Title

Feasibility Study Of Advanced Technology Hov Systems: Volume 2a: Feasibility Of Implementing Roadway Powered Electric Vehicle Technology In El Monte Busway: A Case Study

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Feasibility Study of Advanced Technology HOV Systems

Volume 2A: Feasibility of Implementing Roadway-Powered Electric Vehicle Technology in El-Monte Busway: A Case Study

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FEASIBILITY STUDY OF ADVANCED TECHNOLOGY HOV SYSTEMS

VOLUME 2A

FEASIBILITY OF IMPLEMENTING ROADWAY-POWERED ELECTRIC VEHICLE TECHNOLOGY IN EL-MONTE BUSWAY: A CASE STUDY

by

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December 1992

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EXECUTIVE SUMMARY

Concern over the state's air quality has led California to enact a state law requiring 2 percent of all vehicles sold by 1998 to be emission-free vehicles, and 10 percent by 2003. Electric vehicles' (EV's) are essentially "emission free," in that they themselves do not emit pollutants while running on the road or stopping in traffic, although power plants supplying electric power to them do. EV's have not gained widespread use because they have limited range between battery recharges.

One way to increase the range of EV's between overnight battery recharging, is through the use of roadway powered electric vehicles (RPEV's). These are hybrid electric-electric vehicles using an "inductive" coupling power transfer principle, whereby energy in the battery is supplemented by energy transferred to the vehicle through an inductive coupling system (ICS). RPEV's can operate both on and off the electrified roadway. On the electrified roadway, they draw power directly from the roadway for use in propelling the vehicle. The unused balance of roadway power is stored in the onboard battery. Off the electrified roadway, RPEV's rely solely on the onboard battery power.

STUDY OBJECTIVE

The objective of this study is to assess the feasibility of early deployment of the RPEV technology in existing high-occupancy-vehicle (HOV) facilities in California. To meet this objective, the following tasks were performed:

1. Synthesize the current status of the technology development for RPEV's
2. Select one HOV facility for a site-specific feasibility evaluation
3. Determine the scale of electrification and level of energy transfer required-for the selected site
4. Determine preliminary design of the inductive coupling system (ICS) for the selected site
5. Assess the daily energy demand of this system
6. Develop a technology demonstration plan, and identify issues pertinent to the implementation
7. Estimate probable costs of the technology demonstration plan

PRINCIPAL FINDINGS

Principal findings are presented by the analysis task, as follows.

Task 1: Literature Synthesis

The literature synthesis indicatesthatpractical RPEV systems can be designed for use on the highway. Systems with higher frequency and lower roadway currents than existing prototypes are likely candidates for eventual use on the highway. Such systems have yet to be built and tested.

Task 2: Site Selection and Data Collection

Early deployment of the RPEV could take place on a limited scale in existing HOV facilities. In this regard, El-Monte Busway (a 3+ HOV facility) in Los Angeles was selected as a candidate for a site-specific feasibility evaluation. This HOV facility is located on I-10, and is about 11.6 miles long. Its western end originates in downtown LA at Alameda Street. To the east, the HOV facility ends at the El-Monte Busway Terminal (Figure S1). It has one travel lane in each direction, with the two directions separated by permanent barriers. For about four miles of the Busway to the west, the HOV lane is separated from the freeway lanes by permanent barriers. For the remaining length, the HOV lane is separated from the freeway lanes by buffers of at least 4 feet wide. Entries into and exits out of the Busway are through exclusive ramps only. El-Monte Busway is a 24-hour HOV facility. Traffic volume on the Busway during peak hours is over 1,200 vehicles per hour per lane, and there are over 500 bus trips per day in both directions combined.

Task 3: Electrification Scale and Power Transfer Level for El-Monte Busway

Functional Requirements of RPEV System for El-Monte Busway

1. The system should provide adequate energy to enable buses to operate continuously for at least 15 hours between overnight battery recharging from the wall outlet, with a minimum power rating of 150 kilowatt.

