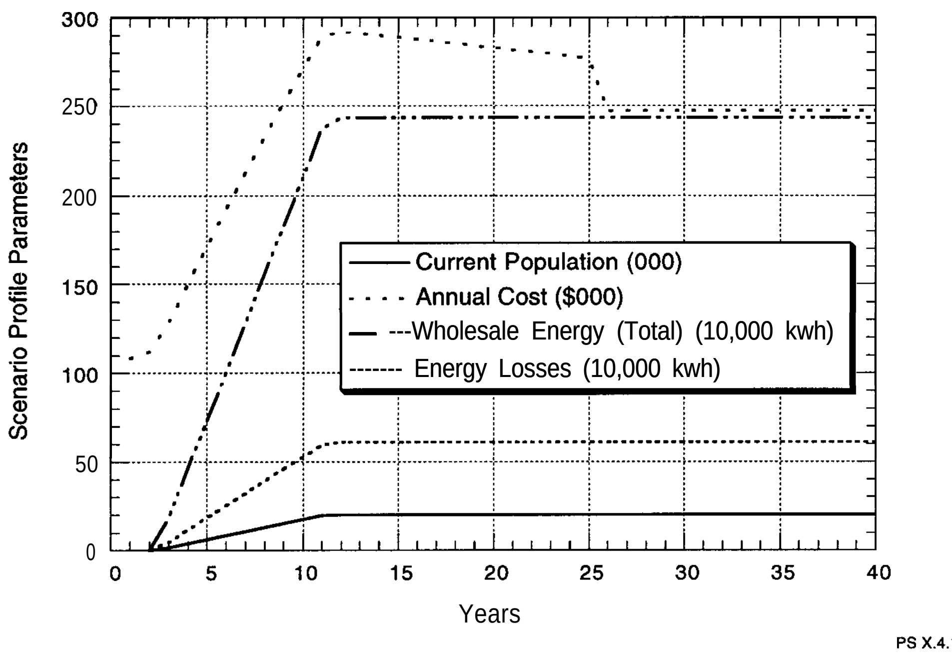


Figure 5.6 Baseline scenario parameters across time

Energy costs are broken into the energy sold to users and the energy lost, which is a direct function of the system efficiency. Energy losses represent the energy purchased at the wholesale level that is not sold to users as retail energy. Losses occur in the power conditioner, distribution network, open roadway, coupled roadway, and vehicle. Energy is sold to users at the rate that the model calculates is required to break even by the year designated. In steady state (after Year 11), the annual energy values are approximately 1800 megawatt-hours sold, 6000 megawatt-hours losses, and 2400 megawatt-hours total.

In the baseline scenario, the system efficiency is 75%. Correspondingly, the energy lost curve in Figure 5.6 is one-fourth of the wholesale energy curve or one-third of the energy sold.

The components of annual total cost are shown in Figure 5.7. Each curve adds to the one below so the curve labeled Wholesale Energy includes Debt Service as well. This convention is followed for all figures that break costs down into its various components.

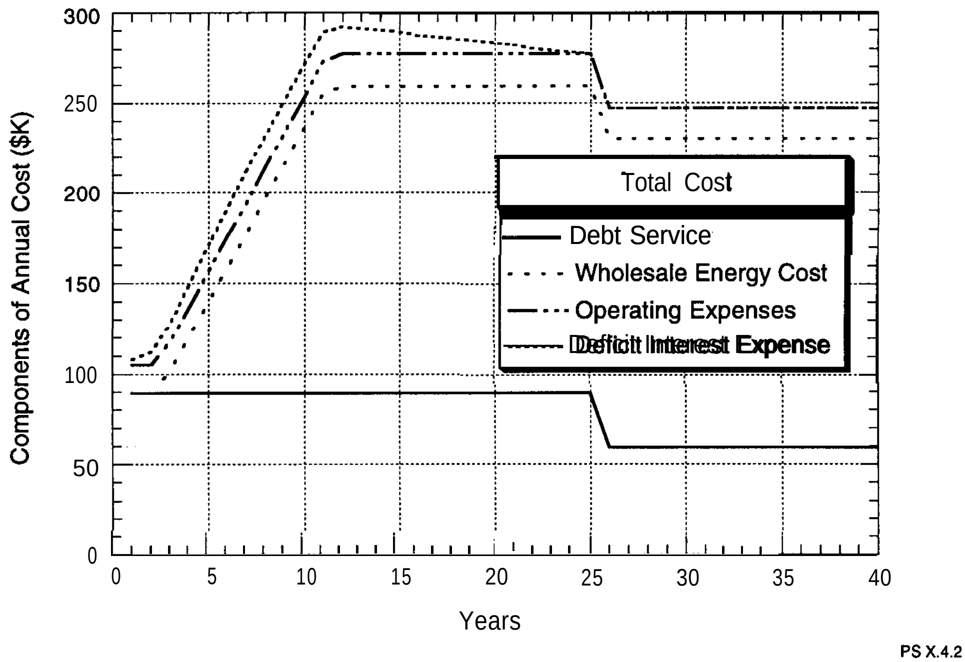


Figure 5.7 Components of annual total cost

The two major cost drivers are Debt Service and Wholesale Cost of Energy. Debt service begins in the first year and continues for 25 years to pay for initial construction. Since we are exarnining only a single lane-mile of roadway, the debt service is constant for the first 25 years. The debt curve drops off in Year 26 due to the lower payments for replacement, dropping by one-third--from $90,000 per year to $60,000 per year.

The wholesale cost of energy includes the energy sold to users and the energy lost by the system. Total energy purchased is a direct function of the user population.

The third term, Operating Expenses, includes maintenance and administration. It is relatively small and nearly constant.

The influence of the interest expense due to cumulative losses on annual cost in the early years is plainly visible. Although the system shows an annual profit in every year after Year 10, cumulative costs are exceeded by the cumulative revenues until Year 25.

Figure 5.8 shows the cumulative contribution these cost components have on the breakeven rate calculations. The sum of all the cost components reflects the rate to break even for that year. This line has leveled off by Year 15 and decreases by less than $0.03/kwh between Years 25 and 40. The baseline point at $0.1785/kwh represents the effective rate that will be charged in all years to break even in Year 25. This corresponds to just under $0.045 per mile and energy consumption of 0.25 kwh / mile.

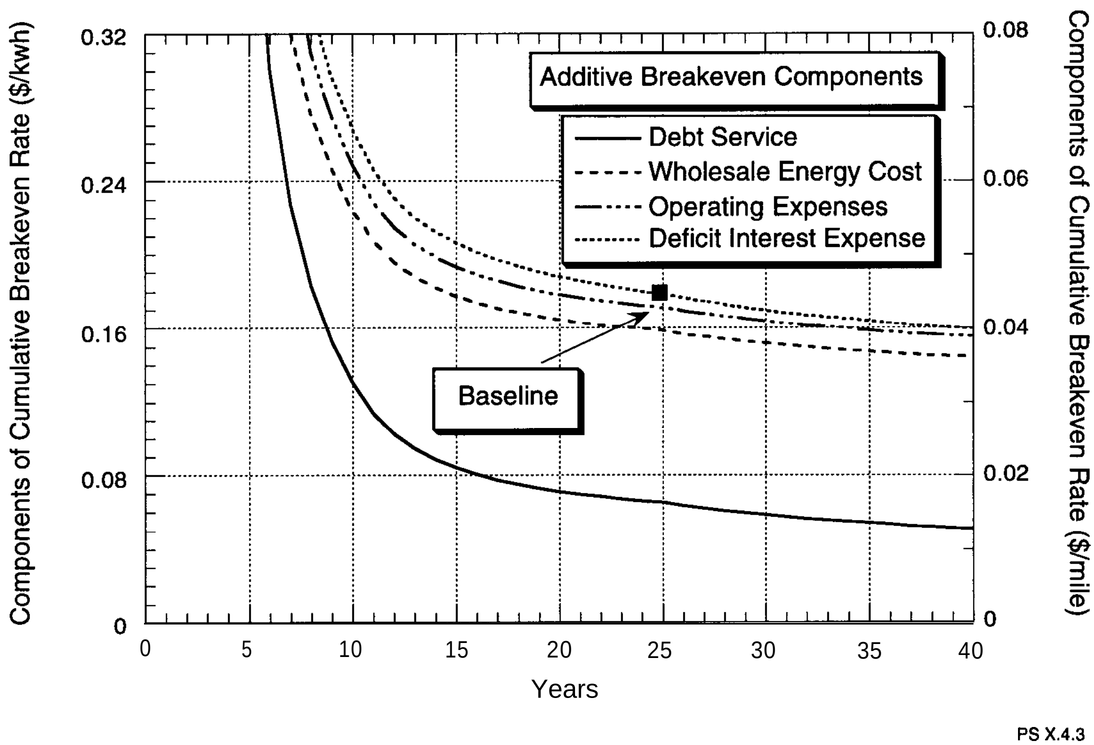


Figure 5.8 Cumulative contribution cost components have on the breakeven rate calculations

Figure 5.9 compares the various rates from the STM and the Steady-State Model. The SSM rate has no time dependence and is shown as a horizontal line at $0.1517/kwh. The annual rate without deficit interest is the rate that would have to be charged each year to cover only that year's expenses. The annual rate levels off in Years 12 through 25 at a rate identical to the SSM. This is expected because the population has reached saturation and the system is in a steady-state condition. After Year 25, the annual rate steps down due to the lower debt service expense.

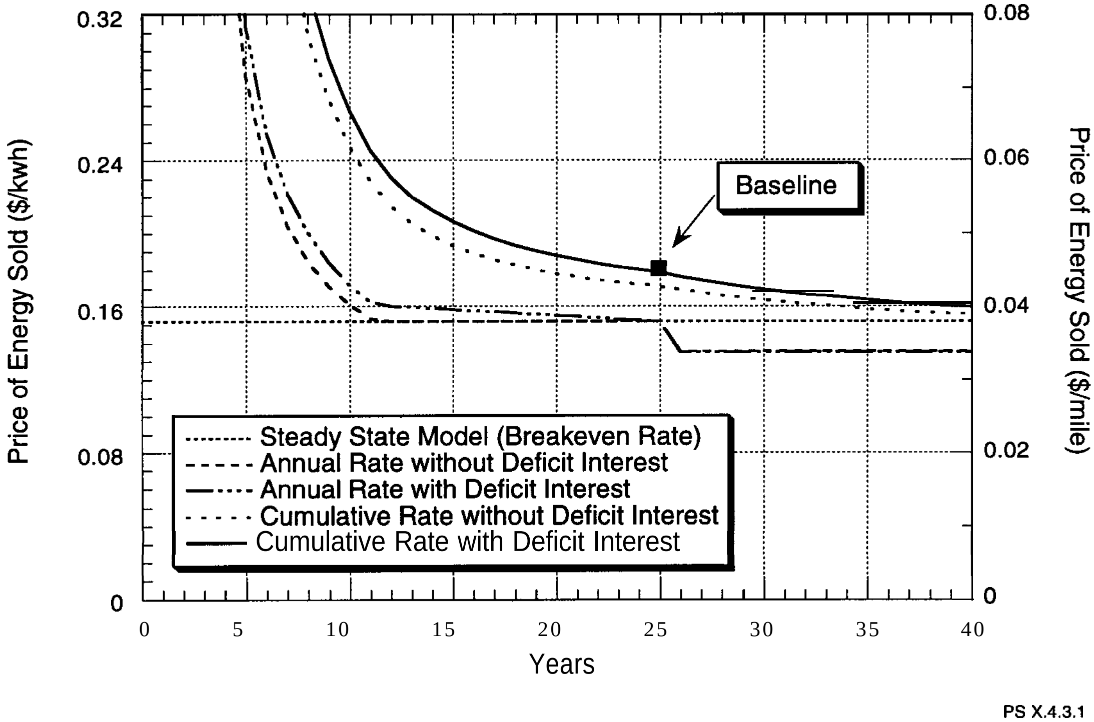


Figure 5.9 Comparison of various rates from the STM and the Steady-State Model

Two cumulative rates are shown in Figure 5.9, with and without deficit interest expense. The annual deficit interest expense, referred to in Figure 5.8, is positive through Year 25. Although the costs in Figure 5.9 are cumulative, and therefore do not decrease, the contribution to effective rate decreases as the cumulative number of kilowatts sold is growing at a faster rate than the cumulative deficit interest. The top curve continually decreases with time although the rate of change decreases substantially by Year 15. Because the Y-axis is range limited, rates during the early years, when the rates are unrealistically high, are not shown.

Figure 5.10 shows the annual cost, revenue, and profit/loss curves. Behavior of the cost curve has been previously discussed. The revenue curve levels off at Year 12 as the population reaches saturation. The system becomes profitable in Year 9 after which profits from each year are used to repay prior losses.

Cumulative costs, revenue, and profit/loss are shown in Figure 5.11. By Year 40, cumulative profits are approaching $250,000. The cumulative profit/loss curve starts rising at Year 10, although it does not reach zero until Year 25. This is a direct result of choosing year 25 as the break even year. Figure 5.9 shows what the required retail price of energy would be to break even earlier. For instance, if a rate of $0.20 were used instead of $0.1785, the breakeven year moves up to year 16. A retail rate of $0.24 moves the brake even year to year 11.5, about the time the vehicle population is reaching saturation. These numbers are actually somewhat conservative, as with a higher retail energy price, the Deficit Interest expense would decrease, and breakeven would actually be accomplished slightly earlier.

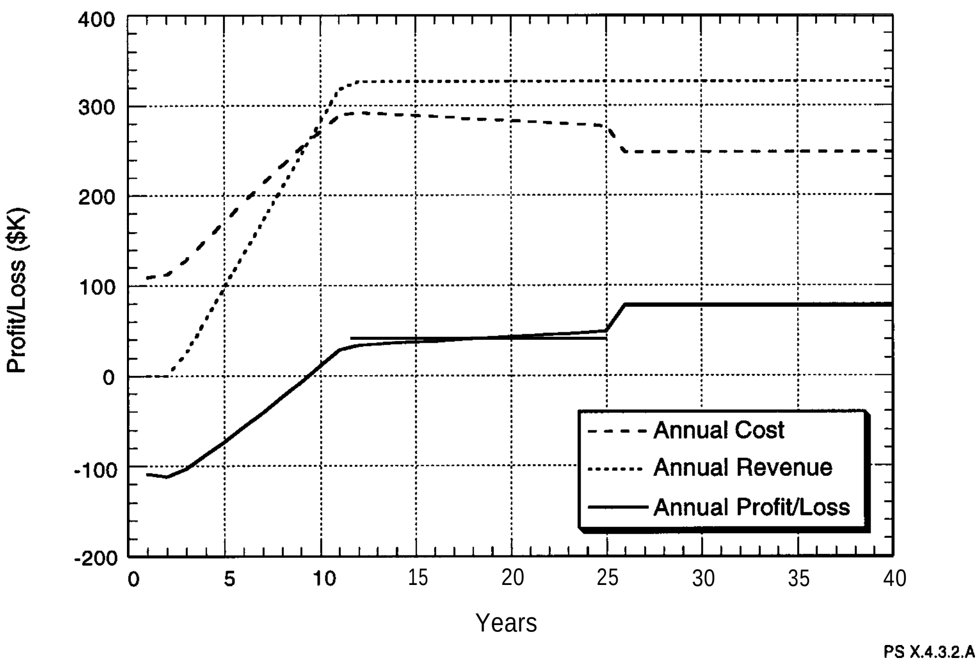


Figure 5.10 Annual cost, revenue, and profit/loss curves

5.4.2.2 Sensitivity with Respect to Market Penetration

Two market penetration scenarios were used to compare the effect on profits that would result if the effective rate were held at $0.1785/kwh (the effective rate calculated in the baseline scenario) while changing market assumptions. The best case allowed 2,000 vehicles on the system beginning in Year 2 and increased the number of new vehicles by 3,000 per year. The worst case pushed back the use of the system until Year 4 and allowed 1,000 vehicles. For the three cases, the population of vehicles grew by 1,500 per year until saturation, which occurs in Years 8, 11, and 17 for the best, baseline, and worst scenarios. Table 5.6 compares the market penetration behavior for the three scenarios. Annual and cumulative cost and revenue curves for the three scenarios are shown in Figures 5.12 through 15.

The retail price of energy is fixed at $0.1785/kwh, so the vehicle population and kilowatt-hours sold are proportional to revenue. When the population saturates, revenue is $325,000 per year for all cases. The slopes of the cumulative revenue curves toward the right of Figure 5.13 are equal because of the constant annual revenue. Annual costs (Figure 5.14) show the same trends as annual revenues, with the Best Sales costs leading the Baseline Sales costs in early years, and curves equal for the later years. Cumulative costs follow the same trends as cumulative revenues, but the cost curves are more closely spaced in the later years.

As indicated by Figure 5.16, cumulative profit for the baseline scenario is negative before Year 25 and positive from then on. The effect of the more aggressive market scenario on profits is shown by the highest curve, and the less aggressive market scenario profit curve by the lowest curve. The market penetration assumptions affect only the revenues and costs in the years before saturation. After saturation, annual costs and revenue are identical for the three scenarios and the lines are parallel. Although the annual revenues after volume saturation are identical, the higher cumulative revenue (due to earnings in the earlier years) for the aggressive scenario is not compensated for later by the less aggressive scenarios. With the Best Sales, the system reaches the cumulative breakeven point in Year 16, a point not reached until Year 32 with the pessimistic market assumptions. The baseline scenario effective rate was used to calculate revenues for the three scenarios.

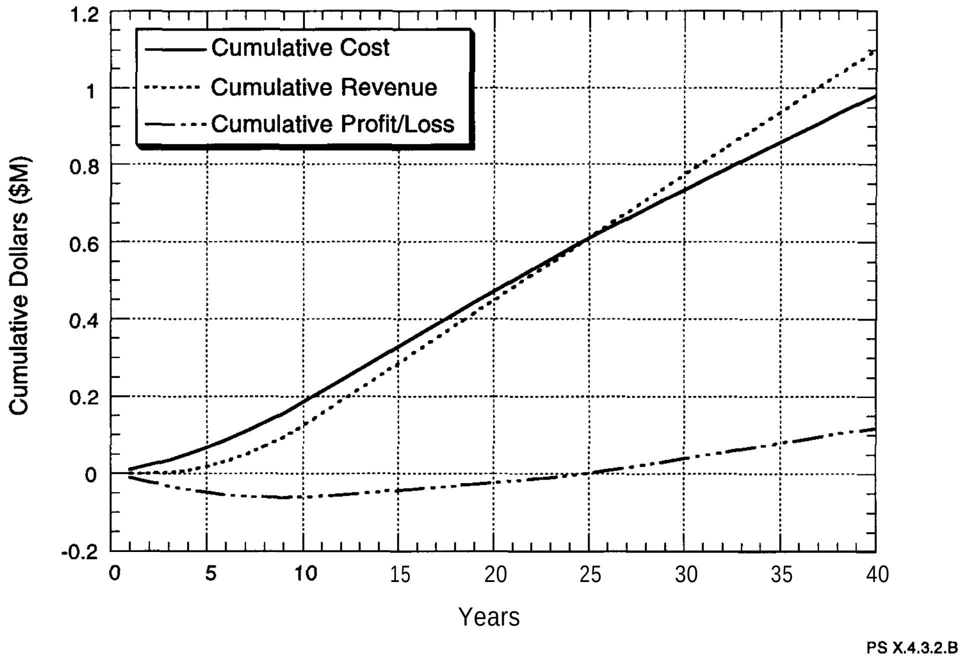


Figure 5.11 Cumulative costs, revenue, and profit/loss curves

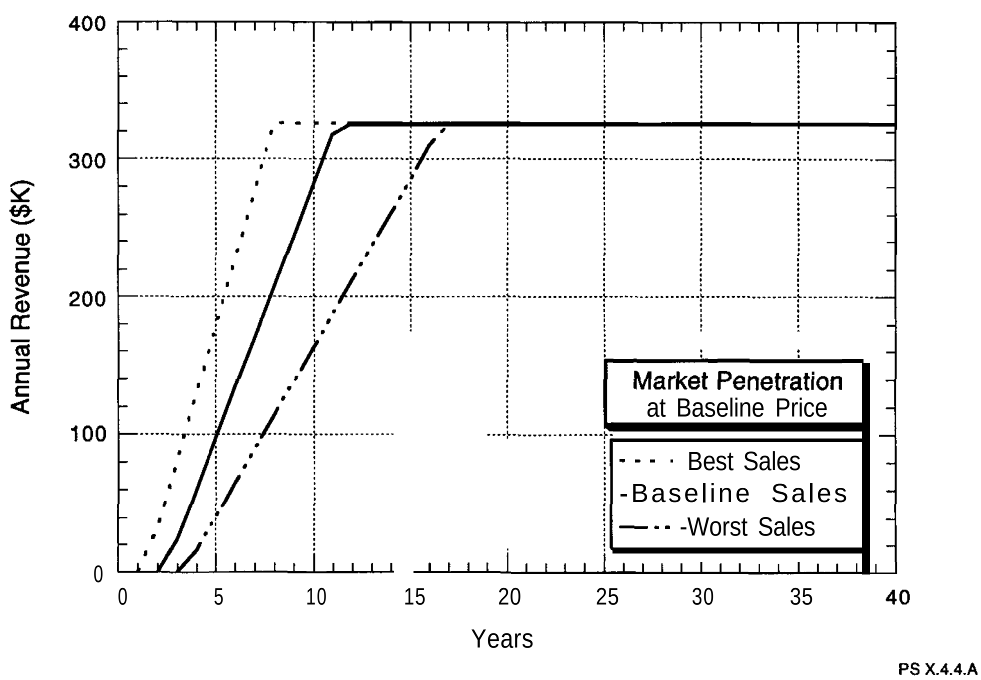


Figure 5.12 Annual revenue

Table 5.6
Summary of Market Penetration Scenarios

Scenario	Initial Number of Users	Yearly Growth of Users	Market Start Year	Year When Full Capacity is Reached	Year When System is Profitable (Annual)	Year When System is Profitable (Cumulative)
Best	2.000	3,000	2	9	6	16
Baseline	1,500	2,250	3	13	9	25
Worst	1,000	1,000	4	18	13	33

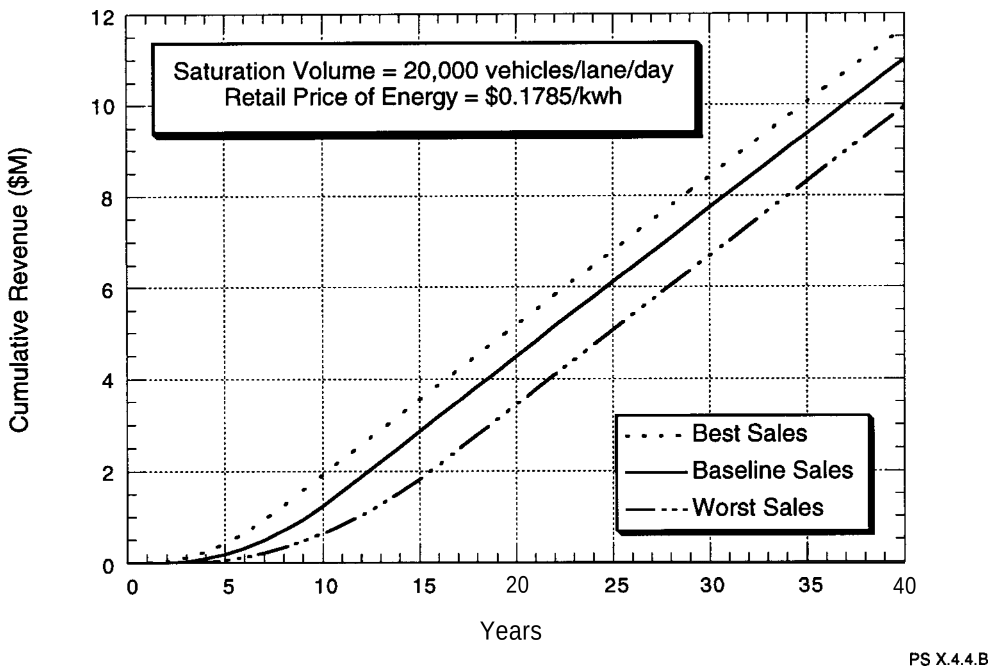


Figure 5.13 Cumulative revenue

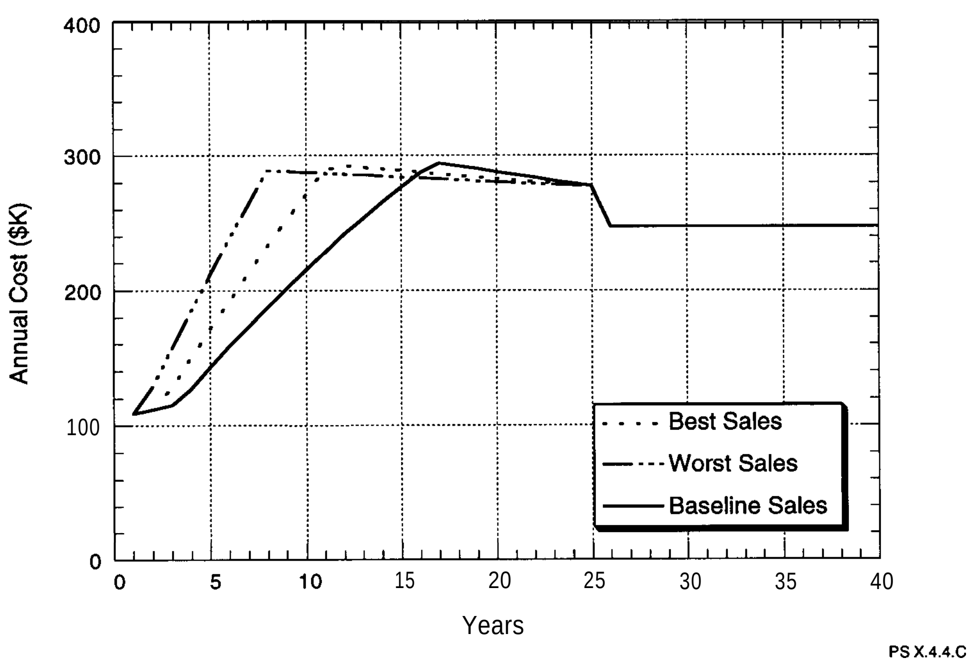


Figure 5.14 Annual cost

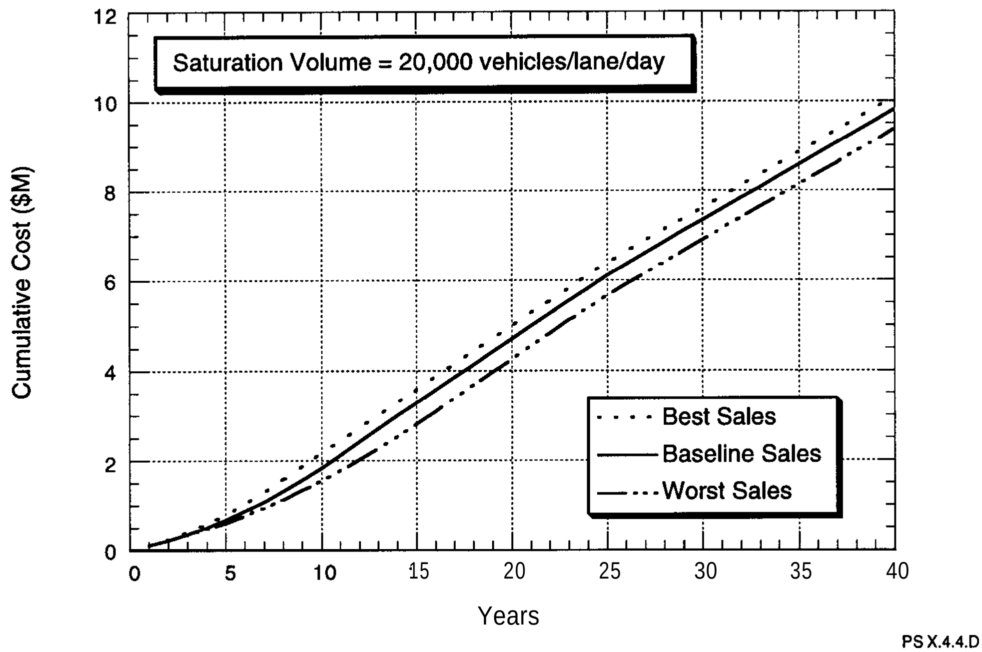


Figure 5.15 Cumulative cost

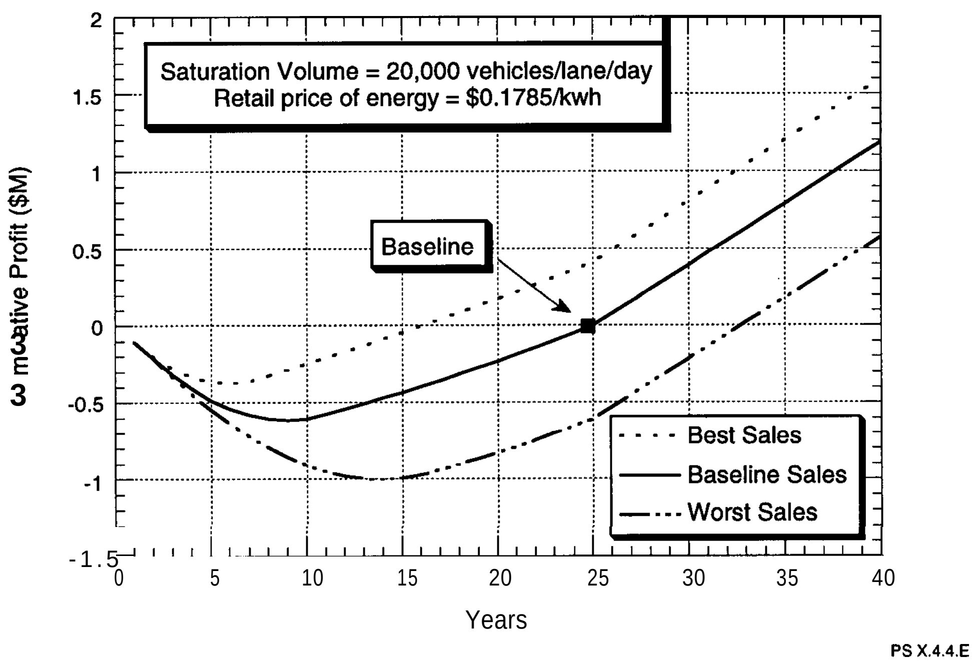


Figure 5.16 Cumulative profit for the baseline scenario

5.4.2.3 Sensitivity with Respect to the Cost of Roadway

The effect of initial roadway cost and replacement cost assumptions is shown in Figure 5.17. Replacement cost is two-thirds of the initial cost per lane-mile. Because of the nature of the debt servicing, changes to the cost are not realized during the period of construction. The effect of the capital cost assumption is spread over the period of the loan, and the magnitude of the change is only partially shown by the cumulative cost at Year 40. There is debt remaining on the loan to finance the roadway replacement (performed in Year 26 and financed with another 25-year loan) that is not paid until Year 50. As is apparent from the figure, costs can double from approximately $8,000,000 to $16,000,000 over the lifetime of the system as roadway construction price is raised from $1.0 to $4.0 million. Since the debt service represents more than one-third of the total cumulative costs, quadrupling the construction cost (and debt service costs) doubles overall costs. The effect of the pricing scenarios on the effective rate required to break even by each year is indicated in Figure 5.18. Doubling the price of the roadway from $1,500,000 to $3,000,000 per mile increases the 25-year breakeven price by approximately 50%, from $0.18 to $0.27/kwh again because debt service represents nearly 40% of cumulative costs in Year 25 for the baseline case.

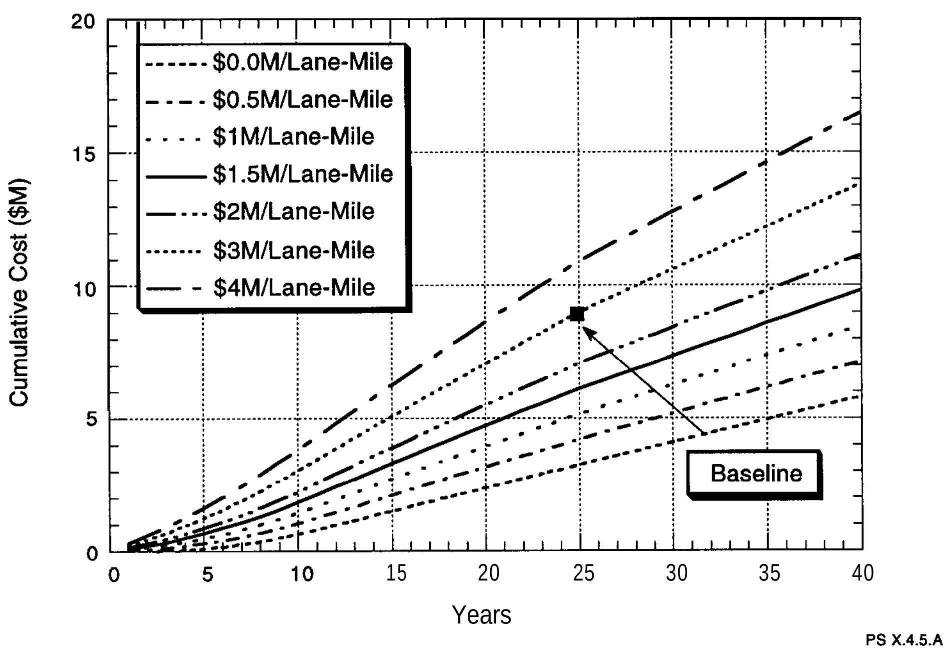


Figure 5.17 Effect of initial roadway cost and replacement cost assumptions

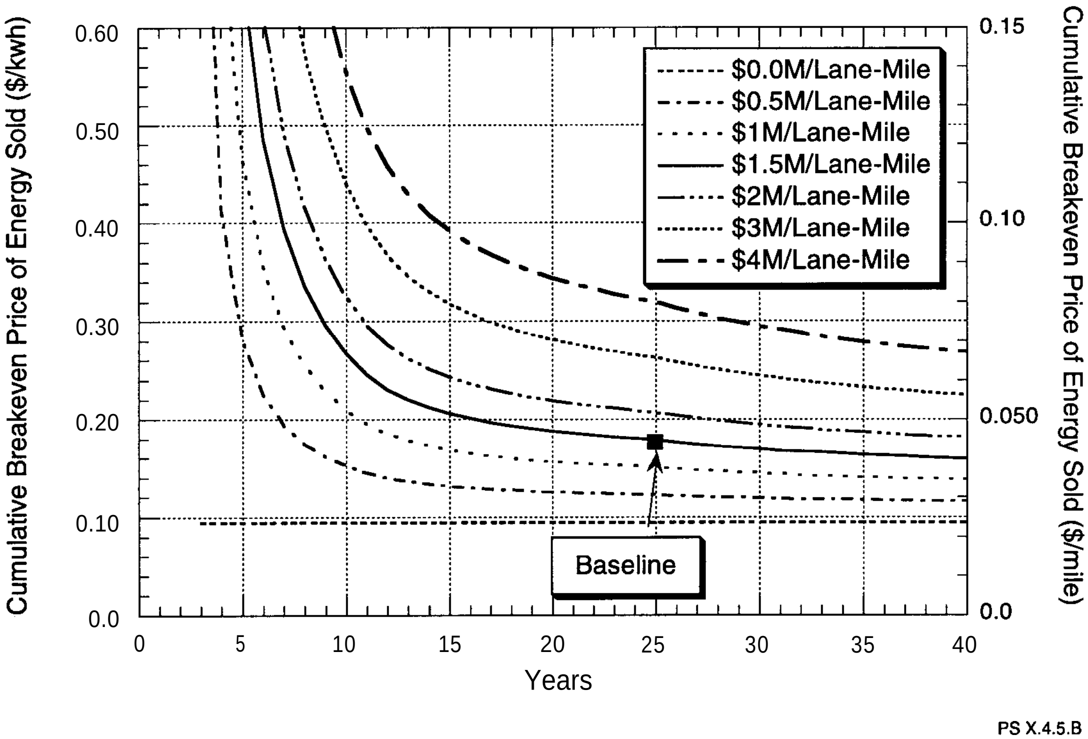


Figure 5.18 Effect of the pricing scenarios on the effective rate required to break even by each year

5.4.2.4 Sensitivity with Respect to the Cost of Energy

The single largest component to the breakeven rate is the wholesale cost of energy. Figure 5.19 shows the breakeven retail rates of energy based on wholesale cost of energy ranging from $0.05 to $O.ll/kwh. A decrease in the wholesale price of energy from $0.07/kwh to $0.05/kwh will cause the effective rate to drop by $0.0267/kwh. The leveraged effect of the wholesale cost on the effective rate is due to system losses, For every kilowatt-hour of energy sold at the retail level, 1.33 kwh (equal to 1/0.75, the system efficiency) must be purchased at the wholesale level. A change of $0.02/kwh then requires a price change of $0.02/0.75 or $0.02667/kwh at the retail level. If wholesale energy cost $0.05/kwh, then the cost to the users would decline to almost $0.15/kwh. All curves are parallel and show the same downward trend with respect to breakeven year as previously seen.

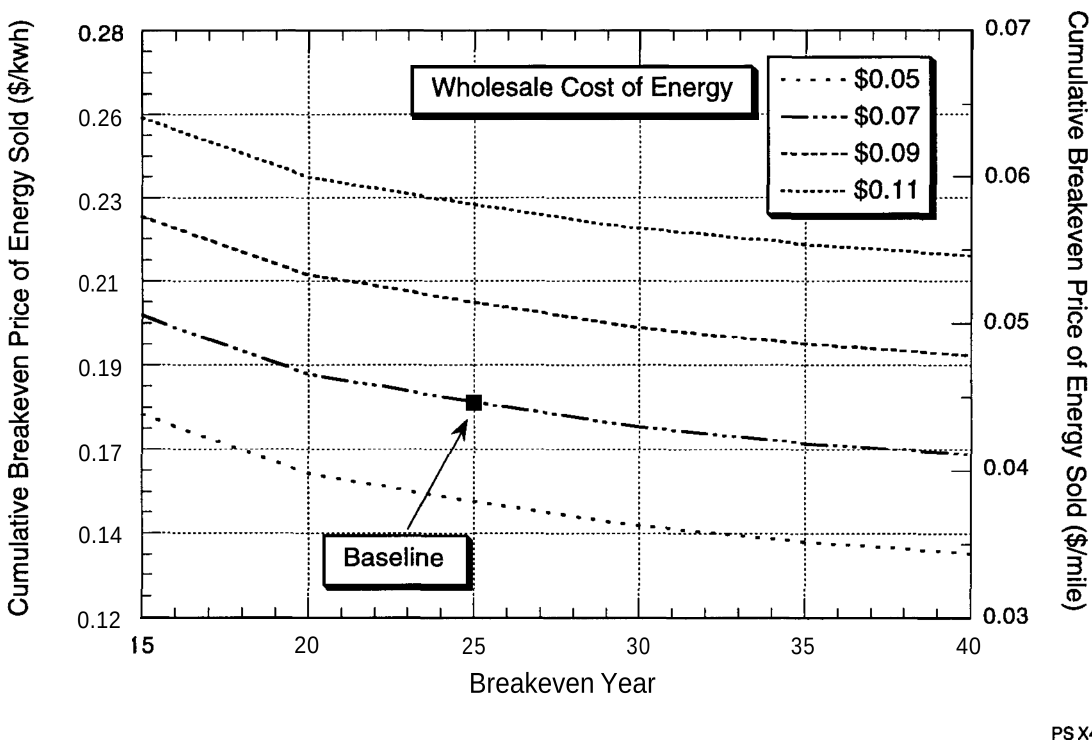


Figure 5.19 breakeven retail rates of energy based on wholesale cost of energy ranging from $0.05 to $0.1 1/kwh

5.4.2.5 Sensitivity with Respect to Market Penetration and Saturation Volume

The effects of market variables on the breakeven rate for Year 25 are shown in Figure 5.20. As the saturation volume increases, the breakeven price of energy decreases. Similarly, an earlier market start year reduces the cumulative breakeven rate. The breakeven rate is reduced by $0.02/kwh if the saturation volume is increased to 30,000 vehicles per lane per day from the baseline figure of 20,000. The curve is not linear so a saturation volume reduction of 5,000 vehicles (from the baseline value of 20,000 per lane per day) increases the breakeven price by $0.02/kwh.

Delaying the initial use of the system from Year 3 to Year 6 increases the 25-year breakeven rate $0.02/kwh. The effect of market start year on breakeven rate is only weakly dependent on saturation volume. This is indicated by the nearly uniform spacing of the curves in Figure 5.20.

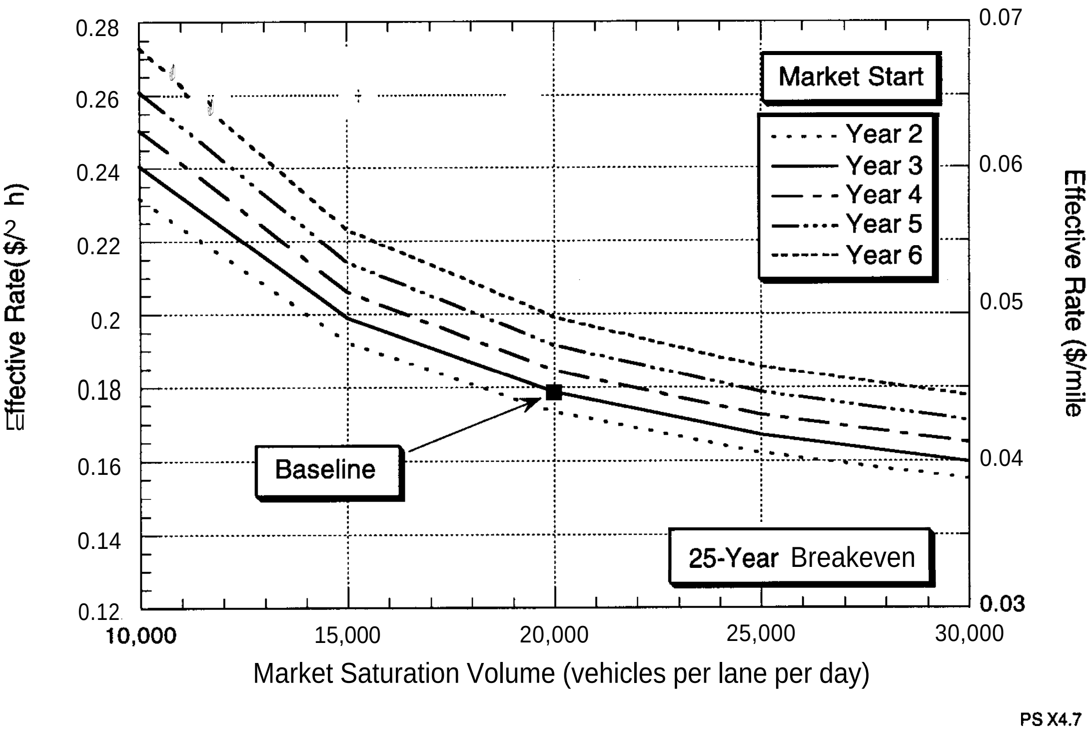


Figure 5.20 Effects of market variables on the breakeven rate for Year 25

5.4.2.6 Sensitivity with Respect to Financing Terms

After the wholesale cost of energy, debt service has the most influence on the breakeven rate. Debt service costs depend on the loan balance (examined in Figures 5.s 17 and 5.18) and the financing terms. Figure 5.21 shows the sensitivity of annual cost with respect to interest rate. The cost curve is flat during the period of initial loan payback in Years 12 through 25 for a 0% interest loan. This is the period during which the early losses are being recovered. The negative slope during this period for curves based on an interest rate greater than 0% are the result of the interest on the debt due to cumulative deficit. The slight non-linearity through Year 11 is also due to the additional interest component. Because the cumulative deficit has disappeared by Year 25, the cost curves are flat from then on.

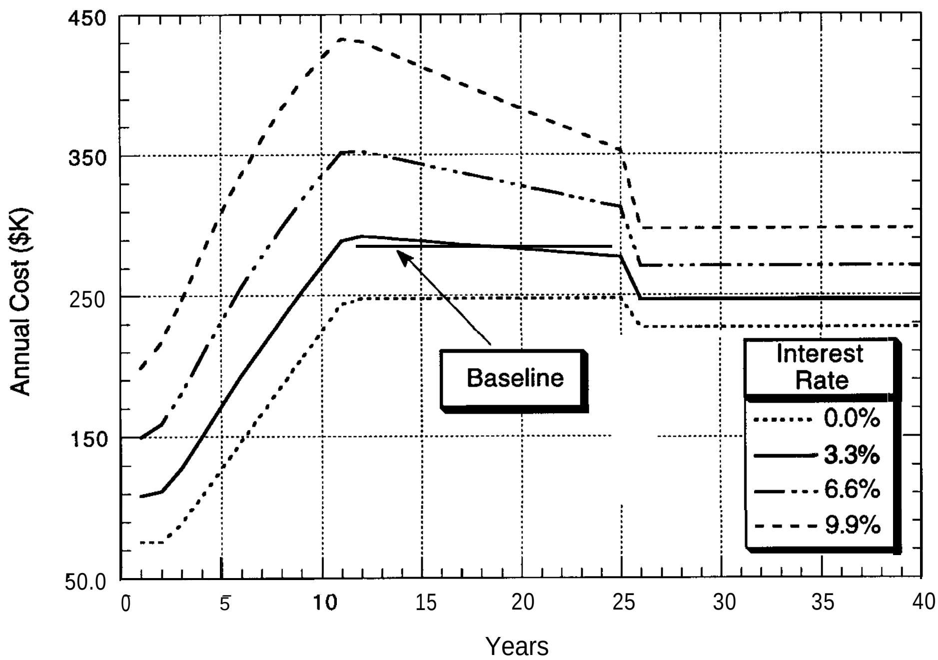


Figure 5.21 Sensitivity of annual cost with respect to interest rate

The effect of the financing terms is to almost double the annual cost for an interest-free loan versus a 9.9% loan. Even an interest-free loan is a conservative financing assumption based on the typical way transportation systems are funded. For our baseline scenario, we have assumed an interest rate of 3.3%, which is very close to the post-war average real cost of money (prevailing interest rates minus the rate of inflation). Since the models assume no inflation, all costs are in constant 1992 dollars and there is no need to discount future costs.

The effect of loan life on the effective rate is shown in Figure 5.22 for several different breakeven years. The baseline scenario uses 25 years for the breakeven calculations and a 25-year loan life. The effect of a shorter breakeven period is apparent as the 15- and 20-year curves have considerably higher breakeven rates. A loan life of 25 years provides the maximum period for payback without overlapping construction and replacement costs for any section.

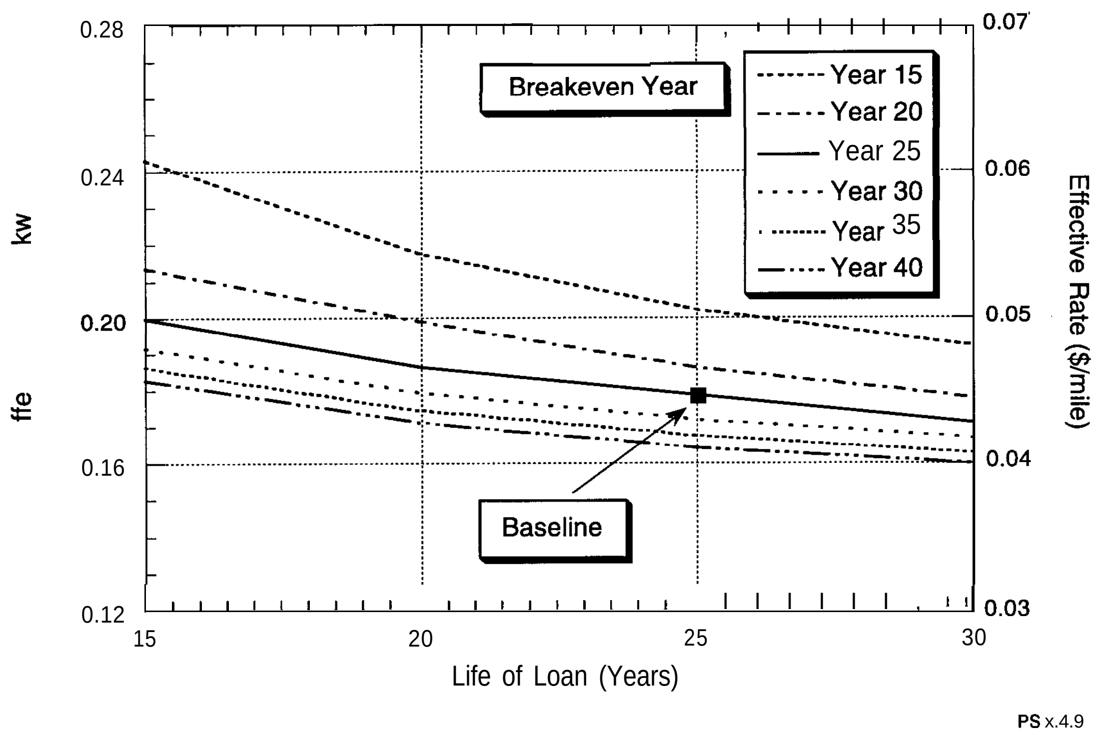


Figure 5.22 Effect of loan life on the effective rate

5.4.3 STM and SSM Comparison

The addition of time dependence in the Startup Transient Model has two significant impacts on the breakeven price of energy sold. The first is the addition of a term to cover interest on the losses incurred during the early years when there are few or no users of the system, yet the original construction loan must be serviced. The second impact is that the average user population over the first 25 years is lower than the steady state user population. The debt service costs (and to a lesser extent, operating costs of administration, operations, and maintenance) are spread over a smaller number of users, increasing the cost per user (or per kilowatt-hour).

The first term, Deficit Interest, reaches a maxirnum in Year 9, just before the system becomes profitable on an annual basis as seen in Figure 5.10. Figure 5.9 showed how this gradually reduces to zero on an annual basis. Figures 5.23 and 5.24 show the STM components for annual costs in Years 20 and 25, respectively.