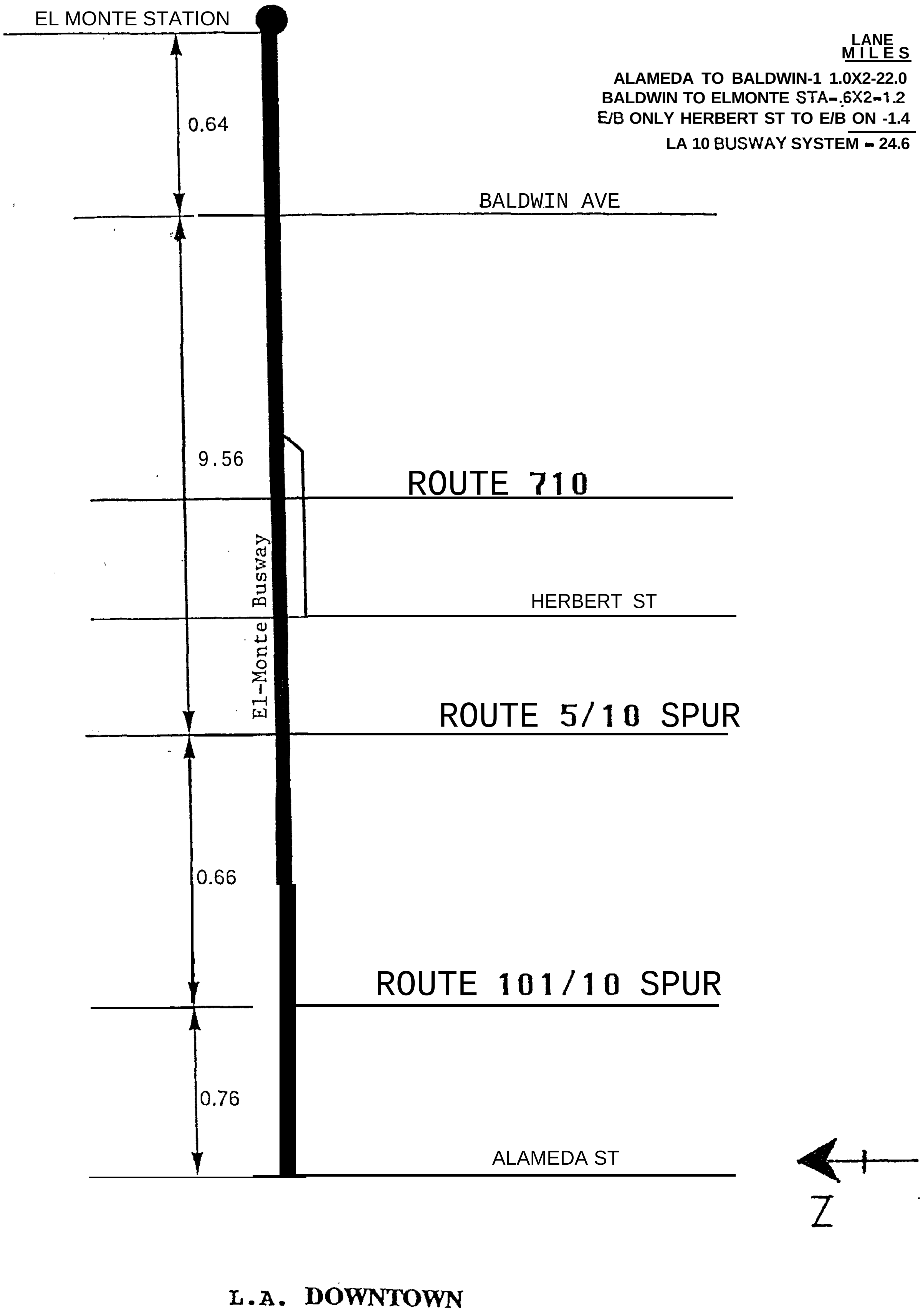


Figure S1: Diagram of El-Monte Busway in Los Angeles

2. The overall system efficiency should be at least 75 percent.

3. Roadway powered electric buses should have acceleration comparable with existing diesel buses.

4. 'Average energy consumption of these buses should be no more than 2.5 kilowatt per mile, in order to provide a good balance between the energy needed by the bus and the energy available from the battery and the ICS.

5. Onboard batteries of the El-Monte buses should not be discharged below 80 percent at any time or under any circumstance during normal daily operation. This is in order to maintain the intended service life of the battery.

Alternative Electrification Scale Scenarios

Six scenarios of possible electrification scales are defined for the feasibility evaluation. Scenarios A through C examine operation of existing bus lines using El-Monte Busway with no changes to routes or schedules. Scenarios D through F use static chargers exclusively to provide shuttle bus services for the LA downtown and El-Monte Busway.

Scenario A: Scenario A involves electrifying the entire length of the travel lanes of El-Monte Busway in both directions. In addition, static chargers are also required at downtown stops used by El-Monte buses, as well as at bus layover points (i.e., the bus's origin and destination) for each bus line.

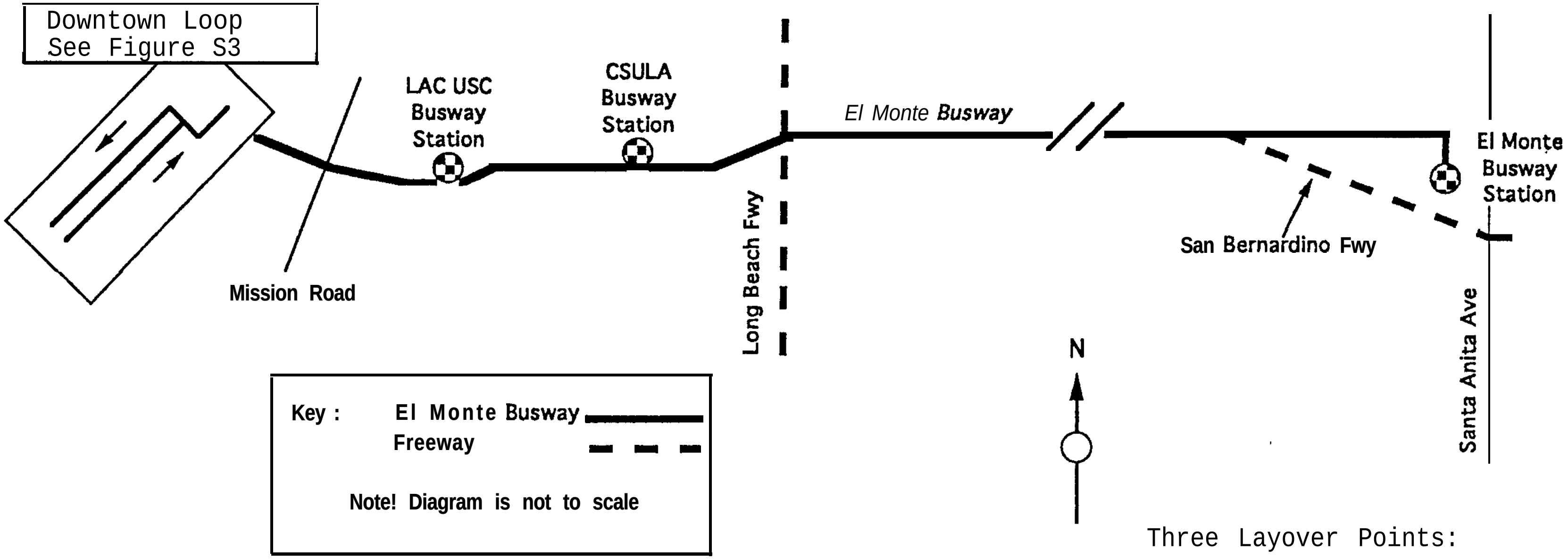
Scenario B: Scenario B involves electrifying the entire length of the travel lanes of El-Monte Busway in both directions, as well as installing static chargers at bus layover points of each bus line. However, static chargers will not be required at downtown bus stops.