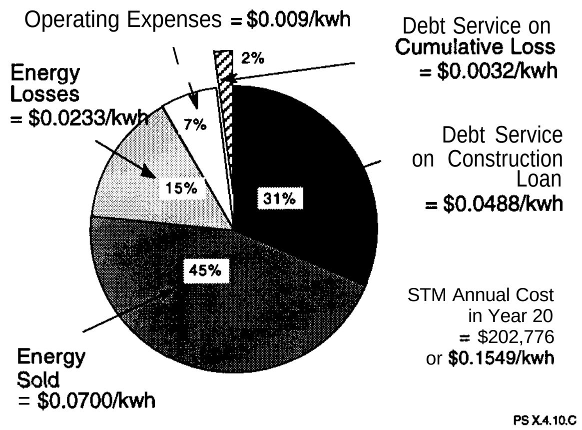


Figure 5.23 STM annual costs in Year 20

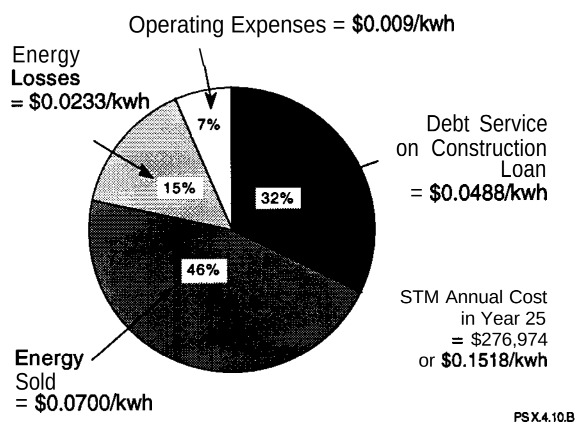


Figure 5.24 STM annual costs in Years 25

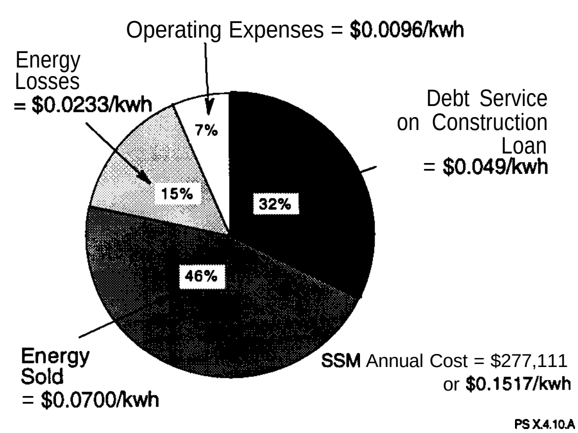


Figure 5.25 STM costs match the SSMin Year 25

In Year 20, 2% of the annual costs or $5,802 are allocated to covering interest on the cumulative deficit as shown in Figure 5.23. By Year 25 (Figure 5.24), that cost has disappeared because there is no longer a cumulative deficit.

By Year 20, the system is stable because construction is complete and the user population has reached saturation. This is shown by subtracting the $5,802, which results in $276,974, the annual cost for Year 25. These costs match the costs and percentage cost components from the steady-state model, as shown by Figure 5.25.

During the first 25 years, 136,700,000 vehicle-miles are traveled on one mile of roadway with the STM baseline market penetration assumptions. This yields a daily average of 14,980 vehicles, about 25% lower than the baseline saturation volume. This requires that fixed costs (primarily debt service of construction loan but to a lesser extent maintenance costs) be split among fewer kilowatt-hours. Figure 5..26 shows the components of the STM effective rate. Comparing it with Figure 5.25 from the Steady State Model, the largest increase is in the Debt Service of $0.0163/kwh, due to the lower average vehicle population. Debt Service on Cumulative Losses (Deficit Interest) at $0.0074/kwh is the second-largest contributor to the increase from the SSM to the STM. Operating Expenses increase only $ 0.0030/kwh, and energy costs show no change.

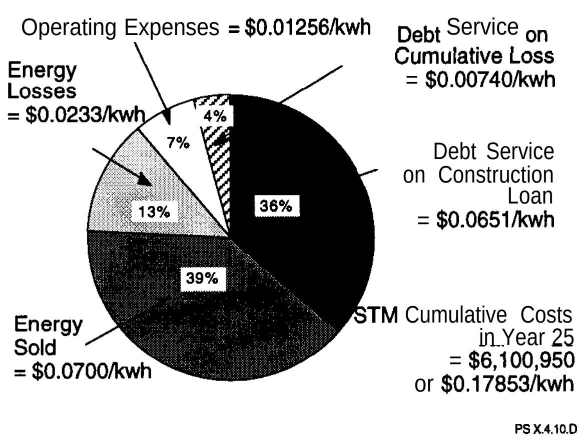


Figure 5.26 Components of the STM effective rate

5.5 RPEV Economic Model (REM)

The technical and market assumptions used in the Start-up Transient Model (STM) have been extended to incorporate an entire RPEV network in the LA Basin. The STM was based on a one-mile section of roadway, and all users were assumed to travel that one-mile portion each day. The changes to the STM required for an economic model of an entire network fall in two areas: assumptions regarding user behavior (e.g., vehicle miles traveled per day) and construction of the roadway network (e.g., number of years of construction, miles per year).

The resulting model is a scaled-up extension a single mile of roadway to a network of RPEV-equipped freeway lanes. Instead of one mile of RPEV built in Year 1, there is a flexible construction schedule. Implementation is based on the number of miles of roadway built annually and the number of years of construction. The market penetration profile and assumptions for the one mile of roadway in the STM are replicated for each new section of roadway.

5.5.1 Description

The RPEV Economic Model (REM) is a time-dependent model spanning 40 years of RPEV costs and revenues. The model incorporates a variable construction schedule that includes initial construction as well as replacement.

The REM is a more flexible model than the STM with separate sub-models for debt servicing, market penetration, construction, and replacement. It is a more general model than the STM in the sense that it can be used to examine specific candidate RPEV sites and will support a phased-in construction schedule.

5.5.1.1 Construction Schedule

Roadway construction is controlled by two variables: the number of lane-miles built per year (referred to as a section) and the number of years for initial construction. The product of these two variables gives the total system lane-miles. Roadway sections are replaced after a useful life using the same construction schedule. Replacement cost does not contribute to O&M expenses. For the baseline scenario, replacement costs are two-thirds of initial construction costs.

5.5.1.2 Financing

The financing assumptions used for the REM are identical to those used in the STM. A conventional long-term loan is used to finance the entire expense of the construction and operation of the RPEV network. The debt model is based on interest rate, loan life, and principal amount. The debt service for any given year is a function of these variables relating to construction in that year and the debt obligations resulting from past years' construction. While the system is cumulatively unprofitable, debt service also includes interest expense required to finance a deficit. The debt model is sensitive to:

- Capital cost per lane-mile

- Number of miles constructed per year
- Roadway construction and replacement schedule
- Financing terms (interest rate and loan life)
- Changes in revenue that will affect profitability

5.5.1.3 Market Penetration

The REM market penetration model is based on the STM model and replicated for each section of roadway. In this way, the number of users on any section of roadway follows the profile described in Section 4.1. An alternate model, in which the number of new vehicles each year increases by a specified percentage from the number of vehicles purchased in the previous year was coded but used only briefly. The alternate model provides for geometric growth and is somewhat cumbersome when it reaches market saturation. The STM model with linear user growth on each section was chosen because it directly links the number of users to the roadway available and ensures that the number of users on each section stays at or below the saturation level. It also allows for easy comparison of STM and REM results.

A roadway section is the amount of roadway completed each year. In the baseline scenario, one system-mile (one lane mile in each direction) is built per week, resulting in sections of 104 lane-miles. The RPEV network selected consists of 1,144 lane-miles and takes 11 years to build. Users populate the system according to the specified profile, with baseline values of zero users the second year, approximately 1,500 users daily on each lane-mile of roadway the third year, and 2,250 additional users on each lane-mile of roadway each year until saturation is achieved. Saturation is achieved on each section 11 years after it is built. System saturation occurs in Year 22. System saturation amounts to 22.9 million VMT daily on the electrified system. Using our assumed 50 miles per user, this corresponds to about 450,000 users each day. The average of 50 miles is assumed because people with RPEV's will be able to make short trips using their battery exclusively. If the vehicles with a low total daily mileage are eliminated from the distribution of all vehicles, the remaining vehicles (those that use the RPEV system on any given day) have a relatively high average daily mileage, hence a high on-system average.

The same VMT could be accumulated with a lower daily on-system mileage and more users. For instance, during Year 3, we have assumed 3000 users on the system daily, each traveling 50 miles. This equals 150,000 daily VMT on the system. This could be as easily be accomplished by 3000 users at 50 miles per day (our baseline assumption) or 5000 users each traveling 30 miles on the system daily. All system economic statistics

(VMT, kilowatt-hours, individual cost components, total system cost, etc.) are identical either way, resulting in the same breakeven price of energy to be charged to the users and same revenue.

The economic analysis also is independent of the number of RPEV owners who choose not to use the RPEV system on any given day. As was shown in Figure 1 at the beginning of this chapter, there will be some RPEV's which aren't operated on the system on any given day. As far as this analysis goes, if certain RPEV's don't use the system on the particular day that we are examining, they are ignored. For instance in Year 3, there may be 3,000 users each of whom drive 50 miles a day on the system. There could be 6,000 RPEV's who drive 50 miles every other day. There could be 2,000 users who use the system every day (for 50 miles) and 2,000 who drive 50 miles on the system every other day. There could be 2,000 who use the system every day and 10,000 who use the system only one day in ten. Each of these scenarios results in 3000 users daily, with 50 miles driven on the system (or more importantly, 150,000 daily VMT). The analysis depends only on the average daily system VMT, not the distribution of trip lengths, total number of RPEV's, or frequency with which any particular RPEV is driven.

One advantage to the approach used is that population growth cannot cause an over-capacity condition. Changes made in the construction assumptions (e.g., lane-miles constructed per year or number of years of construction) are automatically accounted for realistically in the market penetration conditions.

The REM examines a regional RPEV system and is useful to determine not only the number of users on each mile of roadway, but also the total number of vehicles equipped to use the RPEV system. This is accomplished by determining an average daily number of miles traveled on the RPEV system by each vehicle. Two 25-mile trips a day are assumed for each vehicle, which means that two vehicles, each traveling on the system 50 miles a day, will generate nearly one system-vehicle-mile per lane-mile for a 104-mile section. This allows the STM user profile to simply be doubled to determine the number of vehicles required to generate the VMT consistent with the user profile. For example, instead of 1,500 users in Year 3 (as in the STM), the initial number of users is 3,000 in the REM. This is examined in greater detail in Section 5.1.4.

Figure 5.27 shows the cumulative effect of the net number of new vehicles per year (not including replacements due to retirees). Following each of the eleven years of construction, an initial number of users populates a section of roadway. Each year from then on, the population per section grows by the same amount until saturation. The population of each section saturates at a volume of 20,000 vehicles per lane per day. Although construction is completed by the end of Year 11, the population increases until

Year 23. The number of vehicles operating on the section built in Year 4 (lower solid line) remains at zero until Year 6, a one-year delay from the time the section is completed and open for traffic. There are 3,000 vehicles in Year 6, and 4,000 new vehicles per year until saturation is reached in Year 16, twelve years after construction.

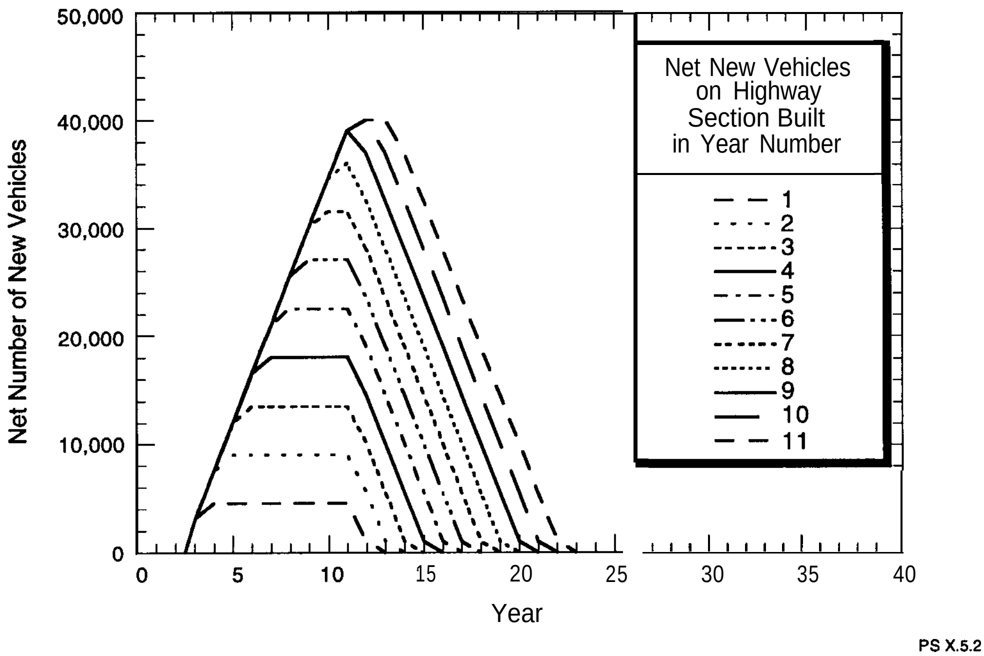


Figure 5.27 Cumulative effect of the net number of new vehicles per year

The model assumes that all retired vehicles are replaced by another RPEV vehicle. The per vehicle costs are solely in terms of the current population (not cumulative new vehicles) and vehicle miles traveled assumptions. The new vehicles that will be purchased are shown in Figure 5.28, which simply adds replacement vehicles to Figure 5.27. New vehicles purchased per year is the sum of the new vehicles due to population growth and the number purchased as replacements for retired vehicles. The effect on the population of users is shown in Figure 5.29. The population grows through Year 22 and remains constant from then on. The vehicle profile for Year 1 in Figure 5.29 matches the STM user profile (Current Population) from Figure 5.6, except for the factor of two required to account for the fact that it takes two vehicles at 50 miles per day each to accumulate one vehicle-mile per lane-mile on a 104-mile section.

5.5.1.4 Baseline Scenario

The baseline scenario assumes that two lane-miles can be built each week and that construction continues for eleven years, resulting in 1,144 lane-miles. Such a system is shown in Figure 5.30.

The debt financing, saturation limits, market penetration profile, technical assumptions, and costs from the baseline STM are incorporated into the REM baseline. A summary and discussion of the baseline variables are presented in Section 2.4 and in Table 5.1. Unlike the first two models, which were reduced versions of the economic model, the REM uses all these variables. The values shown are intended to replicate the system modeled by the STM as closely as possible. Where differences exist, the differences are due to the 104 miles per year under construction in the REM and that the STM models only one mile. In all cases, the user volume compared to the miles of roadway operational are equivalent, so the results are comparable.

The vehicle miles traveled per lane per day is nearly the same for the baseline cases of the STM and the REM. The REM assumes that a standard trip is taken by each vehicle each day.

The baseline scenario assumes that each section is replaced after a 25-year life. Therefore, the replacement schedule matches, but lags, the construction schedule. Initial construction cost per lane-mile is $1,500,000. Replacement costs are assumed to be two-thirds of the initial construction cost or $1,000,000 per lane-mile.

The results format, which spans the system life cycle of 40 years, is shown in Table 5.7. The System Summary portion of this format provides data on the roadway and population status. Costs and energy utilization are tracked across time, both annually and cumulatively and are provided in terms of itemized expense and revenue dollars as well as dollars / kilowatt-hour, dollars / mile and dollars / vehicle.

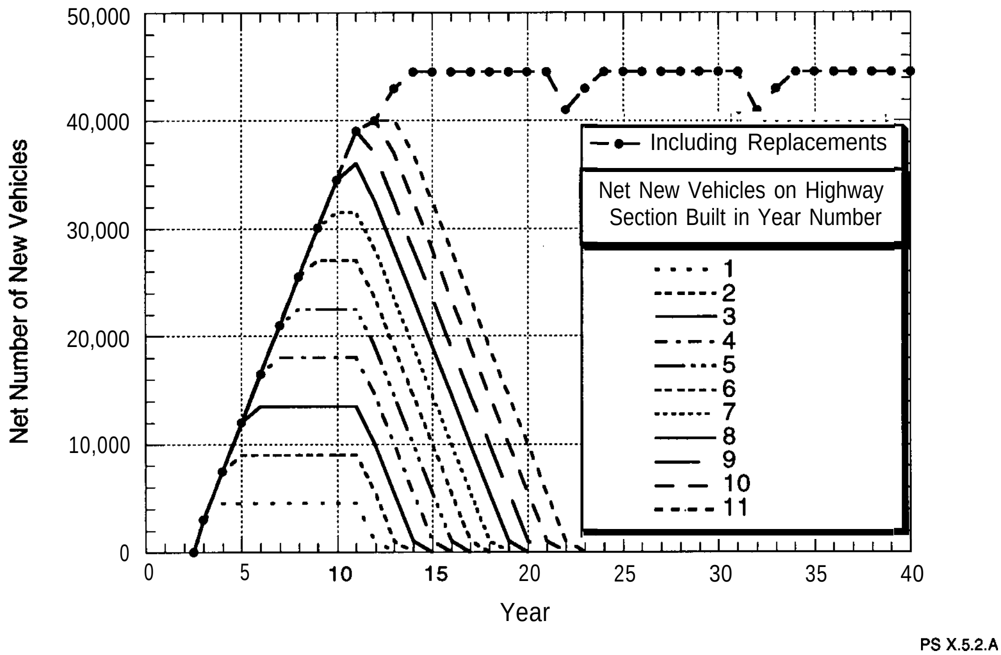


Figure 5.28 New vehicles purchased

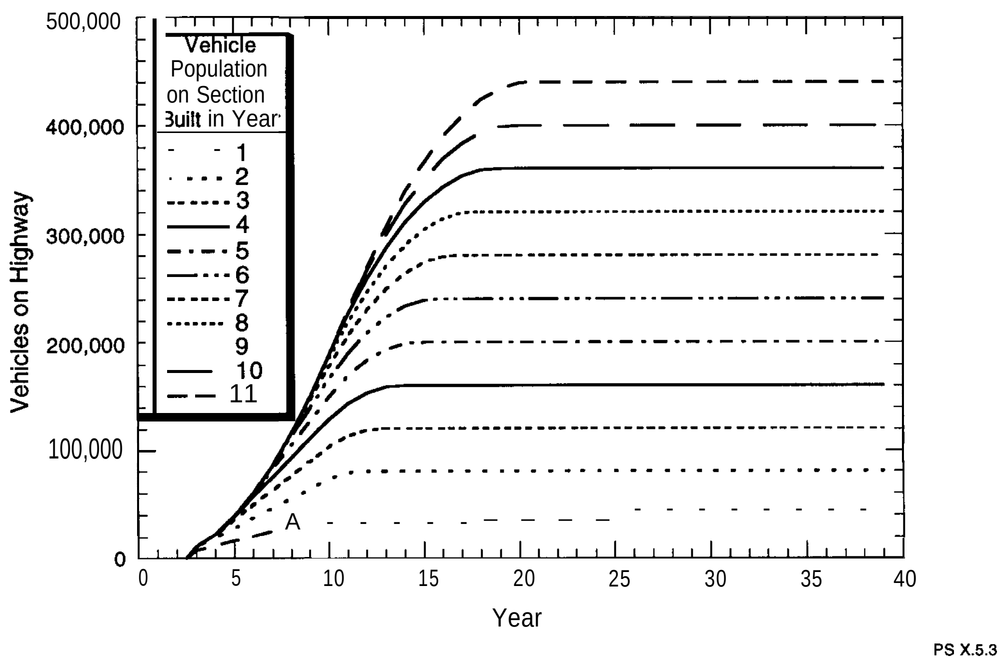


Figure 5.29 Effect on the population of users

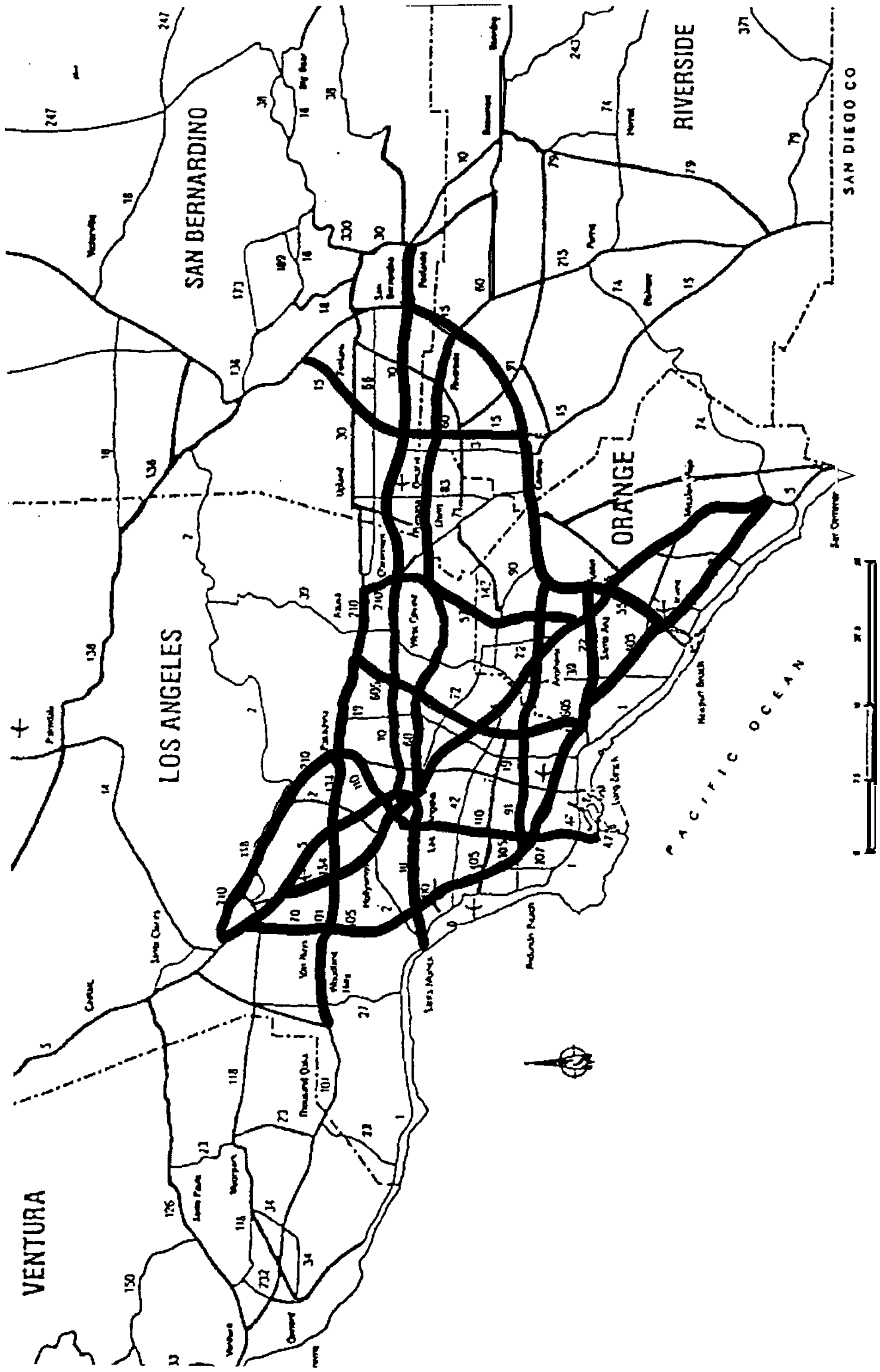


Figure 5.30 L.A. Basin RPEV grid

5.5.2 Results and Analysis

Using the RPEV Economic Model, we have performed a number of trade-off studies that demonstrate the effects on the retail price paid by the users in dollars per kilowatt-hour and dollars per mile. Cost sensitivities relative to the construction schedule and operations and maintenance assumptions have also been performed. Results from a series of changes to the baseline variables show the effects of more optimistic assumptions for each of the baseline variables. A similar series of changes to the baseline scenario incorporating pessimistic assumptions demonstrates the range over which the results could conceivably be expected to change from the baseline.

Table 5.7
REM Model Results Format

System Summary
Year
New vehicles this year
Current population
Annual capital expenditures
Cumulative capital expenditures
Roadway miles paved/replaced
New roadway miles this year (lane miles)
Lane miles of roadway operational (year end)
Effective capacity
Effective volume (vehicle-miles/hour)
Effective volume (vehicle-miles/day)
Effective volume (vehicle-miles/year)
Volume:Capacity ratio
Cumulative VMT

Table 5.7
continued

	Annual
Energy purchased (kwh/yr)	
Energy sold (kwh/yr)	
Energy unsold (Losses) (kwh/yr)	
Expenses	
Debt service	
Energy purchased	
Administration	
O & M	
Depreciation	
Operating expenses	
Total cost	
Revenue	
Energy sold at price specified	
Energy sold using revised rate	
Profit	
Operating income using energy prices specified	
$/kwh Sold	
Debt service	
Energy purchased	
Administration	
O & M	
Depreciation	
Operating expenses	
Total cost	
$/VMT	
Per mile rate	
$/VMT	
Per vehicle year rate	

Table 5.7
continued

	Cumulative
Energy purchased (kwh total)	
Energy sold (kwh total)	
Energy unsold (Losses) (kwh total)	
Expenses	
Debt service	
Energy purchased	
Administration	
O & M	
Depreciation	
Operating expenses	
Total cost	
Revenue	
Energy sold at price specified	
Energy sold using effective rate	
Profit	
Operating income using energy prices specified	
$/kwh Sold	
Debt service	
Energy purchased	
Administration	
O & M	
Depreciation	
Operating expenses	
Total cost	

Table 5.7
continued

Results	
Revised effective rate including debt interest due to deficit	
Annual profit using cumulative rate at year specified	
Cumulative profit using cumulative rate at year specified	
Annual interest payment on cumulative loss	
Revised cumulative loss	
Simple effective rate (no interest on cumulative loss)	
$/VMT	
Per mile rate	
$/Vehicle	
Annualized per vehicle per year rate	
Vehicle per lane per day	

5.5.2.1 Baseline Scenario Cost Results

Figure 5.31 describes the behavior of the important baseline scenario parameters profiled across time. Vehicle population grows from Year 3 through Year 22 when the vehicle population on the last section of roadway reaches saturation as seen in Figure 5.29. Both the revenue and vehicles per day per lane curves level off at this point. Annual cost peaks in Year 22 and then declines through Year 36 when it levels off. Lane-miles of roadway operational increase linearly from the end of Year 1 through the end of Year 11, when construction is complete.

For any scenario, the roadway miles operational affects the two largest cost components: debt service, which is a function of the capital expense requirements, and energy sold, which is dependent on the number of users. Therefore, for any proposed scenario, the general relationships between market and construction variables shown in this figure will remain, although the positioning and slope of these curves across time will fluctuate.