Scenario C: Scenario C involves electrifying the travel lanes of El-Monte Busway. However, static chargers will not be installed at bus layover points or downtown bus stops.

Scenario D: This Scenario uses static chargers exclusively to provide the Downtown/El ***Monte Shuttle*** bus service between the downtown and El-Monte Bus Terminal (Figures S2 and S3). Static chargers will be installed at downtown bus stops and three designated bus layover points along the loop; El-Monte Busway will not be electrified.

Scenario E: This Scenario uses static chargers exclusively to provide the ***Downtown*** Shuttle bus service around downtown LA (Figure S3). The route of this shuttle service is similar to the existing DASH bus service currently operated by the LADOT. It involves installing two static chargers at two designated bus layover points (i.e., at Union Station and Venice Boulevard).

Scenario F: This is similar to Scenario E, except that additional static chargers will also be installed at bus stops



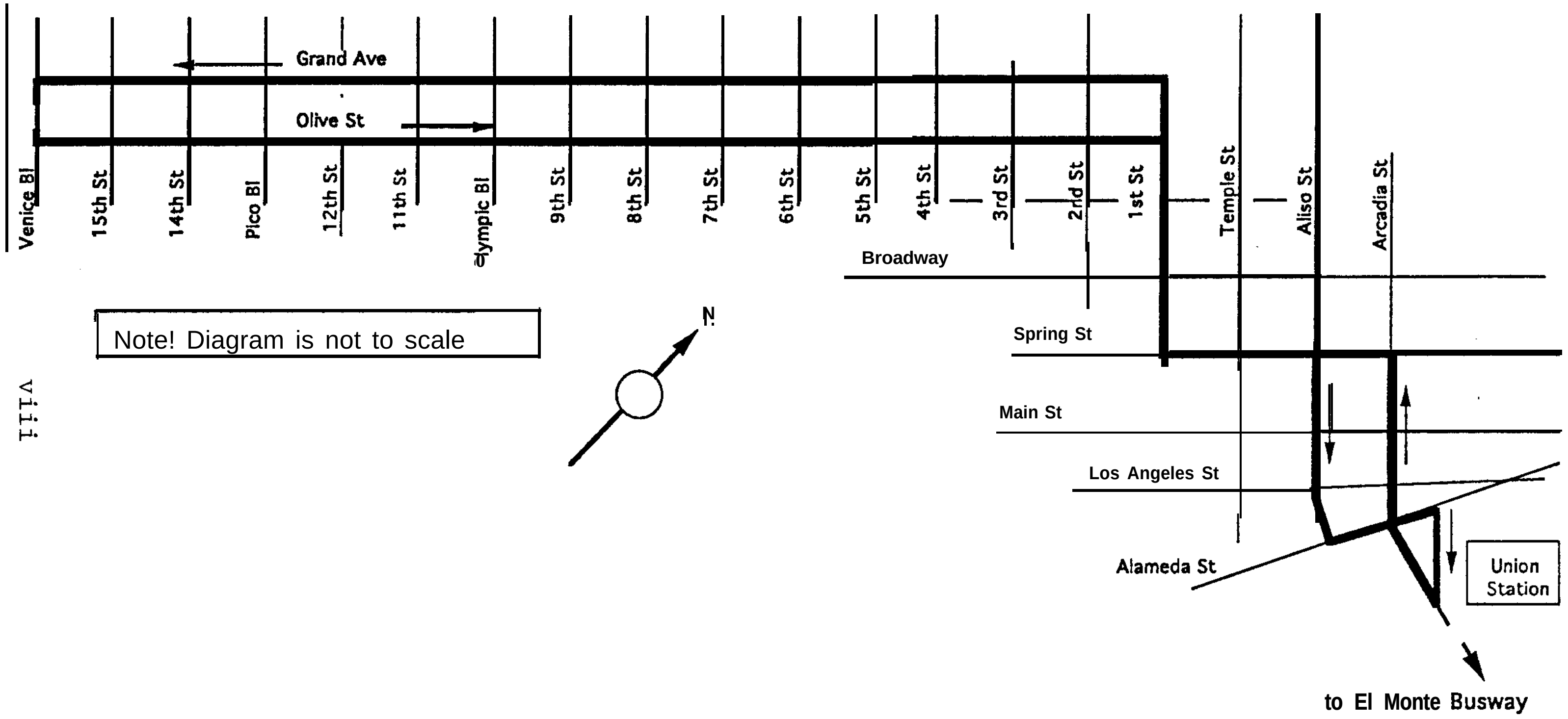
Three Layover Points:

- at El-Monte Terminal
- at Union Station
- at Venice Bl.

Figure S2: Route Layout of Downtown/El Monte Shuttle Bus Service

Two Layover Points for Downtown Loop:

- at Union Station
- at Venice Bl.



Note! Diagram is not to scale

Figure S3: Route Layout of Downtown Shuttle Loop along the *Downtown Shuttle* bus route.

Viability of Alternative Electrification Scale Scenarios

A viable scenario is one that allows buses to operate continuously for at least 15 hours per day without the onboard battery being discharged below 80 percent, with the ICS output current not exceeding 300 amp. Simulation results indicate that:

- Scenario A is viable, with the ICS output current of 300 amp.
- Scenarios B and C are not viable, because the ICS output current required could exceed 300 amp for a number of longer bus lines.
- Scenario D is viable, with the ICS output current of 275-300 amp.
- Scenario F is viable, with the ICS output current of 300 amp or less depending on the number of static chargers used at bus stops.

Task 4: Inductive Coupling System Design

Figure S4 shows the cross section of the ICS for the El-Monte system. Nominal operating point of this ICS would have a roadway excitation of 250 amp-turns. This would yield output current of 150 amp for one pickup. Therefore, two pickups in parallel will provide an output current of (2 x 150) or 300 amp.

Roadway Inductor Design

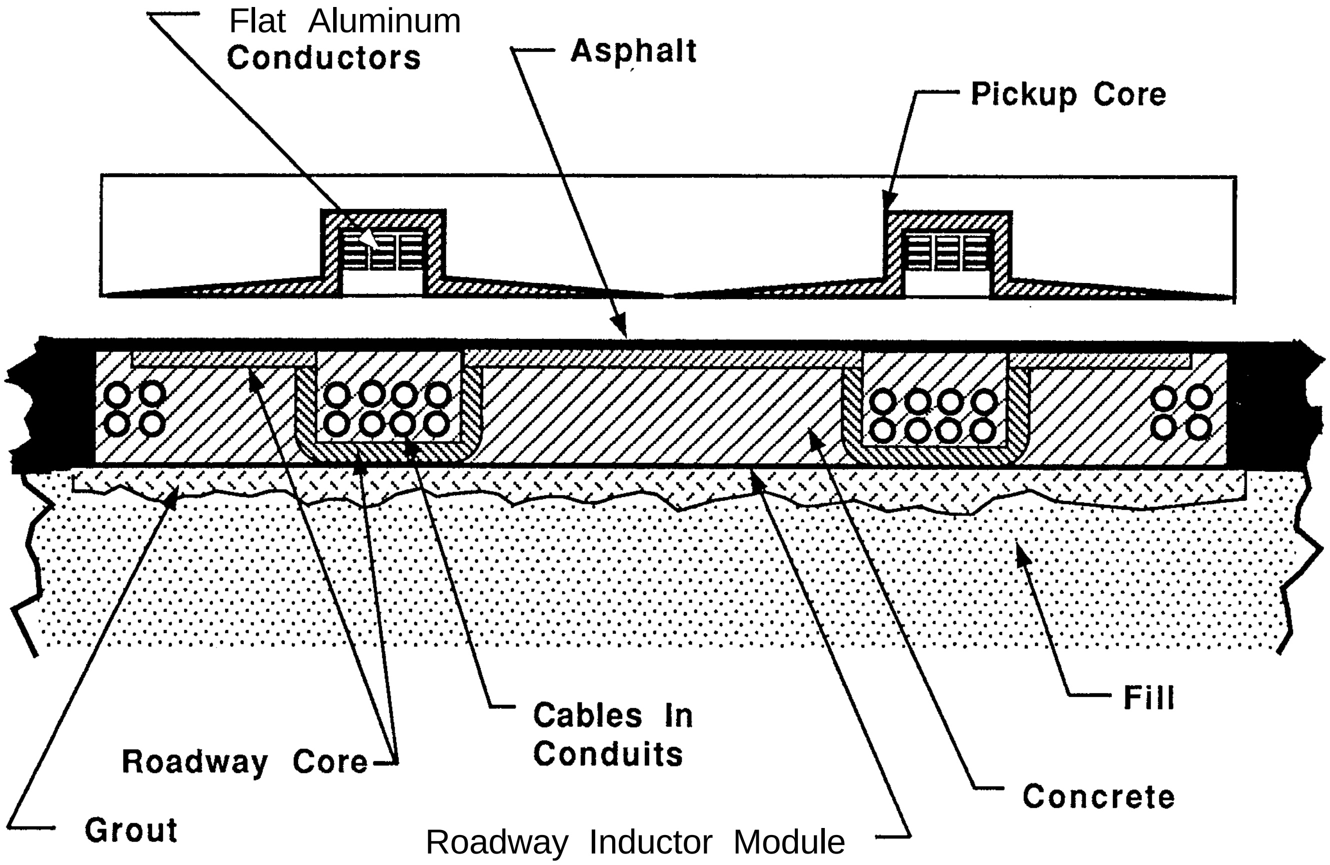


Figure S4: Typical Cross Section of the ICS for El-Monte System

The roadway core modules would be cast as a single W core (Figure S5). The laminated steel core is a three-piece design, featuring a 0.75-inch section made of 0.011 to 0.014 inch lamination. The roadway core module is made by embedding the core pieces, together with the conductor conduits, in a concrete matrix. A layer of fiberglass cloth and epoxy or polyester resin is applied over the cores to protect the steel of the cores exposed at the top surface of the module.