The annual cost curve in Figure 5.31 is broken down into its various components in Figure 5.32. The annual cost includes interest on the debt required to cover

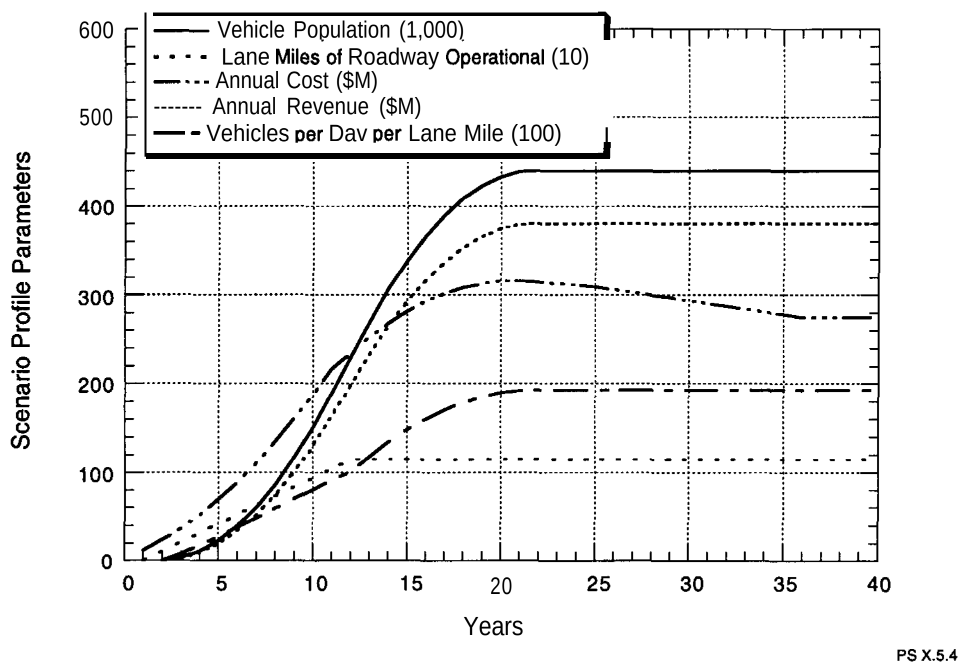


Figure 5.31 Behavior of baseline scenario parameters profiled across time

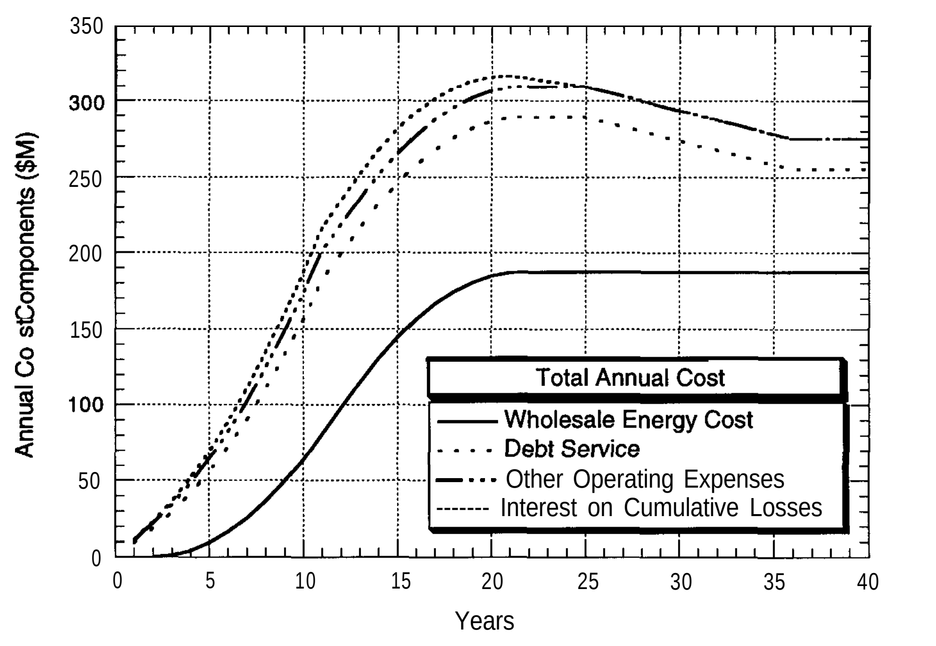


Figure 5.32 Annual cost curve in Figure 5.31 broken down into its various components

cumulative losses. This expense begins in Year 1 and grows until Year 14, the first year of profitable operations. The interest expense required each year from then on until Year 25 declines until the cumulative loss disappears. If interest on debt due to cumulative losses were excluded, annual costs will level off in Year 22 through Year 25. The decline in Year 26 is due to the reduced debt service cost caused by the difference between the initial and replacement costs as well as the end of the interest on cumulative losses. In Year 26, the last annual interest payment on the first of the eleven 25-year loans is paid. Costs continue to drop through Year 35, as each successive loan is paid and replaced with the lower-cost replacement loan. The roadway replacement schedule begins in Year 26 and is completed by Year 36. After this year the cost curve is flat. O&M costs are a percentage of the cumulative costs for initial construction and therefore become constant after Year 11.

The cumulative behavior of these cost components over forty years is shown in Figure 5.33. By the breakeven year, energy is 49% of the cumulative cost, with debt service, other operating expenses, and interest on the deficit representing 39%, 7%, and 4%, respectively. In Year 10, debt service is 58% of cumulative cost. By Year 40, energy is 57% of the cumulative cost, with debt, operating expenses, and interest on deficit expense contributing 34%, 7%, and 2%, respectively.

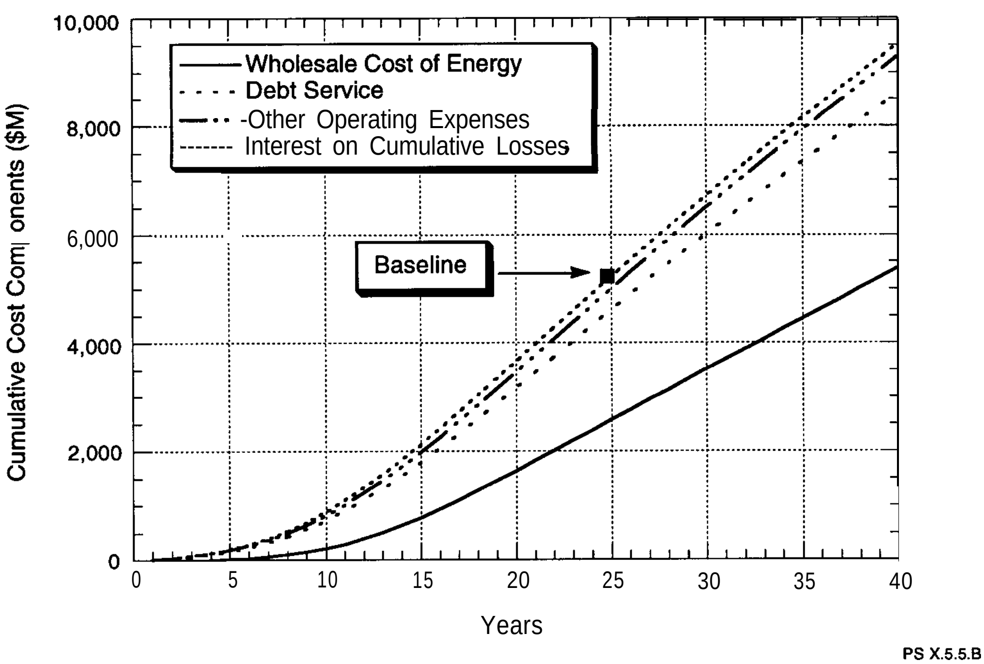


Figure 5.33 Cumulative behavior of cost components over forty years

The components of annual cost in dollars/kilowatt-hour are shown in Figure 5.34. The second scale on the right Y-axis converts the rate into dollars/mile. The top line (sum of all the cost components) reflects the rate to breakeven for that year. The rate, excluding interest on cumulative deficit, equals the SSM rate of $0.1517 in Years 23 – 25 when the population is saturated and before annual debt service declines (Year 26) due to lower replacement costs. The knee of the curve for debt service and all curves above it is between Year 12 and Year 22. During this period, the rate of population growth peaks (Years 12 – 13 Figure 5.27) and saturates in Year 22. The annual breakeven rate drops by less than $0.015/kwh between Year 25 and Year 40 as the original debt is paid and replaced with lower replacement costs.

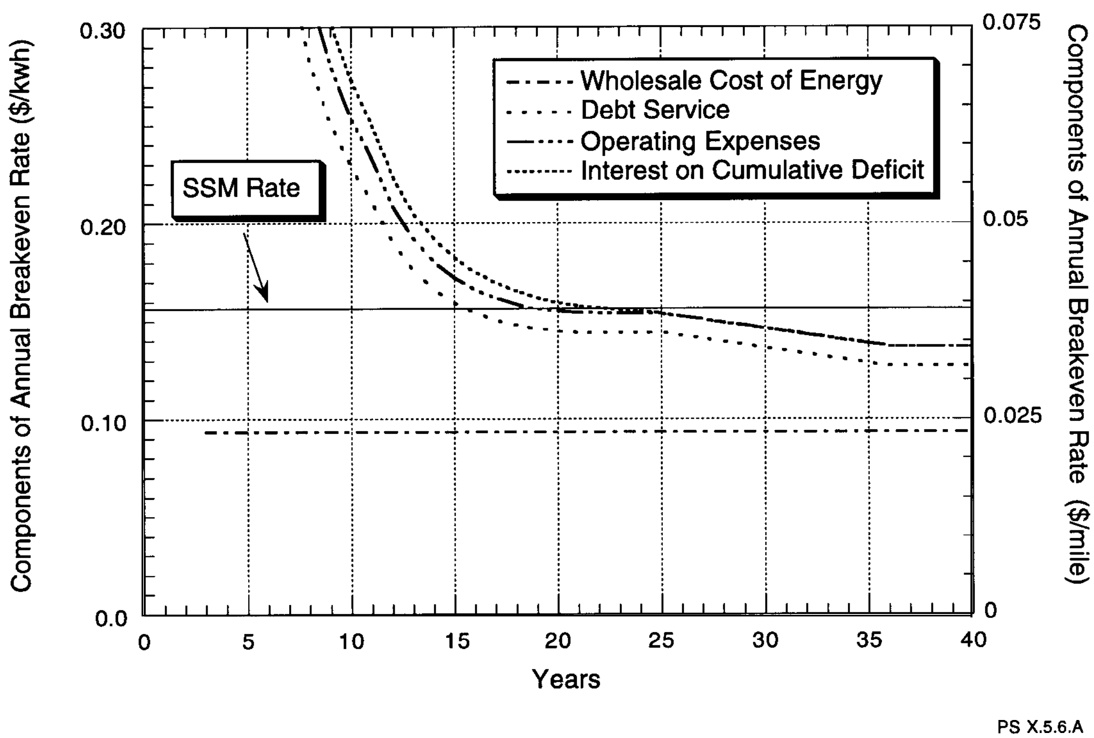


Figure 5.34 Components of annual cost in dollars/kilowatt-hour

Debt service is the component that changes the most over time in its contribution to the annual breakeven rate. In the earliest years, debt service is extremely high due to the limited number of users over whom costs are spread. This component of cost drops rapidly through Year 15 and then levels out as the population approaches steady state by Year 22. From Years 25 to 36, the debt service contribution to the annual breakeven rate decreases as original construction debt is replaced by replacement debt while the user population remains constant.

Figure 5.35 shows the cumulative cost components in dollars/kilowatt-hour. Although the cumulative rate curve does not level off to the extent that the annual cost curve does (Figure 5.34), the rate of change decreases substantially by Year 20. The breakeven year should not be before Year 20 to spread the costs over the substantial population of users on the system by that point. Because the Y-axis is range limited, rates during the early years are not shown.

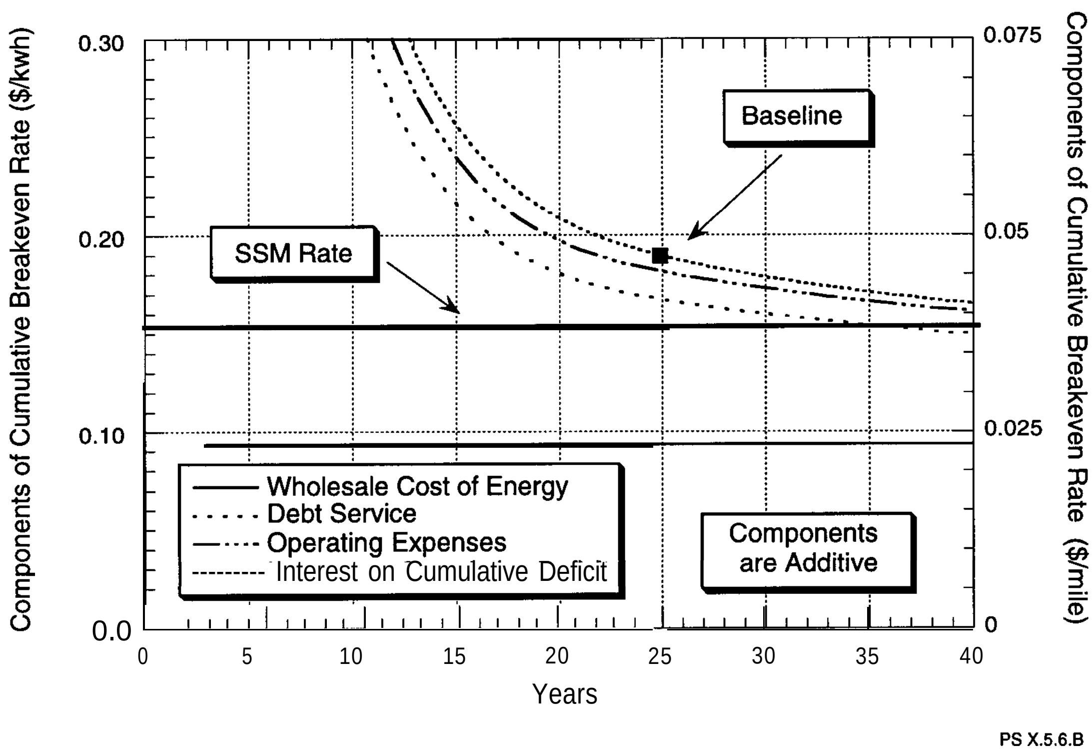


Figure 5.35 Cumulative cost components in dollars/kilowatt-hour

Figure 5.36 shows the annual cost, revenue, and profit/loss curves. The revenue curve levels off at Year 22 as the population reaches saturation. The area between the Annual Profit/Loss curve and the zero axis before Year 14, (when annual profits are first positive) equals the area between the zero axis and the Annual Profit/Loss curve from Year 14 until Year 25. Cumulative costs and revenue are shown in Figure 5.37. The minimum point on the profit/loss curve occurs in Year 14, and the curve crosses through zero in the designated breakeven year. Cumulative profits are approximately $1.5 billion by Year 40.

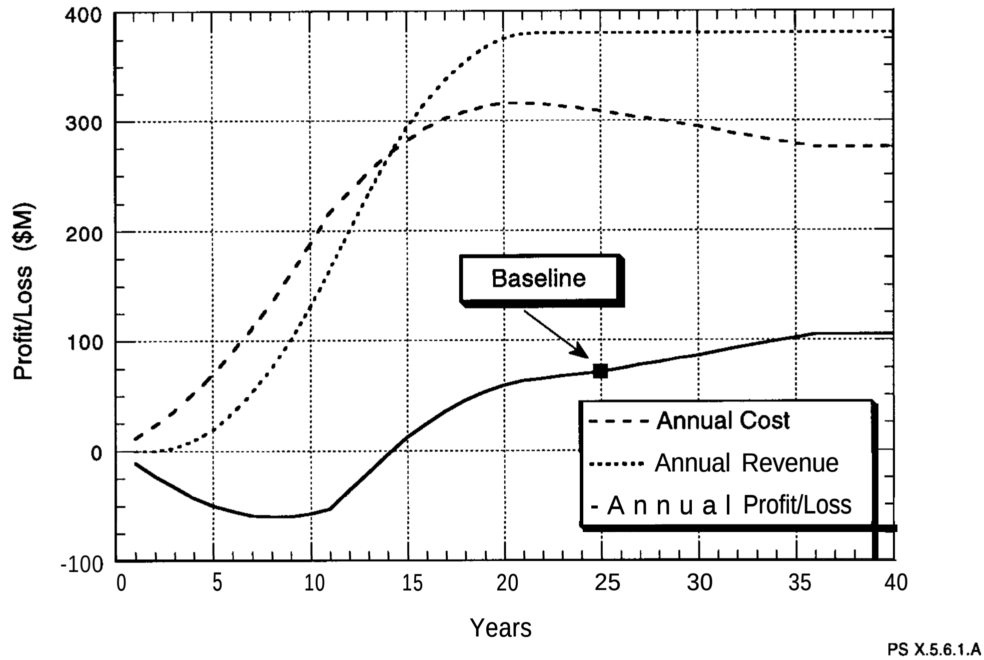


Figure 5.36 Annual cost, revenue, and profit/loss curves.

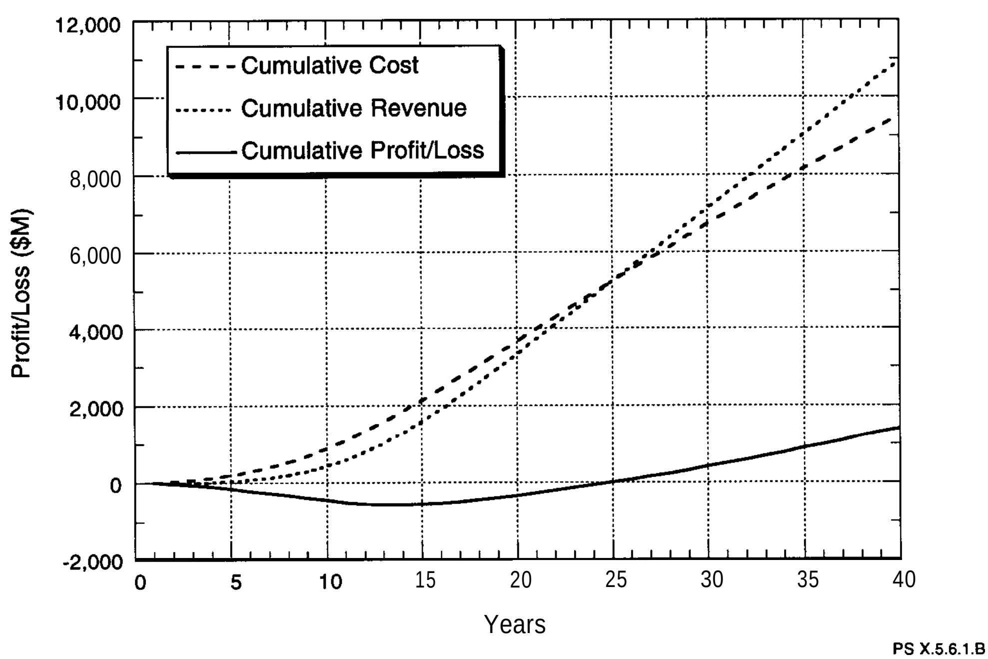


Figure 5.37 Cumulative cost, revenue, and profit/loss curves

Figure 5.38 shows a comparison of retail RPEV rate calculations. The cumulative breakeven rate is cumulative costs divided by cumulative kilowatt-hours sold by year. The effective rate is the value of this function at Year 25. A simple rate does not include any interest expense on cumulative deficit. Therefore, the simple cumulative rate is the same as the cumulative rate except that the interest to cover cumulative losses is not considered. The annual rate is the rate at each year that is charged to break even that year, considering that year's revenues and expenses only. The simple annual rate intersects the annual rate curve at Year 25 when cumulative losses have been completely recovered so interest goes to zero. The simple annual rate flattens out at $0.1517 (the Steady State Model rate) in Year 25, when the vehicle population hits steady state. The REM baseline effective rate is $0.1895/kwh, which is $0.0378/kwh or $0.0094/mile higher than the steady-state rate.

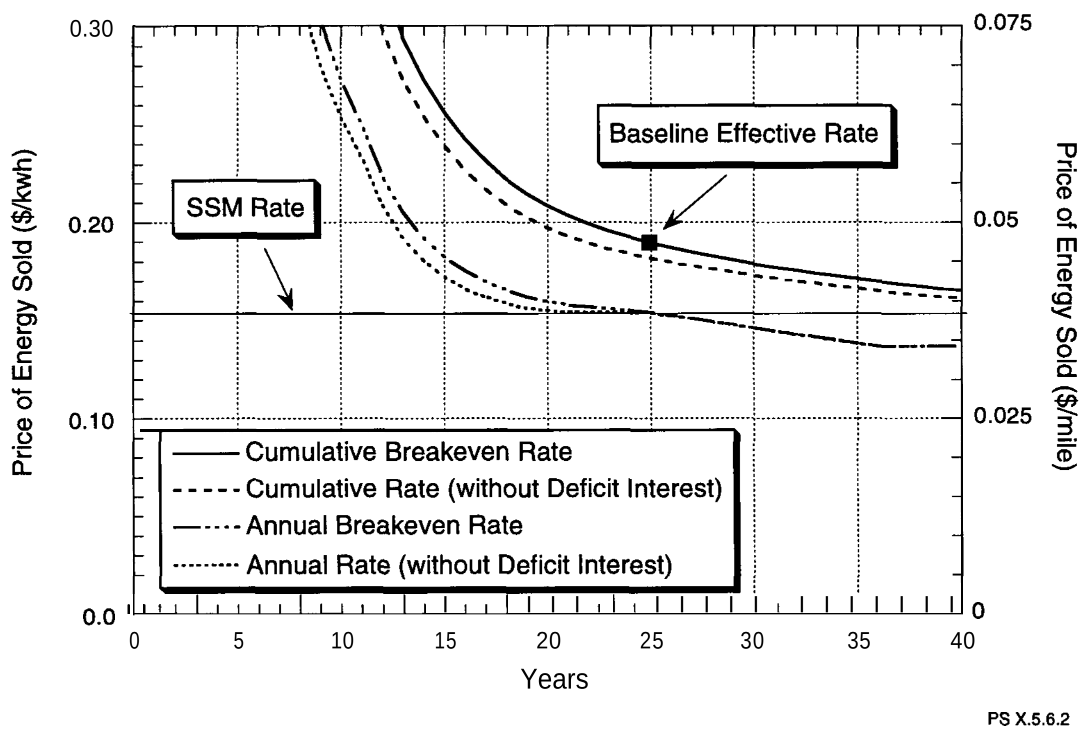


Figure 5.38 Comparison of retail RPEV rate calculations.

5.5.2.2 Sensitivity with Respect to Operating Cost Assumptions

Figure 5.39 shows the effect of various assumptions of administration and operations and maintenance expenses over the life of the program. O&M expense is a percentage of the cumulative cost of construction of new roadway. As the cumulative capital costs accrue, there is an increasing and significant portion of total system cost directly attributable to O&M costs. Administration costs over these ranges have an insignificant effect on the system costs because they are based on debt and energy costs, which are small in comparison to the cost of the capital construction. The baseline scenario assumes that 1% of these operating costs is a reasonable estimate for administration and operating and maintenance. Data supporting this assumption from historical Caltrans costs are summarized in Appendix A.

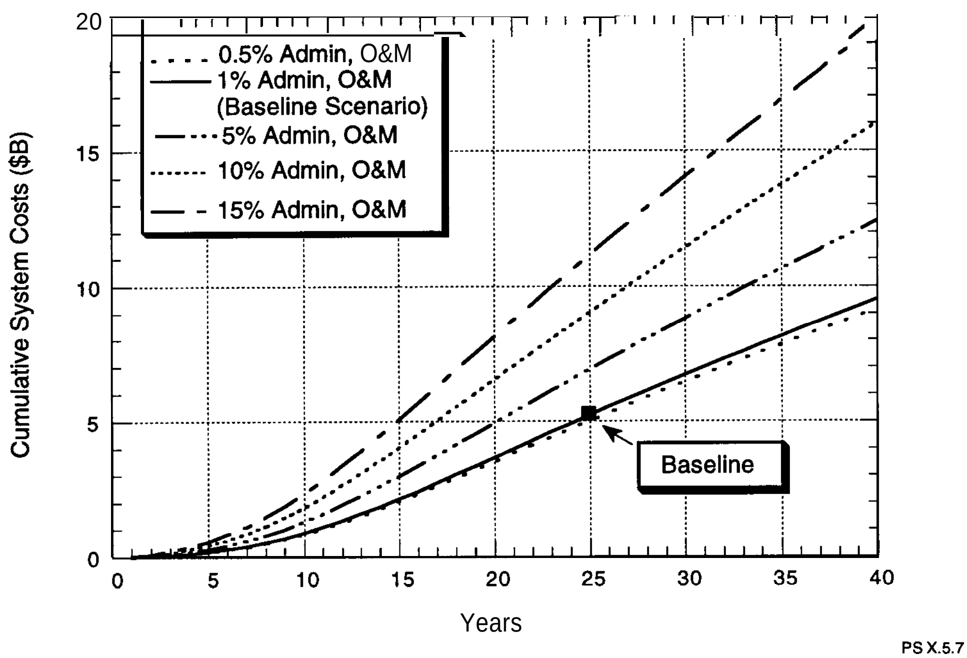


Figure 5.39 Effect of various assumptions of administration and operations and maintenance expenses over the life of the program

With capital construction costs of $1,500,000 per lane-mile and annual O&M costs equal to 1% of construction costs, $15,000 is allocated annually for maintenance of each lane-mile. This amounts to $375,000 over the 25-year life of the roadway. After Year 11, with 1,144 lane-miles of roadway completed, the annual system maintenance budget will be $17,160,000. Raising the O&M rate to 4% results in costs for maintenance over the 25-year life of the roadway equaling original construction, which seems high intuitively as well as in comparison with the Caltrans data from Appendix A.

5.5.2.3 Sensitivity with Respect to Construction Schedule

The baseline scenario assumes construction of 104 lane-miles per year for 11 years, resulting in 1,144 miles of roadway. A candidate system is shown in Figure 5.30, which covers the Los Angeles Basin. If the amount of RPEV roadway were considerably reduced, costs would drop as would the corresponding number of users. Analysis of a reduced system is based on 520 lane-miles, constructed at the same rate as the baseline system through Year 5.

Figure 5.40 shows the cumulative costs for this reduced construction schedule. These results can be compared to Figure 5.41 for the baseline system. The 45% reduction in operational RPEV roadway results in a 59% decrease in cumulative costs by Year 40.

Costs in dollars/kilowatt-hour for the reduced RPEV system are shown in Figure 5.42. These costs can be directly compared to the rates from Figure 5.43. The kilowatt-hour rate charged based on cumulative costs at Year 25 decreases from the baseline rate of $0.1894 to $0.1851, a change of approximately one-half cent per kilowatt-hour. The reduced RPEV system uses the same market penetration assumptions as the baseline case.

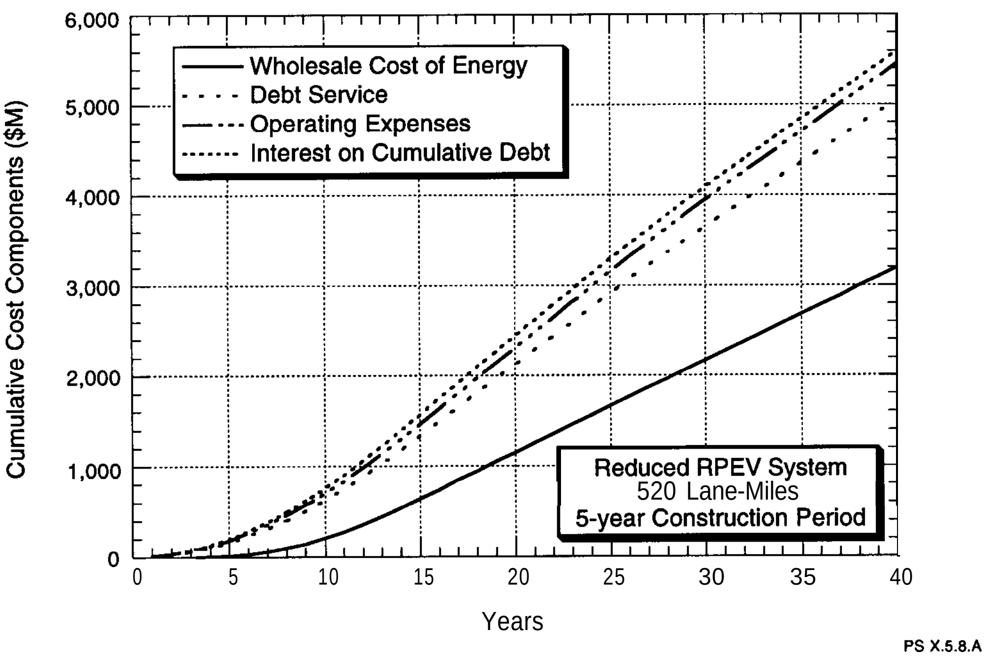


Figure 5.40 Cumulative costs for reduced construction schedule

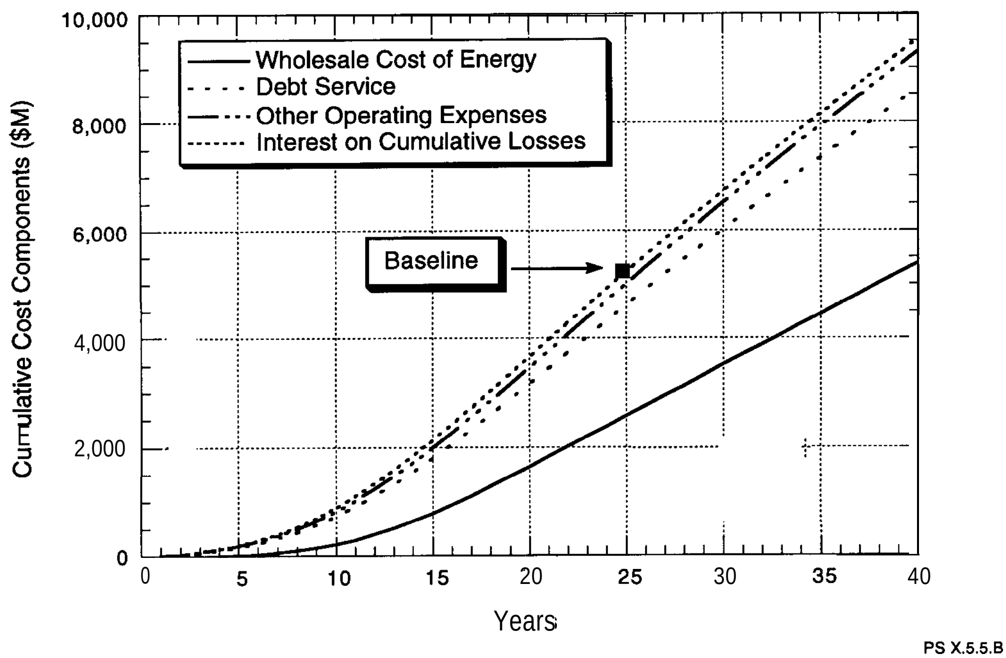


Figure 5.41 Cumulative costs for the baseline system

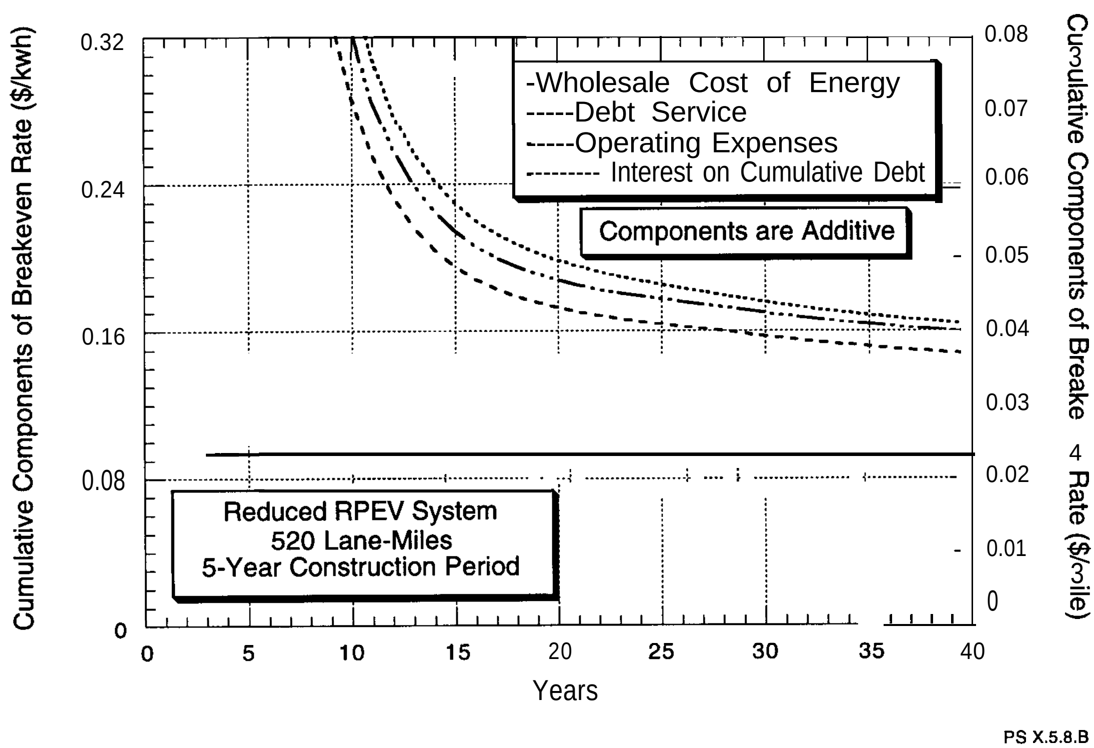


Figure 5.42 Costs in dollars/kilowatt-hour for the reduced RPEV system

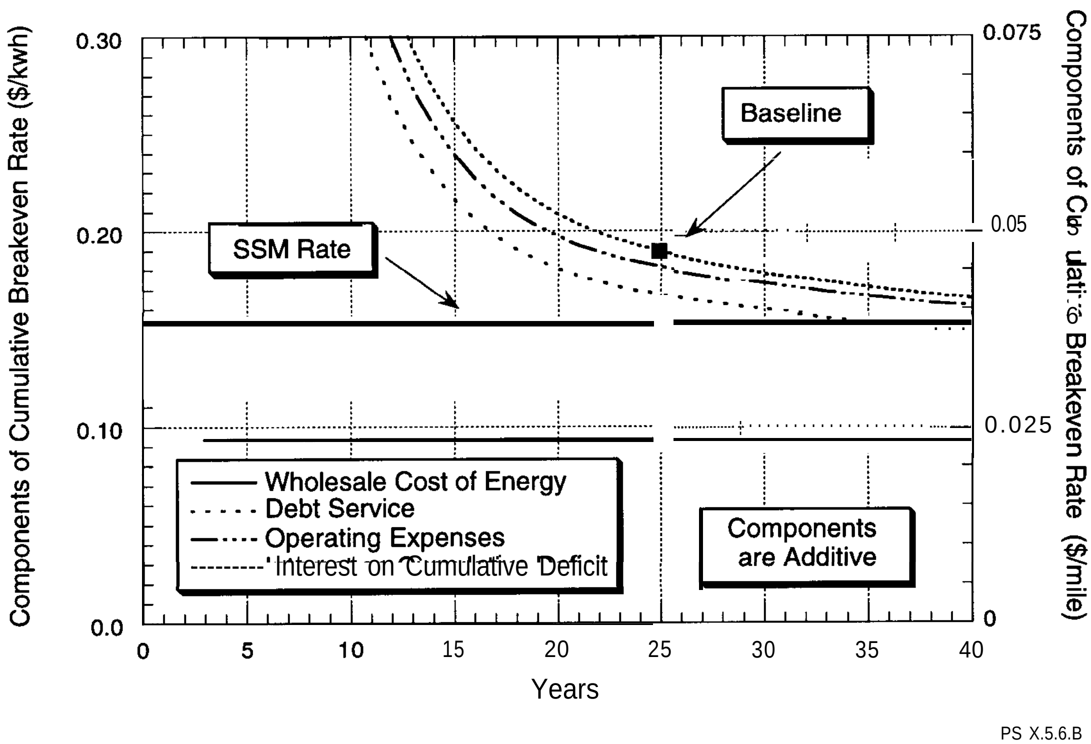


Figure 5.43 Costs in dollars/kilowatt-hour for the baseline RPEV system

The primary reason that the costs are lower for the reduced network compared to the baseline is that all construction is completed in Year 5 and vehicle population reaches steady state in Year 17. The average age of the system in Year 25 is 22.5 years, compared to 19.5 years with the baseline system (or 25 years with the Startup Transient Model). Since the breakeven rate declines over time, the effective rate is lower for scenarios with most or all of their construction in the early years.

5.5.2.4 Sensitivity with Respect to Breakeven Year

Figures 5.44 and 5.45 show the allocation of expenses for Year 25 and Year 30. In Year 25, the breakeven and effective rates are identical. Although the percentage contribution of each cost component to effective rate changes between Years 25 and 30, the contribution of each component in dollars/kilowatt-hour remains constant for energy and decreases for all other components.

In each pie chart, the cost component percentages reflect the cumulative costs divided by the cumulative kilowatt-hours sold. The sum of these is the breakeven rate for that year. The contribution of each component to the breakeven rate in dollars/kilowatt-hour indicates the shrinking portion devoted to interest to cover debt service in Year 30.

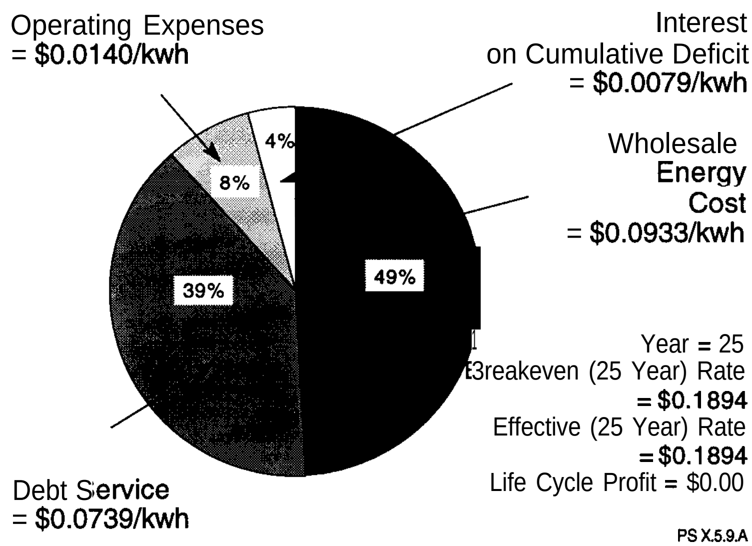


Figure 5.44 Allocation of expenses for Year 25

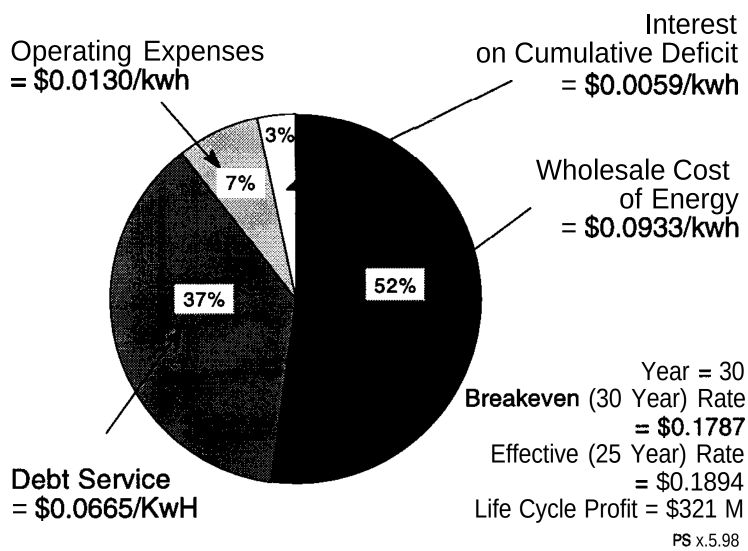


Figure 5.45 Allocation of expenses for Year 30.

Energy expense remains at $0.093/kwh in all years, although as a percentage of breakeven rate it increases from Year 25 to 30 as other costs decrease when expressed as dollars per kilowatt-hour. Debt service decreases during the same period both as a percentage and in dollars/kilowatt-hour as the breakeven rate decreases from $0.189 to $0.179. Charging the 25-year breakeven rate for all years results in cumulative profits of zero in year 25 and $321 million in Year 30.

5.5.3 Sensitivity to Compounded Cost Decreases

Incremental results from a series of sequentially optimistic changes to the baseline scenario are shown in Figure 5.46. The specific changes to the baseline values are identified in Table 5.8. The cost reduction estimates come from such possible circumstances as cost sharing, federal funding, technology changes to either the roadway or system power conditioners, or changes to the vehicle energy consumption requirements.

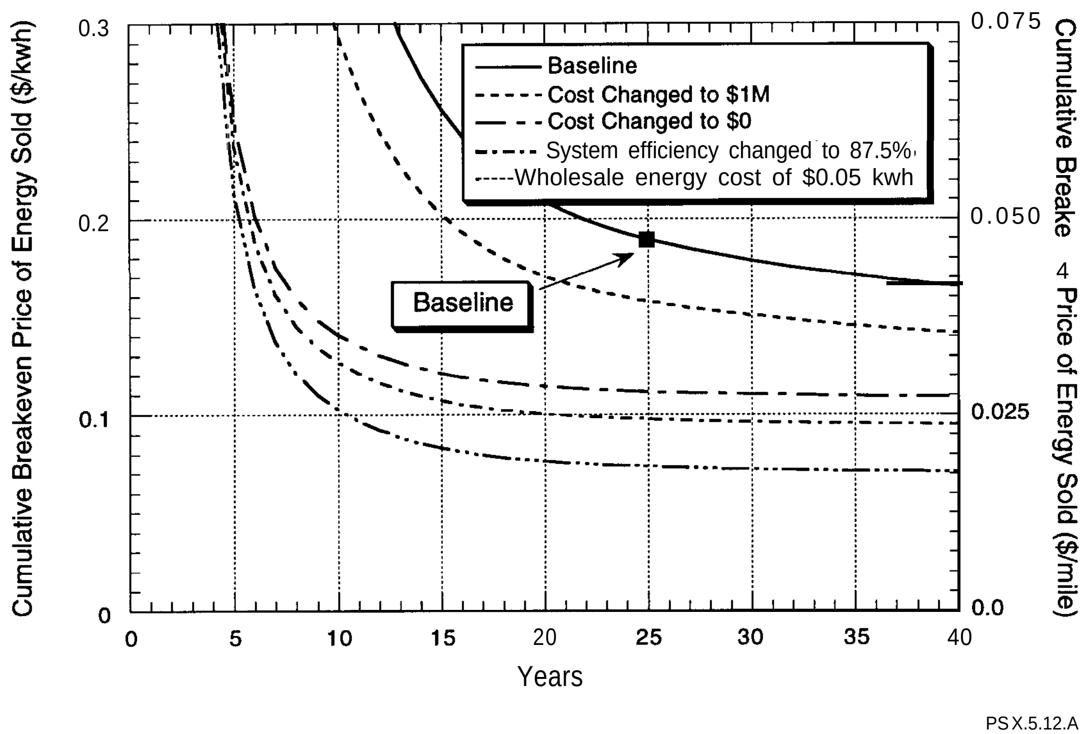


Figure 5.46 Incremental results from a series of sequentially optimistic changes to the baseline scenario

The cost per lane-mile was changed from $1,500,000 to $1,000,000, a reduction of 33%. This change resulted in a reduction of the effective rate by Year 25 of approximately a $0.03/kwh from the baseline scenario effective rate of $0.1894. The user cost expressed in dollars per mile decreases linearly with the price per kilowatt-hour as long as the vehicle energy consumption remains constant. If the capital costs remain $1,000,000 per lane-mile but are borne by another agency (e.g., Federal or State funding of the construction), the effective rate is further reduced because there is no debt service on the

Table 5.8
Cost Decreases from Baseline

Market Penetration	
1500	Number of RPEV users in the initial year of market growth
2250	Number of users escalation per year until market saturation or volume limit
3	Market penetration start year
20,000	Volume limit in vehicles per lane-mile per day
Cost	
$0	Initial cost per lane-mile of roadway
$0	Replacement cost of roadway per lane-mile
Baseline	Administrative cost as a percentage of debt plus energy cost
Baseline	O&M cost as percentage of cumulative new roadway capital cost (not including costs for replacement roadway)
25 years	Useful life of roadway before replacement
$.05	Cost of energy per kwh
$.189*	Retail price of energy per kwh (Used for some direct revenue calculations)
Vehicle	
0.15	Energy consumption in kwh/mile
87.5%	System efficiency
50	Average vehicle-miles per day on the system
Debt	
3.3%	Real interest rate
Miscellaneous	
25	Designated year for cumulative breakeven effective rate calculations
11	Number of years for roadway construction
52	New system miles per year (104 lane miles)

*Output by Model

capital costs. Incorporating this change drops the effective rate at Year 25 to $0.1116/kwh, a reduction of $0.0778/kwh from baseline.

The baseline system efficiency is 75%. Cutting system losses by approximately a factor of two increases system efficiency to 87.5%. This results in a reduction of the effective rate at Year 25 to $0.0976/kwh, which is $0.0918/kwh less than the baseline. An increase to the system efficiency will be expected as the system approaches saturation and realizes reduced energy losses per vehicle because fixed losses will be shared among more vehicles. The final change considered is a decrease in the wholesale cost of energy from $0.07 to $0.05 per kilowatt-hour, which reduced the 25-year cumulative breakeven price to $0.084/mile.

An improvement in the vehicle energy efficiency (reducing demand from 0.25 to 0.15 kw-hr/mile) will cause an increase in the effective rate (per kilowatt-hour) because there will be less energy will be transferred to vehicles, while the fixed costs remain largely unchanged. This increase in cost per kilowatt-hour is more than offset by the reduced amount of energy that each vehicle draws from the roadway, resulting in a net decrease in cost per mile. Figure 5.47 is essentially a repeat of Figure 5.46, but with costs expressed per mile rather than per kilowatt. A sixth curve has been added, showing reduced energy consumption. shows the effect on the cost per mile and the changes to the baseline scenario previously described. The baseline system will cost a user $0.045 per mile (similar to the cost per mile for gasoline-powered vehicles while with the optimistic assumptions, the cost drops to just over $0.01 per mile.

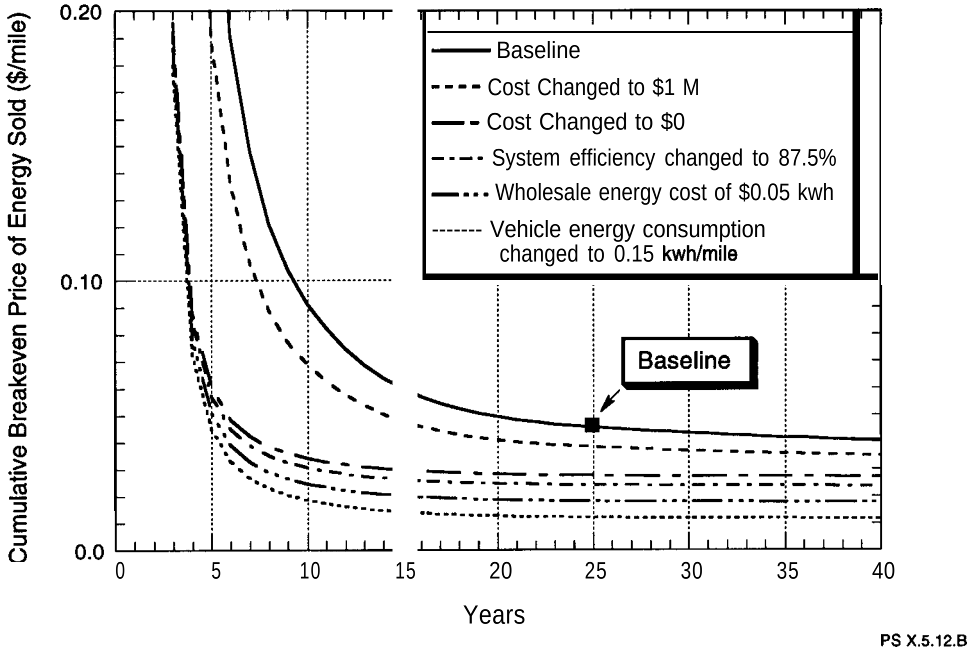


Figure 5.47 Effect on the cost per mile and the changes to the baseline scenario

Figure 5.47 adds improvement to the vehicle energy consumption (in kwh/mile) to the changes shown in Figure 5.46. A reduction in the vehicle energy consumption results in reduced costs for energy purchased as well as less energy lost. Because our measure of dollars/VMT spreads the reduced total cost over the same number of vehicle miles traveled, the effective rate decreases. This change increases the cost per kilowatt-hour to $0.0827, but reduces the cost per mile to $0.0124. This line is not included in Figure 5.46 as it represents an increase in the cost per kilowatt-hour. The effective rate in dollars/mile is reduced from $0.045/mile (baseline) to $0.0124/mile in the most optimistic case. This is obviously much lower than the present cost of gasoline.

5.5.4 Sensitivity to Compounded Cost Increases

Incremental results from a series of sequentially pessimistic changes to the baseline scenario are shown in Figure 5.48. Changes to the baseline values are identified in Table 5.9. The marginal cost increases to each model variable are largely percentage increases, regardless of engineering justification. Increases to the extent shown are considered unlikely; however, they are included to show the results from pessimistic changes to the baseline scenario.