Power Conditioner and Distribution System

Power conditioners would be sized to provide energy for approximately one lane-mile of roadway, thus each can be used to power one-half mile of travel lanes in two directions.

Vehicle Inductor Design

The vehicle pickup, which uses flat-bar aluminum conductors, are the standard "hat section" type. It is made from hydraulically formed and oven-annealed lamination of silicon-iron material of 0.002 inches. Split pickups with two 120-inch, 100-inch, and 60-inch sections will be used for buses, full-sized vans, and cars, respectively.

Vehicle Design

The roadway powered El-Monte bus would be a full-sized bus. The motor would be mounted below the floor level, and the battery mounted under the seats along the entire length of the bus. It has

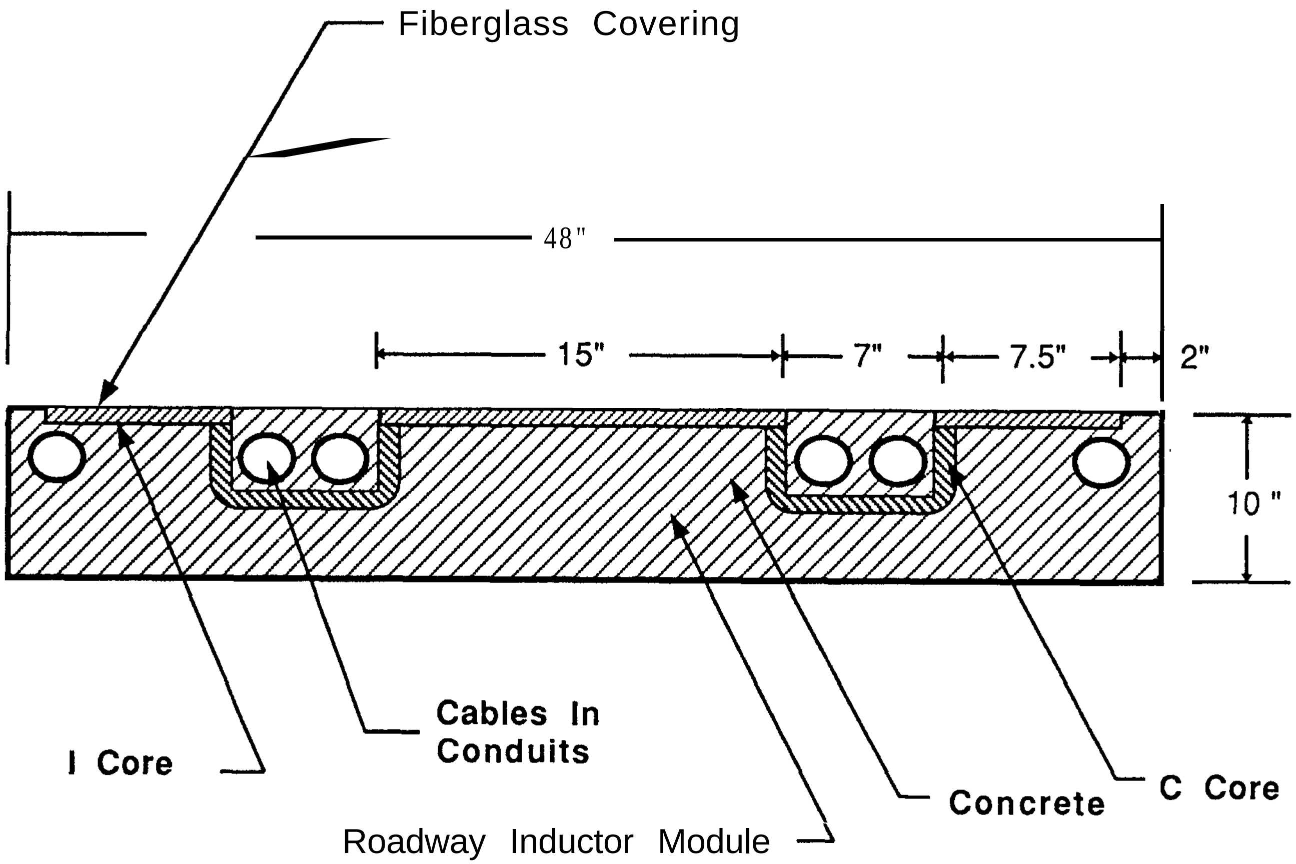


Figure S5: Roadway Core Module for El-Monte System the following vehicle parameters:

- Gross vehicle weight of 31,200 lb
- Power train rating of 240 horsepowers (180 kilowatt)
- Maximum acceleration of 10 feet per second^2
- Drag coefficient of 0.60
- Rated motor torque of 254 ft-lb
- Rated motor speed of 1,600 rpm
- Gear ratio of 45 rpm/mph
- Battery voltage of 500 volts
- Battery amp-hour rating of 400

Task 5: Utility Demand of El-Monte System

Utility demand due to the adoption of Scenario A is the most critical among the viable scenarios identified. Scenario A could increase the utility demand by 7.0 megawatts at night primarily for overnight recharging. Peak utility demand for morning and afternoon rush hours could increase by about 6.2 megawatts. This additional utility demand is negligibly small, since it represents less than 0.1 percent of the existing utility demand within that region.

Task 6: A Plan for Public Demonstration of RPEV

Implementation of the RPEV on El-Monte Busway can take place in three incremental phases, each of which would build on the system already deployed in the preceding phase (Table S1).

Table S1 Three Incremental Phases for Technology Demonstration

	Total Round Trip Time (minutes)	Buses Required	Layover Point Static Charges	Bus Stop Static Charges	Electrified Roadway (lane-miles)	Incremental Hardware Cost** ($M)
Phase I Downtown Shuttle (five-minute headways)	40	8	2	-	-	4.0
Phase 2 Downtown/El Monte Shuttle (five minute headways downtown)						
5-min. headways to El Monte	80	16	3	38	-	5.4
10-min. headways to El Monte	120	11	3	38	-	3.7
15-min. headways to El Monte	160	10	3	38	-	3.2
20-min. headways to El Monte	200	9	3	38	-	2.7
Phase 3 Operation of nine electrified routes	-	68	≈12	38	22	92.8****

Phase I: Implement Downtown Shuttle Bus Service Using Static Chargers Exclusively

Technology demonstration of the RPEV could start with the implementation of the *Downtown Shuttle bus service* using static chargers'exclusively. One possible route for this shuttle service could be the DASH service currently operated by LADOT (Figure S3), with a total route length of about 5.3 miles. Static chargers will be installed at two bus layover points, as well as at some bus stops. To maintain service headway of five minutes, 8 buses will be needed.

Phase II: Implement Downtown/El Monte Shuttle Bus Service Using Static Chargers Exclusively

In Phase II, the Downtown Shuttle of Phase I could be expanded eastward from Union Station, continuing onto El-Monte Busway and ending at the El-Monte Busway Terminal (Figures S2 and S3). Forty-one static chargers would be required at three designated bus layover points, as well as at bus stops along the route. Nine to 16 buses will be required in Phase II, depending on the service headway to be provided (Table S1).

Phase III: Add Dynamic roadway Electrification along El-Monte Busway

In Phase III, the travel lanes of El-Monte Busway in both directions will be electrified (a total of about 22 lane-miles). This 22 lane-miles of roadway electrification is well below the critical mass (about 500 lane-miles) required to yield practical market penetration of private RPEV's. Nevertheless, this initial electrification of El-Monte Busway could be viewed as a significant first step toward achieving a sizable network of roadway electrification for the Los Angeles Basin. About 68 diesel buses currently using El-Monte Busway would be replaced by roadway-powered electric buses, to provide service headway of 30 minutes for all bus lines.

Air-quality benefits of roadway-powered electric buses, vans, and cars are assessed and reported in Volume 2B.

Public Demonstration Schedule

A schedule for the public demonstrations of the three phases, together with a timetable for the various project steps within each phase, are presented in Figure S6. Activities in Phase I could start as early as 1993, and the system could be ready for public demonstration by 1995. Activities in Phase II could start in 1995, with the public demonstration date in 1998. Finally, Phase III could be initiated in 1996, with the public demonstration date in ***2000.***

Implementation Related Issues

Technical Uncertainties for Which Further Research is Needed

1. Research is needed to develop prototype power conditioner and distribution systems for operation in the dynamic and static