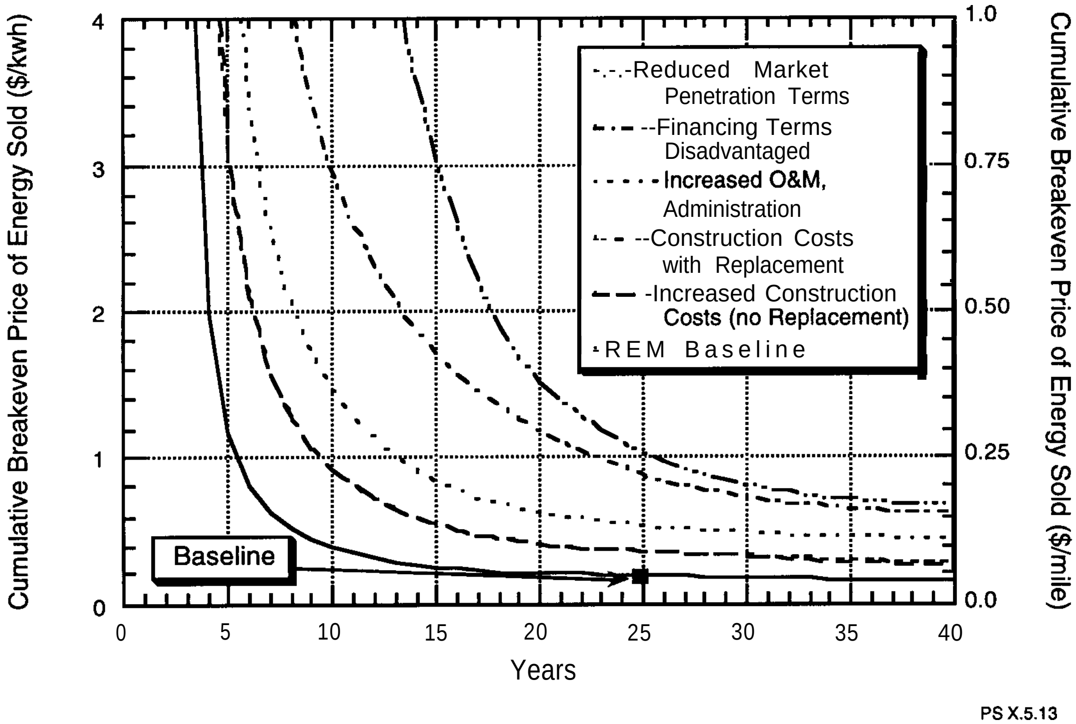


Figure 5.48 Incremental results from a series of sequentially pessimistic changes to the baseline scenario

Table 5.9
Cost Increases from Baseline

Market Penetration	
10,000	Number of RPEV users in the initial year of market growth
20%	Growth rate
6	Market penetration start year
75,000	Maximum number of new users per year (Market saturation)
750,000	Population maximum RPEV total users
Cost	
$4,153,248	Initial cost per lane-mile of roadway
$2,768,832	Replacement cost of roadway per lane-mile
5%	Administrative cost as a percentage of Debt plus Energy Costs
5%	O&M cost as percentage of cumulative new roadway capital cost (not including costs for replacement roadway)
25 years	Useful life of roadway before replacement
$.07	Cost of energy per kwh
$.189	Retail price of energy per kwh (Used for some direct revenue calculations)
Vehicle	
0.33	Energy consumption in kwh/mile
68%	System efficiency
30	Average vehicle-miles per day on the system
Debt	
10%	Real interest rate
14	Years to pay back loan
Miscellaneous	
25	Designated year for cumulative breakeven effective rate calculations
11	Number of years for roadway construction
52	New system miles per year (104 lane miles)

These stepwise cost changes to the baseline assumptions cause the effective rate in Year 25 to increase from $0.189 to $1.257. The cost changes are described below.

Capital cost per lane-mile was assumed to be $4,153,248, instead of $1,500,000 as in the baseline scenario. This assumption is shown with and without the effects due to assumed replacement costs beginning in Year 25. The increase in capital cost causes both the operating expenses and debt service to increase, resulting in nearly doubling the required effective rate.

O&M costs were increased from 1% to 5% of cumulative capital costs. Administrative costs, which were 1% of debt and energy costs, were increased to 5%. These changes resulted in an increase to the operating expenses from $0.037 to $0.187/kwh. In the baseline scenario, operating expenses (administration, operations and maintenance) are 7% of the effective rate; now they are 31%.

Changing the financing terms from 3.3% over 25 years to 10% over 14 years causes the debt service to increase $0.12/kwh, a 14% increase. When added to the two earlier changes, the effective rate has increased to $0.85/kwh.

Assuming there are no users until Year 6 postpones revenues and causes a significant increase in the effective rate to break even by Year 25. In this sensitivity, the user population started at 10,000 new vehicles in Year 6 and the number of new vehicles grew 20% each year.

The consideration of depreciation into the effective rate calculations is indicated by the top line.

5.6 Comparison of the SSM, STM and REM Models

A comparison of effective rates for the three economic models is shown in Figure 5.49. Results from these three models are based as closely as possible on identical cost assumptions.

The SSM, the steady-state model, has no time dependency and therefore is shown as a flat line across the years. The rate reflects a fully saturated system. The Steady State Model is insensitive to startup conditions. During periods of market growth, there are higher costs per user. Therefore, the SSM rate is the lowest of the three rates. The annual rate calculated with the REM reaches approximately this steady-state rate in Year 23 (see Figure 5.50). By Year 23 in the REM, the system has reached a steady-state condition so the annual REM rate and the SSM rates are similar and identical if Deficit Interest is not included.

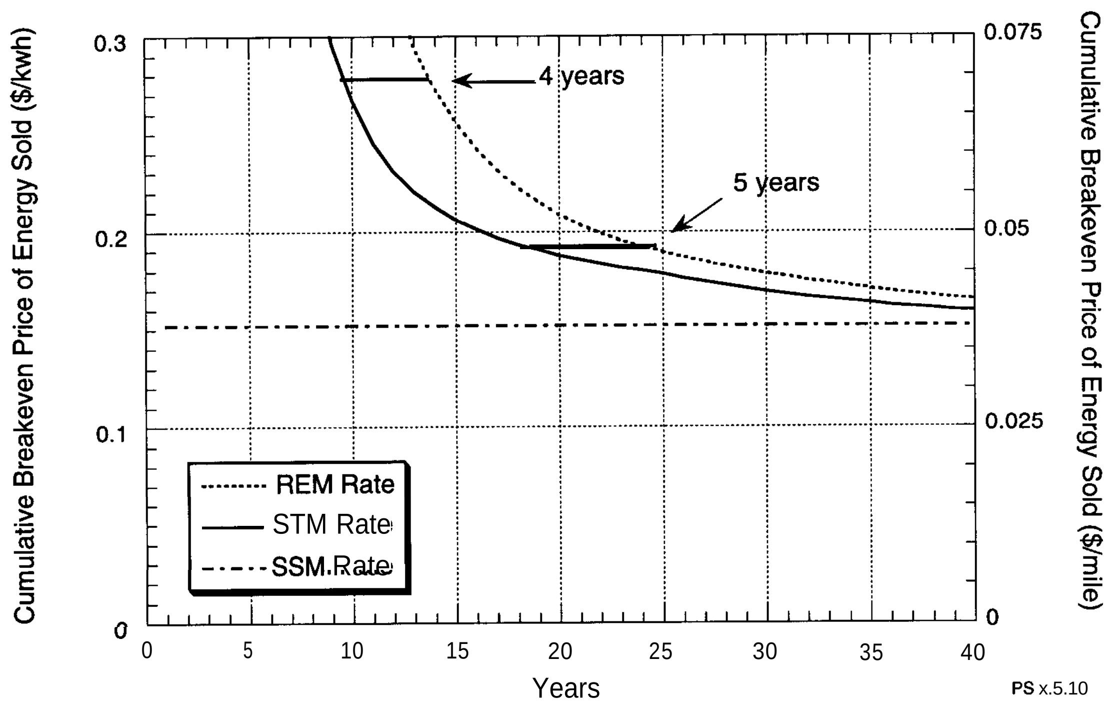


Figure 5.49 Comparison of effective rates for the three economic models

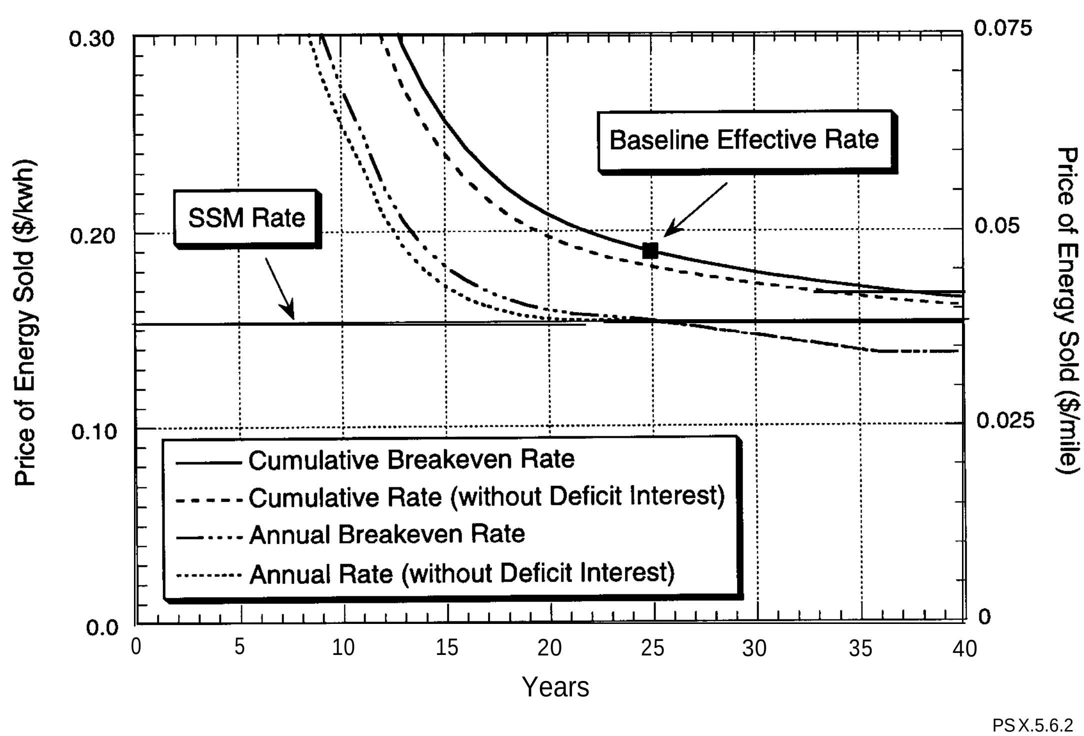


Figure 5.50 Comparison of annual rates for the three economic models

Like the Steady State Model, the Startup Transient Model rate estimates are based on only one mile of RPEV roadway. The Startup Transient model is time-dependent and high costs per user during the market growth year are reflected in the effective rate. In addition to the market growth, additional interest to cover debt due to the deficit is calculated as part of total cost. Although the effect on the rate diminishes, it can be seen in the rate even out at Year 40.

The RPEV Economic Model includes construction scheduling. For the baseline scenario, market growth matches the STM for each section of operational roadway. Construction in the baseline REM spans the first eleven years, therefore the average year in which the system is built is 5.5. Due to the 11 years of construction, the rate curve is shifted to the right of the STM curve by approximately 5.5 years. The REM rate is actually asymptotic to the STM rate.

The REM presents a weighted average of the STM results for each section. For example, in Year 25, the REM results are equivalent to the STM results for Year 25 for roadway built in Year 1, plus STM results in Year 24 for roadway built in Year 2, plus . . . the STM results in Year 15 for roadway built in Year 11. In later years the cumulative costs of the roadway built during the various years are more nearly constant, giving results closer to an unweighted average, or equivalently a steady-state year time shift. For instance, the REM cumulative breakeven price is $0.18/kwh in Year 29, while the STM reaches that price in Year 23.5. At $0.28/kwh, the offset is four years, because the earlier years of construction are weighted much more heavily.

Figure 5.51 compares the contributions to effective rate of each of the three models. In the Steady State Model, most of the total costs are due to the wholesale cost of energy (61%), which contributes $0.0933 to the retail price per kilowatt-hour. The wholesale cost of energy drops to 52% in the STM and 49% in the REM, although the cost of energy remains constant at $.093/kwh. The changes are due to higher costs of debt service and interest on cumulative deficit for the time-dependent models.

5.7 Inflation and Present Value Effects

The analysis in this report used a real interest rate of 3.3% and assumed no inflation. To document this approach, one computer run was made using 10% interest rate and 6.7% inflation rate for revenue and all expenses other than loan payments. Energy was sold at the Year 25 breakeven price from the baseline REM,

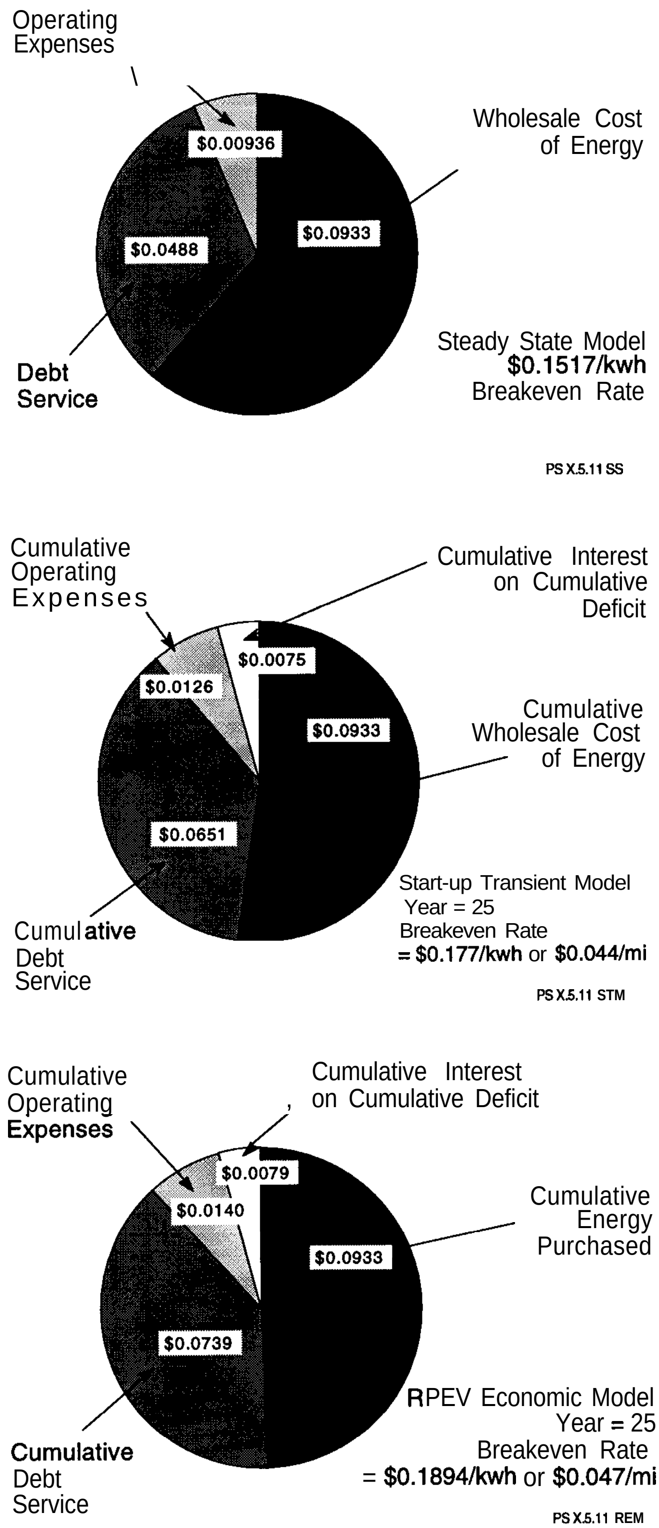


Figure 5.51 Comparison of contributions to effective rate of each of the three models

approximately $0.1894 per kilowatt-hour. This price was inflated 6.7% per year, as were other prices, including the wholesale cost of energy ($0.07/kwh in the first year) and construction costs. Administration and O&M costs are tied to costs that inflate, so there is no need to readjust them. A 10% interest rate is used for both the construction loan and the loan to cover the operating deficits.

The result of this run was a shift in the cumulative breakeven point approximately one year forward, to just before Year 24. This indicates that the assumption of a 3.3% real interest rate is a very good approximation to a 10% interest rate and a 6.6% inflation rate, which is probably a more realistic set of assumptions, but greatly complicates the analysis.

5.8 Market Saturation Assumptions

The baseline REM market penetration model is based on the STM market penetration model. In the STM, a section of roadway is one mile, and only one section was modeled. In the REM, a section of roadway is amount of roadway built in one year (baseline value of 104 lane-miles) and construction of the entire system is phased over a number of years. Each section of roadway in the REM follows a user growth pattern which is essentially the same as the STM - initial users two years after construction, followed by linear growth in the number of users until saturation eleven years after construction.

Consider the section of roadway built in Year 1, consisting of 104 lane-miles. The roadway is opened in Year 2, but there are no users until Year 3. The REM profile of vehicle-miles per lane per day essentially matches the STM profile. That is for each mile of roadway in the REM, there are 1500 users in year three and 2250 each year thereafter until saturation is reached at 20,000 users per lane per day. Obviously users of the RPEV system will travel on more than one mile of the system each day, so the RPEV system has fewer daily users than daily VMT. In the REM each user is assumed to make two trips per day on the RPEV system with an average on-system distance of 25 miles per trip. Three thousand users are assumed for Year 3, resulting in 150,000 VMT per day in Year 3 on the 104 lane-miles built in the first year or 1,442 VMT per lane-mile per day (approximately equal to 1,500 vehicles per lane per day in the third year in the STM). The economic analysis depends on the number of vehicles per day on each lane-mile of the powered roadway. As long as there are 150,000 VMT (daily) on the total 104 lane-miles, the economics will be the same. For instance, these VMT could result from 5000 users each driving 30 miles a day on the system. In fact, there will be a distribution of the number of on-system miles driven by each user, and the numbers chosen were selected by the authors as a reasonable estimate. This is based on two significant factors. First, most people with low total daily mileage will tend to use their battery, so the drivers who choose to use the system on any given day will tend to be those who make longer or more frequent trips. Second, the segments of freeway chosen for the earliest electrification will be those that are most heavily traveled, such as I-10 between downtown LA and San Bernadino. This freeway has four lanes in each direction and these lanes average over 25,000 vehicles per lane per day. The number of users assumed for the RPEV system (1500) during Year 3 represent only about 1.5% of the total users of the I-10 freeway.

The choice of an average trip length of 25 miles was also convenient, as it results in a new user profile exactly twice that in the STM. That is, in the STM, there were 1,500 users in Year 3, and 2,250 each subsequent year until saturation in Year 12. For each section of roadway in the REM, there are 3,000 users in Year 3 and 4,500 new users each subsequent year. This simplifies the REM validation process which relies heavily on comparisons between the two models. The user population grows by 4,500 per year from Year 4 through Year 11, with 1,000 new users in Year 12, bringing the total user population for the section built in Year 1 to 40,000 vehicles driving 2,000,000 VMT/day on 104 lane-miles of the system or 19,230 VMT per lane-mile per day. This is considered market saturation and corresponds to 80% of the approximately 25,000 vehicles per lane per day that currently use the freeways in the baseline RPEV system. This means that assuming all lanes handle equal volumes of traffic, 80% of the vehicles on the RPEV lane are drawing electricity from the system. The other 20% of the vehicles are non-RPEV (or RPEV's which are not drawing electricity from the system, a mode they may choose if their battery is relatively full and they only have a short distance to travel before reaching a conventional charging location).

The freeways that are likely to be electrified first, such as I-10, I-5, I-405, US 101, US 110, and CA 55, average 26,500 vehicles per lane per day. The assumed saturation of 20,000 vehicles per lane per day is 72.5% of this average lane volume. The saturation cap is intended to be an overall system average with the expectation that the daily volume on some freeways will exceed the cap by a noticeable margin. For instance, if 80% of the vehicles on one average lane of Route 55 were RPEV-equipped, the average daily RPEV volume would be more than 25,000 vehicles per lane per day.

System saturation occurs in Year 23 and amounts to about 2.2 million VMT daily. This corresponds to about 440,000 daily users of the RPEV system if they average 50 miles on the system. Clearly the total number of RPEV's will be some multiplier times this number, as not every RPEV will use the system every day. If the only people who purchase RPEV's are those who use then nearly every day, then the total number of

RPEV's would stay under 10% of the total vehicle population. A more likely scenario is that the public will develop confidence in the RPEV system and understand that they can drive anywhere within the entire metropolitan region at any time with an RPEV. In this case, RPEV's might represent 20%, 40%, or even 60% of the total regional fleet of vehicles. Assuming these RPEV owners drive on the RPEV system only infrequently, their presence could be accommodated with little or no change to the infrastructure.

5.9 Conclusions

The retail price of energy required to cover all costs over a 25-year period is less than $0.05 per mile, which is comparable to the cost of gasoline, assuming $1.25 per gallon and 25 mpg. This price assumes that all infrastructure costs are passed on to the users and no benefits from the reductions of emissions in electric vehicles compared to ICE vehicles are included. To improve the air quality in non-attainment areas, such as the Los Angeles Basin, fees may be levied on polluting vehicles, which could be used to subsidize the cost of the RPEV infrastructure. Alternatively, emissions reduction credits generated by the users of RPEVs could be sold on the open market.

The effective retail rate for the baseline scenario (price to breakeven on a cumulative basis in Year 25) is just under $0.19 per kilowatt hour. Table 5.10 shows the sensitivity of this price to key variables. The breakeven price is highly sensitive to:

- the wholesale cost of energy
- capital cost of the wayside infrastructure
- steady-state usage of the system
- interest rate of the construction loan (in real terms)

The wholesale cost of energy is passed on to the users with a multiplier of 1.33, to account for the system losses, which are assumed to be 25%. The wholesale cost of energy accounts for approximately half of the retail price with debt service accounting for most of the remaining. Debt service is directly proportional to the capital cost of the roadway and inversely proportional to the number of users over whom this fixed cost is divided. Increases in the interest rate increase costs, but not in a linear manner, as debt service costs include both interest and principle. Tripling the interest rate from 3.3% to 9.9% increases the retail price of energy approximately 50%, from $0.189 to $0.286/kwh.

Table 5.10
Model Results Summary

Sensitivity	SS	STM	REM	Figure Number SS	Figure Number STM	Figure Number REM
Interest Rate						
0%	$0.1357	$0.1496	$0.1570	3	21	
3.3%	$0.1517	$0.1785	$0.1894			
6.6%	$0.1711	$0.2170	$0.2322			
9.9%	$0.1932	$0.2651	$0.2855			
Wholesale Energy Cost						
$0.05	$0.1248	$0.1516	$0.1625	4	19	
$0.07	$0.1517	$0.1785	$0.1894			
$0.09	$0.1787	$0.2055	$0.2163			
$0.11	—	$0.2324	—			
System Efficiency						
65%	$0.1662	$0.1930	$0.2039			
75%	$0.1517	$0.1785	$0.1894			
85%	$0.1406	$0.1674	$0.1783			
Roadway Cost						
$0M	$0.0943	$0.0943	$0.0943	4	17-18	
$1.OM	$0.1326	$0.1504	$0.1577			
$1.5 M	$0.1517	$0.1785	$0.1894			
$2.0M	$0.1709	$0.2066	$0.2211			
$4.0M	$0.2475	$0.3190	$0.3480			
Market Penetration*						
Optimistic	$0.1517	$0.1677	$0.1744		12-14	
Baseline	$0.1517	$0.1785	$0.1894			
Pessimistic	$0.1517	$0.2000	$0.2225			

* Market Penetration Scenarios

	Initial Number of Users	Number of New Users in Following Years	Years to Achieve Steady State
Pessimistic	4	2,000	17
Baseline	3	3,000	12
Optimistic	2	4,000	8

The retail price of energy required for breakeven operation is moderately sensitive to system efficiency, maintenance costs, market penetration rate, and the breakeven year specified. Increasing the system efficiency from 75% to 85% decreases the wholesale energy cost multiplier from 1.333 to 1.176, saving the user $0.011 per kilowatt-hour. Maintenance costs are about six percent of total system costs, so doubling these costs increases retail costs about one cent per kilowatt-hour. The model results are relatively insensitive to small changes in market penetration and breakeven year, but large changes in the adverse direction-slower market growth or shorter breakeven period-can produce large increases in retail price. The sensitivity to both market penetration and breakeven year is definitely non-linear. Faster market penetration (starting in the second year instead of the third and one-third increase in new users each year) decreases the retail price of energy $0.015 per kilowatt-hour (or $0.0038 per mile). The symmetric adjustment in the opposite direction increases the retail price $0.033 per kilowatt-hour as seen at the bottom of Table 5.10. The effect of the startup transient can also be seen in Table 5.11, where the steady state, startup transient, and regional models are compared. The cumulative average volume in Year 25 for each of the three models in shown in the next to last column of this table. The retail cost components for Infrastructure Debt Service, and Maintenance and Administration (which are approximately constant in terms of total dollars) increase inversely with the cumulative average volume. These costs are roughly one-third higher for the STM compared to the Steady State Model and 50% higher for the REM.

The cumulative averages move closer to the steady-state value of 20,000 vehicles per lane per day in Year 40. Since the number of users in Years 25 – 40 is higher than the number of users used to calculate the retail price of energy, the system is profitable for both the STM and REM after Year 25.

Administrative costs are the smallest cost component, and the price charged the users is relatively insensitive to this variable.

The energy consumption of the vehicle (kilowatt-hours per mile transferred to the vehicle) has opposite effects on the price per kilowatt-hour and the price per mile. As the energy transfer rate decreases, the total kilowatt-hours sold decreases, which increases the price per kilowatt-hour, as many costs (infrastructure debt service and maintenance) remain constant. The percentage increase in the retail price of energy (dollars per kilowatt-hour) is less than the percentage change in energy consumption, resulting in a lower price per mile to the user. In all these calculations,

Table 5.11
Summarv of SSM. STM. and **REM Baseline Results**

	Wholesale cost of Energy	Infrastructure Debt Service	Maintenance, Administration	Deficit Interest	Effective Rate	Cumulative Average Volume (Year 25) (veh/lane/day)	Cumulative Average Volume (Year 40) (veh/lane/day)
Steady State	**$0.0933**	$0.0488	$0.0094	—	$0.1517	20,000	20,000
Startup Transient	**$0.0933**	$0.0651	$0.0126	$0.0075	$0.1785	15,604	17,295
RPEV Economic Model	**$0.0933**	**$0.0739**	$0.0140	$0.0079	$0.1894	13,892	16,247

it should be remembered that the vehicles are assumed to be charging on the powered roadway, so a portion of the cost per mile on the system is providing additional range for the vehicle. If there were no net charging of the batteries while on the system, all costs per kilowatt hour would be higher and all costs per mile would be lower.

This analysis has been performed using relatively conservative assumptions. It shows that the cost of energy to the user is comparable to existing ICE vehicles, even though a significant portion of the energy transferred to the vehicle (perhaps 25%) is being used to recharge the battery. The RPEV user needs to purchase less energy than a pure battery EV because most battery losses are eliminated. (For a battery EV, the AC energy consumption is often nearly twice the DC energy consumption due to losses in the charger and the battery and overcharging the battery.) In any event, the cost of energy will still be somewhat higher when operating in RPEV mode compared to pure battery mode. This gives incentive to RPEV owners to use the RPEV system only as much as necessary to accomplish a particular trip, which will tend to keep the time of day profile of energy drawn from the utility reasonably flat.