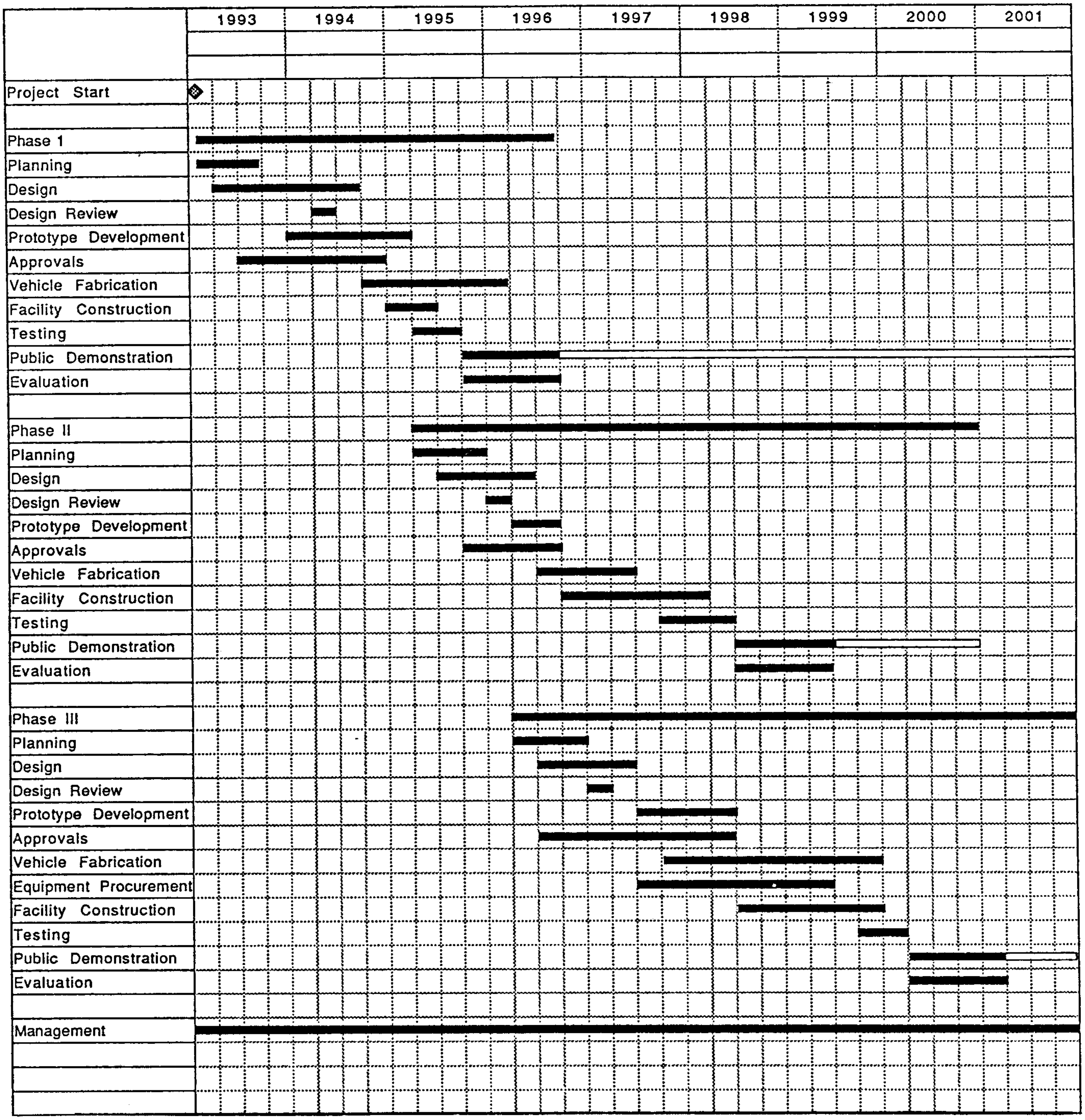


Figure S6 Public Demonstration Schedule and Project Activity Timetable modes. Such prototypes do not exist at this time.

2. Research is needed to investigate the battery charge acceptance and service life under dynamic and static modes of operation.

3. 'The roadway cores under the dynamic mode of operation will be subjected to continuous and repeated traffic load. Research is needed to determine how long the roadway cores would last under such conditions.

4. Ongoing research investigating potential impacts of the EMF's on the environment, health, as well as interference with other communication media and onboard electronics (antilock brake systems, radios, etc.) has to be completed. These impacts are critical for determining the feasibility of deploying the RPEV on the highway.

5. Research is needed to determine how to best install dynamic roadway electrification as a retrofit, so as to minimize costs and traffic disruption.

Organizational Arrangements

Agencies or organizations to be responsible for installing and maintaining the electrified roadway and facilities should be identified from the outset. Key organizations for these responsibilities are as follows: CALTRANS, LACTC (Los Angeles County Transportation Commission), LADWP (Los Angeles Department of Water & Power), and SCE (Southern California Edison). As early as possible in the project planning, cooperation among organizations must be obtained to assure smooth operation once the system is in place. Key organizations are as follows: CALTRANS, SCRTD (Southern California Rapid Transit District), **LADOT**, **SCE**, **LADWP**, LACTC, SCAQMD (South Coast Air Quality Management District), CTC (California Transportation Commission), CEC (California Energy Commission), CARB (California Air Resources Board), SCAG (Southern California Association of Government), and local private transit operators.

At the earliest possible date, consideration should be given to forming an oversight committee, to be charged with seeing the plan through implementation; assuring good cooperation among agencies and organizations; monitoring the system performance; and making recommendations concerning system improvements and timely implementation of future phases.

Use of Electrified Facilities by Private Vehicles

The use of the electrified facilities by private vehicles need to be addressed as early as possible, particularly:

(i) Should users be charged the costs of the infrastructure, in addition to the utility charge? To whom will users pay these charges, and what are possible user billing methods ?

(ii) During the early deployment of the RPEV when the critical mass of the electrified roadway is not yet achieved, are incentives needed to encourage private vehicles to adopt the RPEV? Tax credits, licensing and insurance benefits, free roadway energy, and other possible incentives should be studied.

Legal and Liability Issues

Potential legal and liability issues surrounding the deployment of the RPEV have to be addressed and resolved. Some examples of these issues are as follows: possible health risks due to the magnetic fields, inadvertent roadway heating, and interference with working parts of-vehicles that may culminate in safety risks.

Training Needs

Personnel of the responsible agency have to be trained to operate and maintain the power distribution network, keep the roadway sealed to prevent corrosion of the roadway cores, inspect the roadway for possible corrosion of the roadway cores, and apply necessary remedies. Training for electric vehicle maintenance is also essential because it is different from that of internal-combustion-engine vehicles. It includes the battery, motor, and electrical system.