One of the most important impacts of the RPEV system will be psychological, in that it will provide owners and potential owners of electric vehicles with the security of knowing that they can get to their destination anywhere within the Los Angeles Basin without running out of energy. Such a psychological boost may well be needed to get any substantial percentage of drivers to give up ICE vehicles in favor of electric vehicles. Simply put, the existence of an RPEV network will undoubtedly increase the number of miles driven in pure battery mode as users will know they have the powered roadway to fall back on when necessary and that using the RPEV system will not be prohibitively expensive.

The RPEV system can provide energy to vehicles at a cost nearly identical to ICE vehicles and may well be the only way to increase the EV market share from 5 – 10% to 50% or more.

A. Caltrans Capital Cost and O&M Data

Among the cost categories tracked by the three models described in this report are the non-recurring initial capital outlay and the recurring expenses for operation of the RPEV system. Specifically, there are cost categories for

- Original construction
- Operations and maintenance
- Administration
- Refurbishment of the roadway after 25 years of life

The initial construction is a one-time expense in the year of construction. Operations, maintenance, and administration are recurring costs that are linked to capital outlays. Annual operations and maintenance are modeled as a percentage of the cumulative construction costs. Annual administration cost is a function of annual debt and energy expense. Replacement of the roadway is scheduled for 25 years following the original construction at two-thirds of the original construction cost.

Expenditures for operations and maintenance of the roadway refer only to work performed on the roadway between periods of initial construction and replacement 25 years later. Replacement is budgeted for separately and financed in the same way as the original construction debt.

The purpose of this analysis is to determine the appropriate value for the parameter used to determine maintenance costs (as a function of cumulative capital outlays). This is done by examining Caltrans 1990 maintenance costs compared to the cumulative capital outlays.

Table A.1 shows the actual capital outlays for Caltrans by year, corrected into constant 1991 dollars. Data were only available for 1970-1990. A 25-year period was selected over which total capital outlays were summed, matching the estimated life of the RPEV infrastructure. This is conservative as Caltrans is obviously maintaining some facilities, such as the Bay Bridge, that were constructed more than 25 years ago. Since Capital Outlay data were not available for the years 1965-1969, the dollar value for 1970 was used for that five-year period. During the period 1970-1975, capital outlays were declining yearly, so use of the 1970 value for 1965-1969 is conservative. Similarly, the construction cost factor data was only available for 1972-1991. The 1972 value of 0.30 was used for years 1965-1972. Due to inflation, this factor should be lower in the years prior to 1972, resulting in a higher multiplier to convert these capital outlays to 1991 dollars, which would increase the cumulative capital outlays. Total State Operations for 1990 are $1,235,392,000 (in 1991 dollars). As a percentage of 25 years of capital outlays, approximately 5% of this sum is spent by State Operations annually. Thus, 5% is a conservative estimate of Operations and Maintenance (O&M) as a percent of capital outlays because State Operations functions encompass a great deal more than O&M.

Expenditures for State Operations are subdivided into accounts for

- Rehabilitation
- Operational Improvement
- Local Assistance
- Program Development
- New Facilities
- Administration
- Operations
- Maintenance

Several of these categories represent functions that are separately expensed in our models. For example, expenditures for Caltrans rehabilitation refer to refurbishment of roadway (e.g., repaving). In our model, roadway replacement is expensed through long-term debt financing. Therefore, costs for rehabilitation should be subtracted from State Operations in the Caltrans data to produce more focused estimates of annual maintenance as a function of cumulative capital cost. Local assistance is non-Caltrans roadway. Program Development is planning. New Facilities includes expenditures for design, development and leasing. Administration is accounting expenses, which is separate from O&M costs in our model. Operations is maintenance studies and traffic accident research.

When costs for these non-applicable categories (everything except maintenance) are deducted from the State Operations budget, it is reduced by 64%. In other words, Maintenance accounts for 36% of the annual State Operations expenditures. This is consistent for both 1989 and 1990 expenditures. All highway maintenance is done out of the State Operations budget. This maintenance portion accounts for approximately 1.69% of the estimated cumulative capital outlays.

The Caltrans budget and expenditure data do not include matching federal aid money that typically pays for a large portion of the capital outlay for any specific project. The portion covered by federal money varies, depending on the type of project. As a rule of thumb, matching federal aid is allocated (maximally) as follows:

- Interstate programs may apply for matching federal funds up to 91.5% of capital cost
- State highway programs may apply for matching federal funds up to 75% of capital cost
- Local programs may apply for matching federal funds up to 88% of capital cost
- Matching funds for U.S. highway programs are now considered under the same rules as for the state programs.

Matching funds for portions or all of a specific program are subject to annual caps, which are determined federally. Programs that do not receive matching funds are sometimes funded entirely by the state.

Including additional federal matching funds with the total Caltrans capital expenditures is more indicative of total capital outlays and therefore lowers the percentage of maintenance compared to capital outlays. If, on average, the Caltrans capital outlays and federal matching funds each cover 50% of project costs, the estimate of annual maintenance drops from 1.69% to 0.85% of cumulative capital outlays. This is probably a conservative assumption regarding the portion of programs receiving matching federal funds.

Assumptions concerning operations and maintenance of the RPEV system are based on a percentage of the cumulative new roadway capital costs. Analysis of historical Caltrans data supports percentages ranging from 0.8% down to 0.1%. This conclusion is conservatively low because:

1. Data from Caltrans includes maintenance performed on roads older than 25 years which, if subtracted from maintenance figures would lower the maintenance percent; and
2. Costs of refurbishing the system after 25 years are not included in this maintenance pool. Refurbishment is financed separately, as long-term debt.

Based on the above analysis, we feel that the 1% O&M costs assumed in our models is a conservative number and the actual cost may be significantly lower.

Table A-I Operations and Maintenance as a Percentage of Cumulative Capital Outlay

Year	Capital Outlays (Current Year Dollars)	1987 Factor	Conversion Factor to 1990 Dollars	Capital Outlays (1990 Dollars)
1990	379,873	1.1350	1.0000	379,873
1989	241,487	1.1130	1.0198	246,260
1988	204,290	1.0440	1.0872	222,097
1987	226,106	1.0000	1.1350	256,630
1986	257,695	0.9500	1.1947	307,878
1985	294,244	0.9270	1.2244	360,266
1984	159,088	0.9330	1.2165	193,531
1983	143,008	0.8190	1.3858	198,186
1982	79,438	0.8130	1.3961	110,901
1981	98,099	0.9060	1.2528	122,894
1980	106,796	0.8210	1.3825	147,641
1979	251,285	0.8010	1.4170	356,066
1978	251,477	0.6210	1.8277	459,624
1977	349,438	0.5370	2.1136	738,570
1976	111,506	0.4770	2.3795	265,324
1975	336,909	0.4670	2.4304	818,826
1974	309,861	0.4560	2.4890	771,255
1973	406,907	0.3120	3.6378	1,480,255
1972	476,249	0.3000	3.7833	1,801,809
1971	529,703	0.3000	3.7833	2,004,043
1970	545,419	0.3000	3.7833	2,063,502
1969	545,419	0.3000	3.7833	2,063,502
1968	545,419	0.3000	3.7833	2,063,502
1967	545,419	0.3000	3.7833	2,063,502
1966	545,419	0.3000	3.7833	2,063,502

Total Capital Outlays	21,559,438
1990 State Operations	1,216,106
State Operations as Percentage of Cumulative Outlays	5.64%
1990 State Operations (Maintenance Only)	399,985
Maintenance as Percentage of Cumulative Outlays	1.86%

Fraction of Capital Outlays

Federal Contribution	State Contribution	Maintenance as Percentage of Capital Outlays
0.00	1.00	1.86%
0.50	0.50	0.93%
0.70	0.30	0.56%
0.90	0.10	0.19%

All Dollar Values in Thousands

B. Costs of RPEV System Equipment

The cost of RPEV equipment will clearly drop from current prices as the volume of RPEV equipment increases. With the exception of a few of the power electronics components in the onboard controller (primarily capacitors), all elements of the wayside and onboard equipment have been hand-built to order. The number currently required is not sufficient to justify any significant investment in tooling. Most of the components are custom designed to our specifications with the engineering time spread out over only a few pieces. Manufacturers have indicated that prices will come down substantially with larger volumes. The pickup cores manufacturer has ideas for completely automating the manufacturing process, resulting in a cost reduction of several fold compared to their existing methods. The investment of several hundred thousand dollars would cut the cost of the cores from $860/foot of pickup to $350/foot or less.

1.1 Vehicle Costs

The cost of the onboard equipment has been largely ignored to date. There are two reasons for this. The early research work has been sponsored to a large extent by departments of transportation (both federal and state) and their primary concern has been with the wayside infrastructure. Secondly, in the research projects to date, roadway costs have dominated due to the large amount of roadway per vehicle, on the order of 500–1,000 feet of roadway per vehicle. In the REM analysis, on the other hand, during the first twenty-five years of system operation, the vehicle population comes to a cumulative total of more than one million vehicles or approximately 500,000 vehicles active during any year after the system reaches population saturation. This is equivalent to five or ten feet of roadway per vehicle. Clearly, for such a system vehicles cannot be ignored when considering the capital cost of the roadway.

The cost of several RPEVs of varying sizes is shown in Table B-1 as the incremental cost compared to a pure battery EV. For instance, both vehicles have a motor and controller. The size of this equipment depends on vehicle size and is not a function of how the energy is supplied to the motor controller, resulting in zero cost differential between an RPEV and a pure battery EV. The battery EV is assumed to have a range of 80-100 miles, while the RPEV's autonomous range is assumed to be half this value.

Table B-I
Estimated Vehicle Costs—Large-Scale Production

Roadway Powered EV	Compact Car	Large Van	Full-Size Bus
Onboard Power Electronics			
AC Capacitor	200	300	400
Inductors	150	200	250
AC Switches	200	300	400
Rectifier	50	75	100
Filter Capacitor	50	75	100
Miscellaneous	50	100	150
Subtotal	700	1,050	1,400
Pickup cores	400	800	1,600
Pickup Conductors	100	125	150
Onboard Controls	200	200	200
(communication sensors, computer)			
Labor	100	150	200
Battery	1,500	3,000	10,000
Total	3,000	5,325	13,550
Pure Battery EV			
Battery	3,000	6,000	20,000

The RPEV costs can be broken down into four categories, namely

- Onboard power electronics (or onboard controller)
- Pickup inductor
- Battery
- Miscellaneous equipment, including computer, communications, sensors, and pickup suspension system

The third item is the only one possessed by the battery EV, although the battery is twice as big (and twice as expensive) as the RPEV's to provide for twice the autonomous range.

Three vehicle types are considered in Table B-l-a compact car, a large van, and a full-sized bus. These were chosen to represent a wide range in vehicle sizes, with gross vehicle weights (GVWs) of approximately 3,000, 8,000, and 30,000 pounds. Interpolation should yield reasonable results, such as the average of the car and full-sized van giving an adequate set of values for a mini-van. The vehicle power levels (both drivetrain and inductive coupling system) do not scale directly with GVW, as heavy vehicles typically have lower acceleration rates than passenger cars. The ICS power ratings are assumed to be 25, 50, and 100 kilowatts for the three vehicle types.

The values presented in Table B-l are rough estimates and should not be taken as definitive numbers. The subject of vehicle unit costs has not been studied with the same level of scrutiny as the roadway costs.

1.1.1 Onboard Power Electronics

The onboard power electronics consists of several components, which are specifically identified in the upper portion of Table B-l. The cost of these components does not scale directly with GVW or inductive coupling system output power. In general, the number of components does not change with coupled power rating- each system will have a single rectifier. The size of the components increases with ICS power rating, but the component cost does not increase linearly with size. The cost of the onboard controller (all power electronics components) for the three vehicle types is $700, $1,050, and $1,400.

1.1.2 Inductive Pickup

The cores and conductor packs make up almost all of the pickup costs. The cost of the cores scales linearly with the length of pickup as well as with power rating. The cost of the conductors, on the other hand, increases only slightly with size. The total pickup cost estimates are $500, $925, and $1,750. Since the cores are much more expensive than the conductors, these costs are nearly linear with power rating.

1.1.3 Miscellaneous Equipment and Costs

This category includes the onboard computer, communications equipment, sensors, and pickup suspension, as well as labor to assemble and mount all hardware. The cost of the communications and control equipment is constant for all vehicle types, while the other costs increase slightly with ICS power rating.

1.1.4 Battery

The battery (size, weight, cost) is assumed to scale with vehicle weight. This is the only cost component where the cost increases faster than the power rating. The battery represents at least half of the total cost for all vehicles, increasing from 50% (car) to nearly 75% (bus).

1.1.5 Examination of Incremental Vehicle Capital Cost

The battery is the only cost listed for the pure battery EVs. Due to the assumption of an autonomous range equal to twice that of the same size RPEVs, the pure battery vehicle costs are always equal to or greater than the RPEV's. For the passenger car considered, the total vehicle cost is $3000 for either. The capital cost of the battery for the pure battery bus at $20,000 is nearly 50% more expensive than the projected $13,550 cost of the RPEV system and battery bus.

Battery EVs are currently much more expensive than corresponding ICE vehicles. This is primarily due to the extremely low production volumes of EVs. Many experts believe that in large-scale production, the capital cost of pure battery EVs will be the same as ICE vehicles if the cost of the battery is not included. If this assertion is true, the RPEV will also be more expensive than ICE vehicles. The capital cost of the RPEV will be similar to the cost of a battery EV for smaller vehicles. For larger vehicles, the RPEV will be less expensive than pure EVs.

2.1 Roadway Costs

The cost of the wayside infrastructure includes the roadway inductor, the power conditioners and distribution system, and labor involved with installation as well as engineering. If this technology is implemented on a wide scale, presumably equipment that eases fabrication and installation of the system components will be developed. For instance, the process for slip-forming of concrete freeway medians has dramatically reduced the cost of this type of installation compared to forming in place. Analogous special-purpose equipment will be developed for the RPEV system if hundreds or thousands of miles of the roadway inductor were to be installed.

The cost components of the wayside infrastructure are summarized in Table B-2. There are two columns, the first representing the projected costs assuming normal, expected development of the technology. The second column presents more optimistic figures, many of which represent a breakthrough such as the use of an alternate material for the roadway cores..

2.1.1 Core Modules

The core modules are expected to account for approximately half of the total installed system cost. The cores are currently made of grain-oriented silicon steel laminations. The nominal cost projection of $900,000 per lane-mile assumes the same basic technology will continue to be used, although the cost of the manufacturing and assembly process will be reduced by a factor of two from present costs by appropriate investments in tooling, and automated manufacturing equipment as well as large volume discounts on materials. The cost of $500,000 in the right-hand column represents a breakthrough, most likely the use of a powdered iron core, which would have very dramatic reductions in both material costs and fabrication costs. The use of a completely automated pressing process, currently in use for this type of material, could reduce labor costs for the cores to nearly zero.

2.21. Conductors

The conductors are assumed to be custom made for the RPEV application. They consist of multi-conductor cables which will be pulled through conduits cast into the core modules. This cost is intended to include associated equipment such as connectors. There is only a slight difference between the nominal cost ($100,000) and optimistic cost ($80,000) for the conductors.

2.1.3 Power Conditioner and Distribution System

The power conditioners and distribution network is the hardware element with the largest uncertainty, as the power conditioner for a large-scale operational system will have several additional requirements compared to the power supplies used at the existing test facilities. The power conditioners will feed multiple segments through a distribution network. Switches and sensing/communications equipment will allow only those segments that are occupied by an RPEV to be energized. A single power conditioner will probably power approximately one lane-mile of roadway. Such a power conditioner may have a peak power rating of 0.5 to 1.0 megawatts and may cost $300,000 to $400,000, with the balance of the $500,000 nominal cost going to the distribution and sensing/communications equipment. The optimistic figure may be achievable through a lower cost of the power conditioner or the ability of a single unit to power more than one lane-mile. In most installations, at least one lane in each direction will be powered, allowing a single unit to supply a length of 0.5 miles. By locating the power conditioner at the center of this piece of roadway, the maximum distribution line would be about 0.25 miles, or slightly over 1,000 feet.

2.1.4 Engineering

The cost of engineering should be relatively low due to the standardization of components, especially the roadway core modules. Even though the equipment being installed is complicated, it can be designed so that the interfaces, both mechanical and electrical, are very simple. This will cut engineering costs, as well as the effort required for installation and construction management.

2.1.5 Installation

The installation cost of the wayside infrastructure is also a source of significant uncertainty. The construction of the test track at the Richmond Field Station involved very substantial effort that was independent of the roadway inductor and distribution system installation, including a new culvert and large sections of new pavement. This makes it difficult to use the RFS construction costs as a basis for projections of future costs. In addition, the designs have evolved, especially with regard to the installation of conductors. Another factor that complicated the cost estimation process is the uncertainty about how much of the installation of the RPEV system will take place as part of new construction or major maintenance work on a section of roadway. Considering all these factors, the costs are estimated at $350,000 (nominal) and $250,000 (optimistic).

2.1.6 Total Cost

The total wayside infrastructure cost for the conservative and aggressive categories is $1.95 and $1.18 million per lane-mile, respectively. The analysis was performed using $1.5 million dollars per lane-mile, which was chosen as a round number roughly half way between the two estimates. Certainly $2.0 million per lane-mile could have been used, and was in fact considered. $1.5 million was chosen because it represents our best engineering judgment for the true cost and there was adequate conservatism in many of the other modeling and analysis assumptions.

If it is critical to keep the cost of the infrastructure to $1.5 million per lane-mile, that can almost certainly be accomplished by reducing the amount and/or grade of material used in the roadway cores. This will reduce the cost of the roadway inductor at the price of increased losses (reduced system efficiency).

3.1 Conclusions

The cost of the vehicles for use on the RPEV system will probably be equal to or lower than the cost of a comparable pure battery vehicle; however, the capital cost of both of these electric vehicles will probably be somewhat higher than comparable ICE vehicles.

The capital cost of the infrastructure will probably be about $1.5 million per lane-mile, although there is an uncertainty of approximately ± $0.5 million depending on the extent of advances of the technology. Roadway core modules, power conditioners, and installation are the major cost components, and all still have a reasonable amount of uncertainty.

The REM baseline case involves the construction of 1,144 miles of roadway and the purchase of 800,000 RPEVs during the first twenty-five years of operation. The capital cost of the wayside infrastructure is about $1.7 billion. Assuming the vehicle population consists of 90% cars, 5% vans, and 5% heavy vehicles (large trucks and full-sized busses) the incremental portion of capital costs of the vehicles (compared to a similar ICE vehicle or battery vehicle excluding the battery) is about $2.9 billion, or nearly double the cost of the wayside infrastructure.

Table B-2 Estimated Roadway Costs-Large-Scale Production

	Conservative Cost $/lane-mile	**OptimisticCost $/lane-mile**
Core Modules	900,000	500,000
Conductors	100,000	80,000
Power Conditioner and Distribution System	500,000	250,000
Engineering	100,000	100,000
Installation	350,000	250,000
Total	1,950,000	1,180,000

C. Inflation Effects

The analysis in the body of this report was performed assuming zero inflation. The baseline interest rate was 3.3%, with sensitivity analysis performed at 0, 6.6, and 10.0% interest rates. That approach was chosen as the analysis is much simpler to perform without inflation--cumulative costs and revenues can be calculated without having to be concerned with the year in which they occurred. A more realistic approach may be 10.0% interest and 6.7% inflation, with the difference of 3.3% corresponding to the real interest rate.

The analysis is intended to give a quick look at results with inflation. The methodology is not completely rigorous, although inflation has been properly incorporated into the most significant variables. Results are presented in both current-year dollars and 1992 dollars.

1. Methodology

This analysis is based on the REM baseline case, with adjustments made as necessary to match the desired interest and inflation rates. Most variables-such as network size, construction rate, market penetration rate, and vehicle energy consumption-remained constant. Revenues and costs that are not directly tied to interest rates were inflated for every year by the inflation factor for that particular year. (This inflation factor is 1.0 in the first year of the project, which corresponds to starting the project in 1992. A later start date would multiply all dollar amounts by a constant and would not change the shapes of any of the curves or the break-even year.)

At 6.7% inflation, costs double in just under eleven years, resulting in an inflation factor of over 2.0 in Year 12, 4.1 in year 23, and 8.5 in Year 34, and 12.5 in year 40. Revenues, energy costs, and other operating costs (operations, maintenance, and administration) were calculated by taking the corresponding values for the REM baseline case and multiplying by the inflation factor The REM baseline Year 25 break-even rate of $0.1894/kwh was used for the baseline case revenue calculations.

The costs that are directly tied to the interest rate (construction loan debt servicing and cumulative deficit interest payment) were calculated completely independently of the baseline case. For the construction loan, a 25-year fixed 10% loan was assumed. The principle is $1.5 million per lane-mile, multiplied by the inflation factor for the construction year ($1.50 million in Year 1, $1.60 million in Year 2, $1.71 million in Year

3, . . .). Similarly, the replacement costs of $1.0 million per lane-mile were inflated to correct them to the year in which these expenses occur. Inflation increases the replacement costs to $4.74 million per lane-mile in Year 25 and $9.68 million in Year 36.

The annual inflated costs and revenues are calculated, resulting in an annual profit/loss. The annual profit/loss is accumulated over the years with the deficit interest cost in any year equal to 10% of the cumulative loss as of the prior year. As with the baseline case, after the system becomes profitable on a cumulative basis, the profits are assumed to be withdrawn from the system, so there is no interest income earned on cumulative profits in the later years.

2. REM Results with Inflation

The model results from the inflation runs show trends similar to the REM baseline, especially when the results are presented in 1992 dollars rather than current-year dollars. The early years are unprofitable but, as usage of the RPEV system increases, the system becomes profitable, first on an annual basis and later on a cumulative basis. After the break-even point, profits amass quickly.

2.1 Profit and Loss

The annual costs, revenue, and profit, along with cumulative profit are presented in Figure 1 for the inflation case. With results in current-year dollars, all curves increase after Year 20, when the system becomes profitable on an annual basis, which is approximately six years later than for the REM baseline case. The system breaks even on a cumulative basis in Year 29 four years later than the baseline case. The curves from Figure 1 are converted into 1992 dollars by dividing each value by the inflation factor for the corresponding year. These values are presented in Figure 2 In constant 1992 dollars, the revenue levels out as soon as the population stabilizes, in Year 22. The cost curve displays some unusual ripples between Years 20 and 40. The deficit interest costs decrease as soon as the system is profitable on an annual basis (Year 20.) However, roadway replacement starts in Year 26, which increases annual costs, as the original construction loan (with an original principle of $1.5 million per lane-mile) is replaced with a loan for replacement of the roadway. Even though this cost is only $1.0 million in 1992 dollars, with the inflation factor for Year 26, this loan is $5.06 million per lane-mile. Between Years 26 and 30, the increase in the infrastructure loan partially offsets the decrease in payments on the cumulative deficit. By Year 30, the cumulative deficit has been paid off. Through Year 36, the annual costs increase as the original construction loan continues to be replaced by the more expensive replacement loan. Starting in Year 37, the debt service remains constant in current-year dollars, resulting in a decrease when expressed in 1992 dollars. This decrease in costs results an upward bend in the annual profit.

It is interesting that even though the annual profit curve does not cross zero until Year 20, the cumulative profit reaches its minimum in Year 15. This seemingly contradictory situation results from the cumulative deficit increasing at a rate lower than 6.7% during this five-year interval. As can be seen in Figure 1, the cumulative deficit is increasing in current-year dollars during this interval, but more slowly than the rate of inflation.

The baseline case results are presented in Figure 3 for comparison with Figure 2 results. Since both are expressed in 1992 dollars, comparisons are easy to make. The most obvious difference is that in the inflation case, loses are larger in the early years. In the baseline case, cumulative losses never exceed $500 million, but are more than twice that in the inflation case. The causes of this are investigated in the next two sections. After the system is profitable on a cumulative basis, the annual cost, revenue, and profit are similar for both cases, with annual revenues just under $400 million, costs of nearly $300 million, and profits of nearly $100 million per year. During the first ten years after becoming profitable on a cumulative basis, the system earns profits of approximately $700 million for both sets of economic assumptions.

2.2 Cost Components

The source of the increased losses during the early years of the inflation case can be determined by analysis of the cost components. Figure 4 presents this data for the inflation case in current-year dollars. As with the baseline case, all the cost components except energy are very high in the first years of operation when usage of the system is very low. Unlike the baseline case, the system costs increase dramatically in the late years due to inflation. The wholesale energy cost is constant in 1992 dollars, so its increase from $0.10 to $1.20 is a direct measure of inflation. The deficit interest remains nearly constant at a moderate level from Years 10 through 25. In fact in the interval from Year 15 to Year 25, the deficit interest is approximately equal to the debt service on the construction (infrastructure) loan. The cost components are converted into 1992 dollars in Figure 5. As previously asserted, the wholesale energy cost remains constant, as it does in the baseline case, shown in Figure 6. The Operating Expenses (operations, maintenance, and administration) represent a small portion of the total costs for both cases, approximately $0.01 per kilowatt-hour after Year 15. Debt service on the construction loan is higher in the early years and lower in the later years for the inflation case. These higher construction loan costs in the early years ($0.19 vs. $0.135 in Year 10) cause the much higher cumulative losses for the inflation case, which in turn result in high deficit interest expenses for the inflation case. As was previously mentioned, the deficit interest expense equals and even surpasses the construction loan expenses in the inflation case, while they are approximately one-quarter the construction loan costs for the baseline (no inflation) case.

2.3 Loan costs

The construction loan costs were expressed as components of the annual cost per kilowatt hour in the previous section. Since the number of kilowatts sold at the retail level is changing until the user population saturates in Year 22, the cost curves are somewhat distorted. Annual and cumulative costs for both cases are presented in Figure 7. The values for the inflation case are presented in 1992 dollars. The cumulative costs for both cases are within ten percent in Year 25, and are virtually identical in Year 31, twenty-five years after the “average construction date” of Year 6. (Since the roadway is built at a constant rate from Year 1 through Year 11, the average construction date is Year 6, and 25 years after that date, half of the original construction loans have been repaid.) The annual costs for the inflation case (dotted line) average approximately 50% higher than those for the baseline case (solid line) during the first ten years. After Year 16, the annual costs for the inflation case are lower, but by this point a large cumulative deficit has been established that takes four more years to repay, compared to the baseline case.

The costs are nearly identical in Year 40, but the baseline costs are constant, while those for the inflation case are dropping, as they will continue to do for the next ten years, resulting in higher profits for the baseline scenario from Year 40 until Year 50 or 55.

3. Conclusions

The inflation case examined shows trends very similar to the baseline case when the results are converted into constant 1992 dollars. Even though the infrastructure loan has cumulative costs approximately equal for both scenarios, those costs are heavily loaded in the early years for the inflation case. The higher costs (and losses) in the early years for the inflation case increase the interest on the cumulative deficit and delay the system cumulative break-even point by approximately four years. The baseline case generates higher profits in the later portion of the loan’s life than the inflation case.

Alternate forms of financing, such as interest-only bonds with staggered maturity times, should be investigated, as they represent a more common financing method for capital-intensive projects.

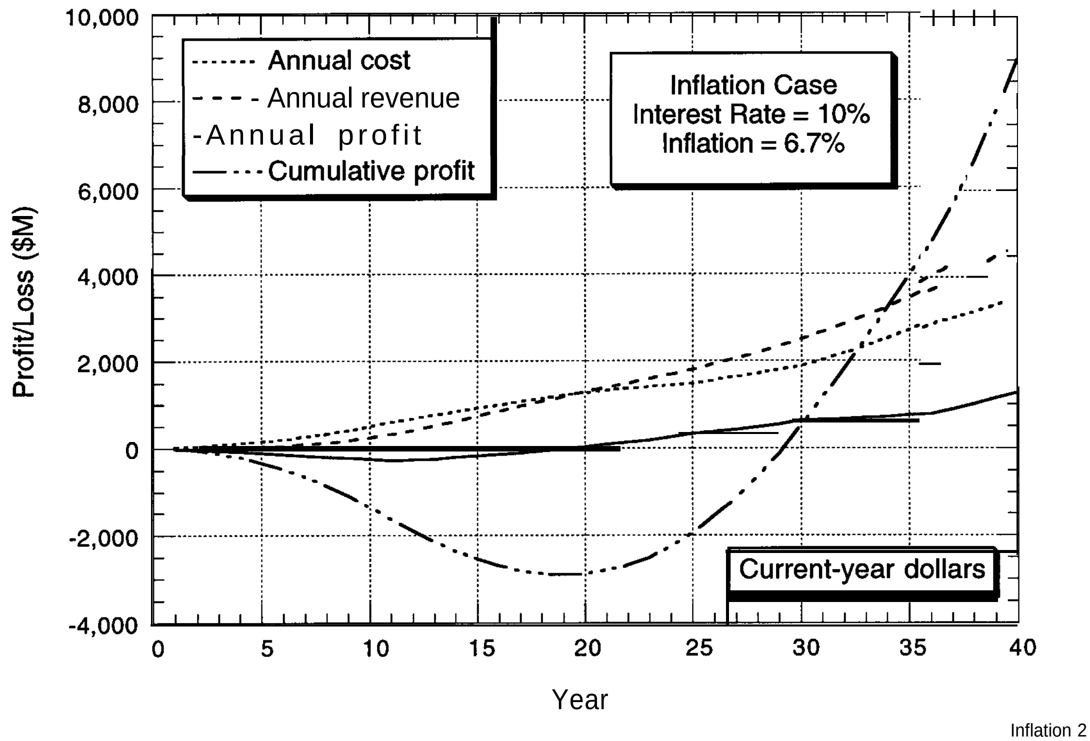


Figure 1

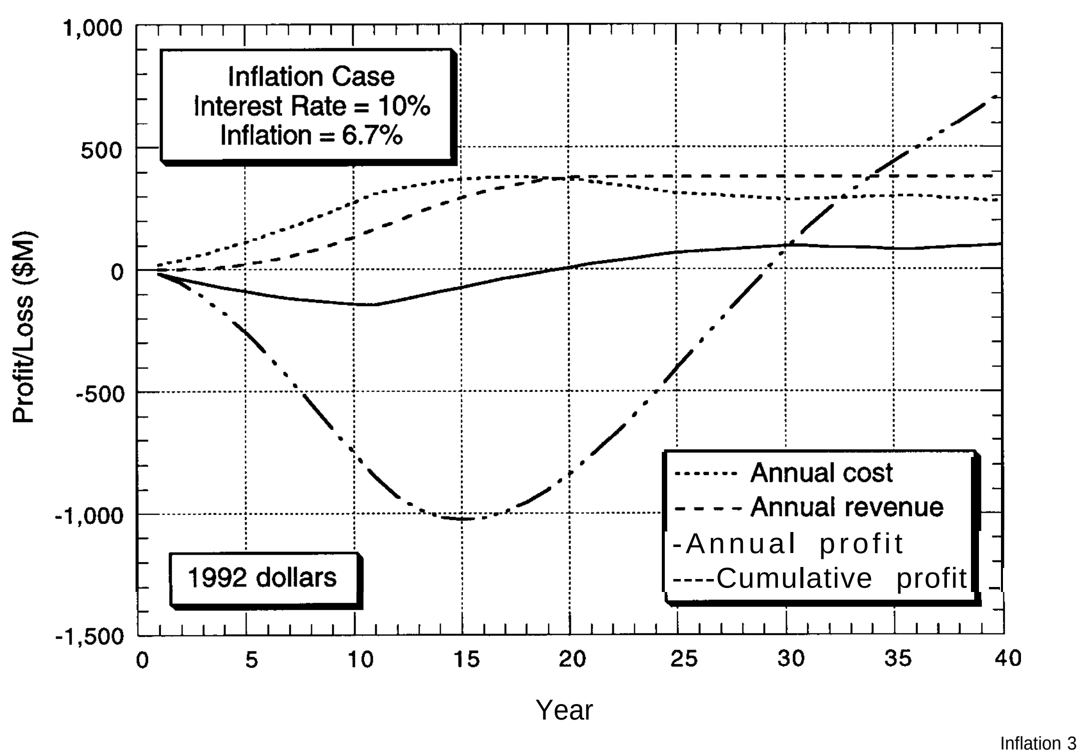


Figure 2

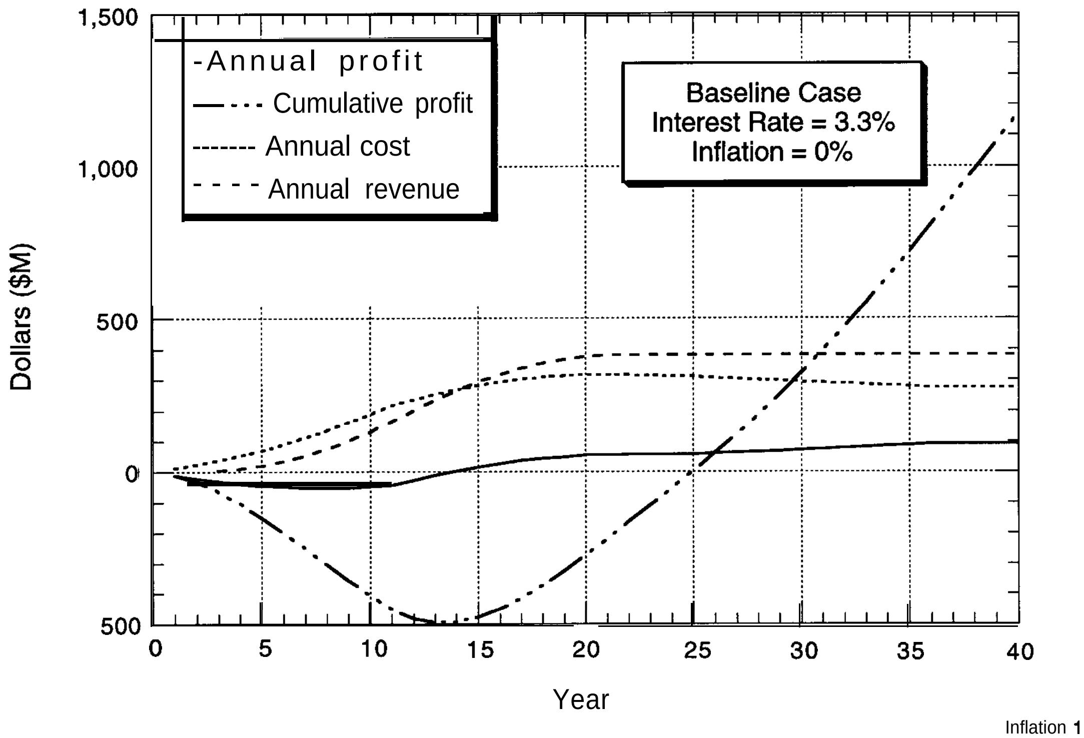


Figure 3

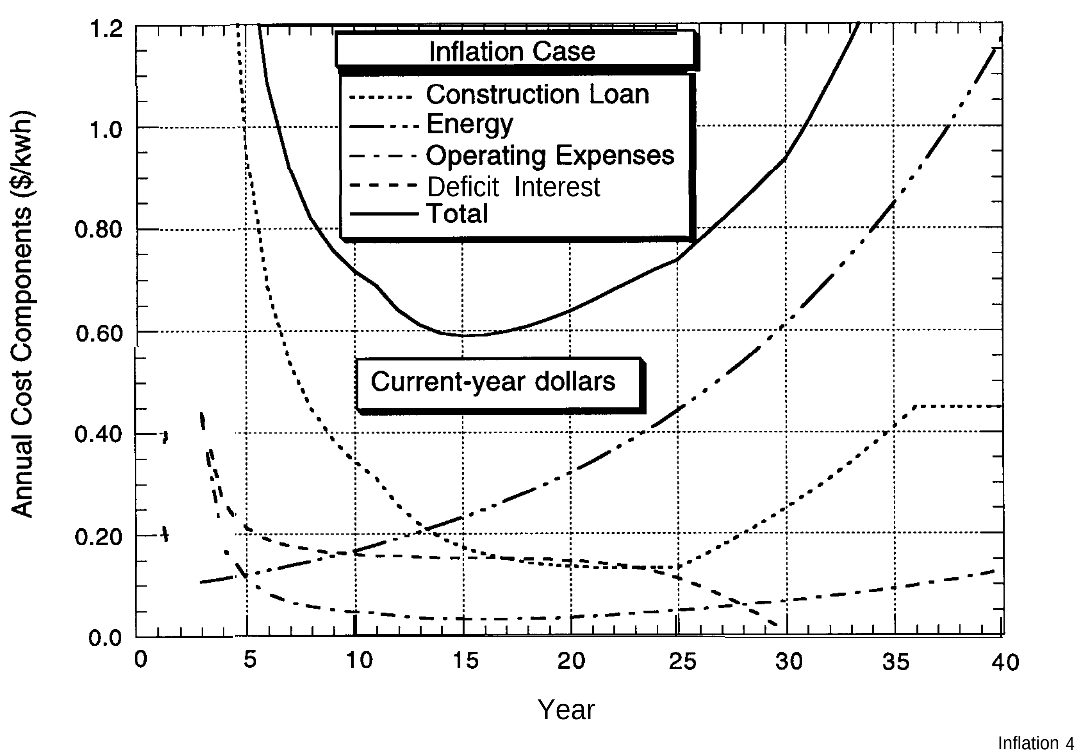


Figure 4

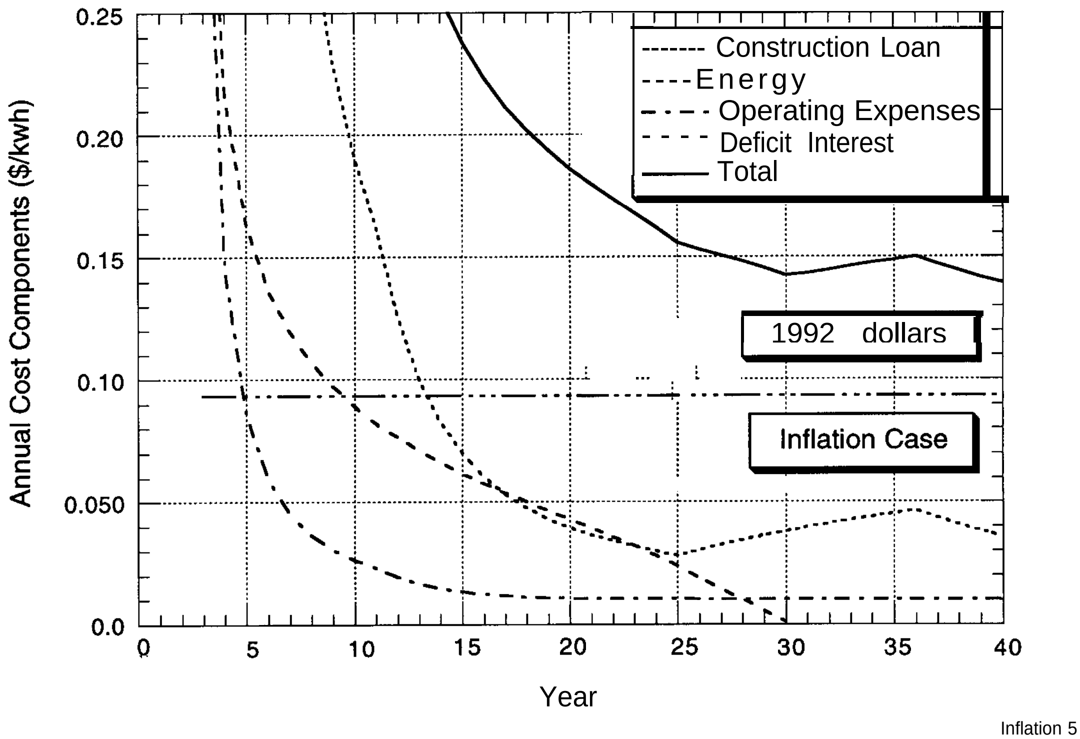


Figure 5

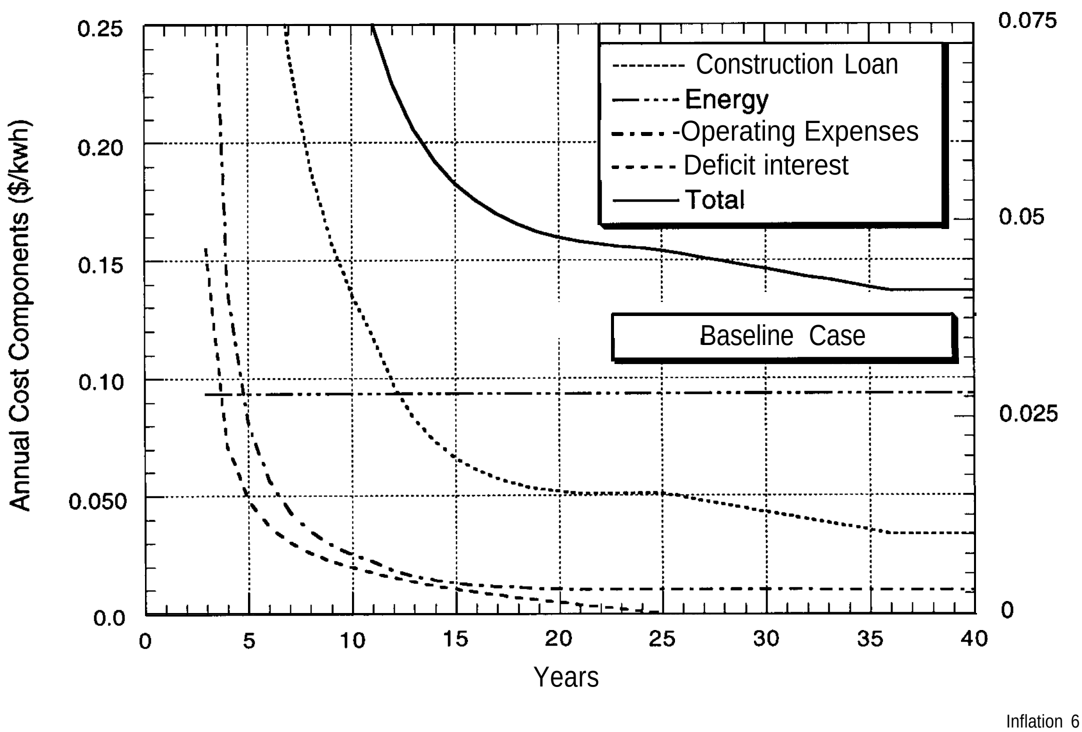


Figure 6

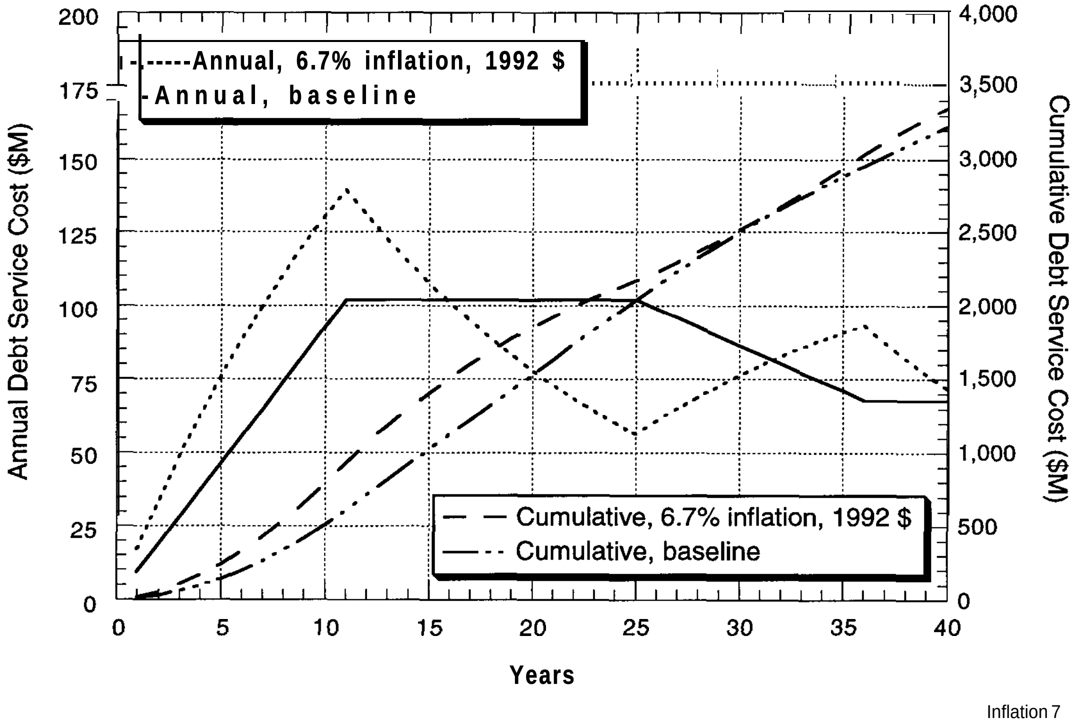

Annual, 6.7% inflation, 1992 $
Annual, baseline
Cumulative, 6.7% inflation, 1992 $
Cumulative, baseline
Annual Debt Service Cost ($M)
Cumulative Debt Service Cost ($M)
Years
0
25
50
75
100
125
150
175
200
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
5
10
15
20
25
30
35
40
Inflation 7

Figure 7

Glossary

acoustic noise — audible sound as contrasted to electrical or signal noise

airgap — distance between the supply (roadway) inductor poleface and the pickup inductor poleface, usually the magnetic gap (i.e., low permeability); due to non-magnetic materials (generally fiberglass or plastic) that cover the cores, the mechanical airgap is always equal to or smaller than the magnetic airgap.

anechoic chamber — a chamber (approximately) free of echoes or reverberations, used for acoustic measurements; all interior surfaces of such a chamber are designed to absorb the maximum amount of acoustic energy

Annual Rate- Price of energy sold that generates revenues for a specific year to equal that year's costs.

Annual Simple Rate- Annual breakeven rate with Deficit Interest excluded from costs

AWG -American Wire Gauge

Breakeven Rate- Retail price of energy that causes costs to equal revenues. It can be used on an annual or cumulative basis. Is always a function of time, except for the Steady State Model.

Breakeven Year- Number of years from start of construction until cumulative costs equal cumulative revenues as used in the definition of Effective Rate.

Brooks coil- a short coil with windings placed concentrically

calorimetry — determining energy loss (as in an energized core by measuring temperature rise of the device and surrounding media (water, air), which are usually contained in an insulated vessel

capacitive load — an electrical load with capacitive reactance, that is, voltage follows current

crisscross -the transposition of parallel conductors in the pickup or roadway winding to maintain equal conductor currents

Deficit Interest- The interest paid on a loan made to cover operating losses in the early unprofitable years of the system. In later years, it decreases as profits reduce this loan balance, which goes to zero in the breakeven year.

di/dt inductors -current rise limiting inductors

dynamic testing -testing with the vehicle in motion

eddy currents -electrical currents induced in a conductive material by a magnetic field

Effective Rate- Retail price of energy that generates cumulative revenues equal to cumulative costs at the specified breakeven year (Year 25 unless otherwise specified).

extremely low frequency (ELF) — electric and magnetic fields

flux — usually magnetic flux

free field — where sound is not affected by either the source or surfaces (compare with near field and reverberant field)

fringing -or fringe flux is magnetic flux that enters or leaves a magnetic core through the edge or side rather than the pole face. This fringing effectively increases the pole face area, but also increases the flux density near the sides or edges.

gate signal -low voltage used to turn on an SCR or transistor

inductive coupling system (ICS) — a system to transmit power across a large airgap with magnetic fields

isolation inductor — an inductor used in the onboard controller to decrease the damping ratio (increase Q) in the inductive coupling system. This increases the magnitude of the response of the vehicle portions of the ICS, increasing the output current. The isolation inductors also help maintain low harmonic content in the various system waveforms.

magnetic induction -flux level

mutual inductance — measures the magnetic field that links the roadway and the pickup. This is the flux that couples power to the vehicle and is the most important of the three inductances in the coupled condition.

near field -within a foot of the sound source (compare with free field and reverberant field)

nominal values — 400 Hz frequency, roadway current of 1200 amps, coupled excitation of 3.0 volts per foot of core

normalize — rescaling of a variable, generally accomplished by dividing by the nominal or design value

onboard controller — the electronic components on the vehicle that regulate the power received by the vehicle from the ICS

open roadway inductance — the inductance of a segment of RPEV roadway with no vehicle present

pickup core — individual laminated iron pieces of which the pickup inductor is **composed**

pickup inductor -the cores and conductors formed into a large inductor

pickup leakage flux — detrimental to power coupling and results in a reduction of voltage at the pickup terminals. The smaller this is, especially in comparison to the mutual inductance, the better. This leakage does not represent an actual loss of energy as it is a reactive, not resistive component.

POISSON — magnetic analysis program used to predict coupled and open roadway magnetic properties

pole piece — "I" laminations of silicon-iron used as the pole faces in the ICS roadway inductor

power conditioner -a large power supply that converts 3-phase 60 Hz power to single phase high-frequency power

power distribution hardware — switch, busbars, and cables that route power from the power conditioner to the roadway

power factor- the cosine of the angle between the current and voltage from the power condition to the roadway

reactive load — an electrical load that has no (or very little) reactive component (i.e., a large resistor)

reluctance — magnetic resistance

REM- RPEV Economic Model

resistive load — a resistor (usually water cooled) into which power from a battery or inductive coupling system can be dissipated as heat

reverberant field -sound bouncing off a surface (compare to free field)

roadway core modules -roadway cores assembled into a larger unit and held together with epoxy resin or concrete for; for the Richmond Field Station track they are 9 feet 4 inches long and 20 inches wide

roadway cores -the individual laminated iron pieces of which the roadway inductor is constructed

roadway inductor — the roadway core modules and conductor installed in the road surface to make a single large inductor to supply power to an RPEV

roadway leakage inductance — the perceived inductance caused by flux that does not couple with the pickup inductor

SCAG- Southern California Association of Governments

section (of roadway inductor) — a length of roadway inductor with essentially continuous cores; the conductors are not transposed within a section

segment (of roadway inductor) — a length of roadway inductor, generally composed of several sections that is energized or de-energized as a unit

segment switching — the switching of segments on and off to ensure that the segment occupied by an RPEV is energized, while the others are de-energized to avoid open roadway losses

Silicon Controlled Rectifiers (SCR) **—** a solid-state device that conducts in one direction (similar to a diode) but must be turned on by a gate signal before conduction can begin. Two SCRs connected in parallel with a positive conduction direction can be used as a switch for ac current.

Simple Cumulative Rate- Cumulative breakeven rate with Deficit Interest excluded from costs

skin effect — the tendency of current to flow near the surface of a conductor at higher frequencies

solid-state switches — sometime referred to as contactors, a reference to the mechanical switches they often replace

SSM- Steady State Model

static testing-test while the inductive coupling system is stationary

steering assistance system — a device that indicates to the driver of an RPEV the centerline of the roadway to allow the driver to better center the pickup inductor over the roadway inductor

STM- Startup Transient Model

thermal time constant — the characteristic time associated with thermal transients (dynamics) in an object or system

triac — a small integrated device that is essentially two SCRs in parallel; see SCR.

turn — a winding of wire or cable through an inductor or transformer core that starts and ends in the same location

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