Task 7: Projected Costs of The Public Demonstration Plan

Cost estimates for each of the three phases are expressed as an additional amount required for that phase relative to the cost already incurred in the preceding phase. The projected hardware cost (which include the hardware and installation, but not the engineering) for implementing the Downtown Shuttle bus service of Phase I is about $4.0 million. The incremental hardware cost for Phase II is projected to be $2.7 million to $5.4 million. The incremental hardware cost for Phase III is projected to be $93 million. This estimate of $93 million does not consider the fact that the acquisition of new electric buses would mean that the transit agency will not have to replace existing 68 diesel buses when their service life expires. If this is taken into consideration, the hardware cost of Phase III will drop from $93 million to $74 million.

FEASIBILITY OF IMPLEMENTING ROADWAY-POWERED ELECTRIC VEHICLE TECHNOLOGY IN EL-MONTE BUSWAY: A CASE STUDY

INTRODUCTION

Air pollution is a serious problem facing many metropolitan areas in the U.S. Major components of air pollution are vehicle emissions -- hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NOx), oxides of sulfur (SOx), and particulate matters (PM's). The following statistics illustrate the magnitude of the problem in California. In 1987, annual average daily tonnage of mobile-source pollutant emissions in the South Coast Air Basin (SCAB) of Southern California contributed about 66 percent of emissions from all polluting sources. In that same year, mobile-source emissions of HC, CO, NOx, SOx, and PM's contributed about 44, 88, 61, 26, and 5 percent from all pollution sources (SQAQMD 1990). Concern over the state's air quality and vehicle emissions has led to the enactment of a state law requiring 2 percent of all vehicles sold in California by 1998 to be emission-free vehicles, and 10 percent by 2003.

There are a large number of alternative cleaner-fuel vehicles that have been extensively researched and promoted in the U.S. -- methanol, compressed natural gas (CNG), reformulated gasoline, electric vehicles (EV's), and various hybrid vehicles, to name a few. Of these, EV's are essentially "emission free," in that they themselves do not emit pollutants while running on the road or stopping in the traffic, although power plants supplying electric power to them do.. Evidence in the literature indicates that emissions of HC, CO, and NOx for EV's (from electricity generation at power plants), on a per-mile of travel basis, are extremely low relative to emissions from existing internal-combustion-engine vehicles (ICEV's). Further, it is also far easier to manage and control emissions from far fewer stationary power plants than from millions of moving vehicles; power plants can also be located remote from urban centers (Nesbitt et al, 1990). Other cleaner-fuel vehicles mentioned above do emit some pollutants on the road, although their emission levels are generally known to be lower than ICEV's.

Electric vehicles are not a new technology, but their widespread use has not materialized because of their relatively limited range between battery recharges, and the fact that the existing battery technology requires 6-8 hours for a full recharge. With currently available battery technology, it appears that the range of most EV's is on the order of 40-50 miles when driven at 55 mph. One way to increase the range of EV's between overnight battery recharging, in the absence of advanced battery technologies, is through the use of roadway powered electric vehicles (RPEV's). These vehicles are hybrid electric-electric vehicles using an "inductive" coupling power transfer principle. RPEV's can operate both on and off the electrified roadway. On the electrified roadway, they draw power directly from the roadway for use in propelling the vehicle. The balance of this roadway power that is not used is stored in the onboard battery. Off the electrified roadway, they rely solely on the onboard battery power.

The RPEV shares some similar features with the trolley bus and light rail systems, for example, it embodies a distributed energy source and a means of power collection for moving vehicles. However, the RPEV is uniquely different from the trolley and light rail systems. The electrification of the RPEV (which is based on an inductive power transfer principle) can be used to benefit both transit and non-transit vehicles (e.g., cars, vans, pickups, and trucks), while the electrification of the trolley and light rail systems (which is based on a conductive power transfer principle) benefit only transit vehicles. In addition to extending the range of electric vehicles, the power drawn from the roadway could also enable electric vehicles to achieve better acceleration.

The inductive coupling system (ICS) of the RPEV uses a magnetic field to transfer power across an air gap from the roadway inductor, buried underneath the pavement's surface to the vehicle (Figure 1). This system can be thought of as a large transformer with an air gap. The primary of this transformer is the roadway inductor, and the secondary is the pickup inductor. The RPEV's system concept is shown schematically in Figure 2, which includes the various components and power flows between them. One important feature of the RPEV is that most of the power collected from the roadway during dynamic charging can go directly to the motor and thus prevent battery losses of a magnitude typically found in EV's. This is a difference in the onboard energy storage requirement between the RPEV and the EV, and the total stored energy becomes less important for-the RPEV.

Many transportation professionals believe that early deployment of the RPEV technology on selected existing highway facilities, even on a limited scale initially, would go a long way to advance this technology toward full maturity and a critical mass.

STUDY OBJECTIVE

The objective of this study is to evaluate the preliminary engineering feasibility for early deployment of the RPEV technology in existing high-occupancy-vehicle (HOV) facilities in California. Such an early deployment could be a stepping stone toward larger-scale implementation on freeways. To this end, the following tasks were performed:

1. Review the current status of the RPEV technology
2. Select one HOV facility for an in-depth site specific case study
3. Determine the electrification scale and energy transfer level required for the selected HOV facility
4. Determine preliminary design of the ICS for the selected site
5. Assess the daily energy demand for this system
6. Develop a technology demonstration plan, and identify issues pertinent to the implementation
7. Estimate probable costs of the technology demonstration plan

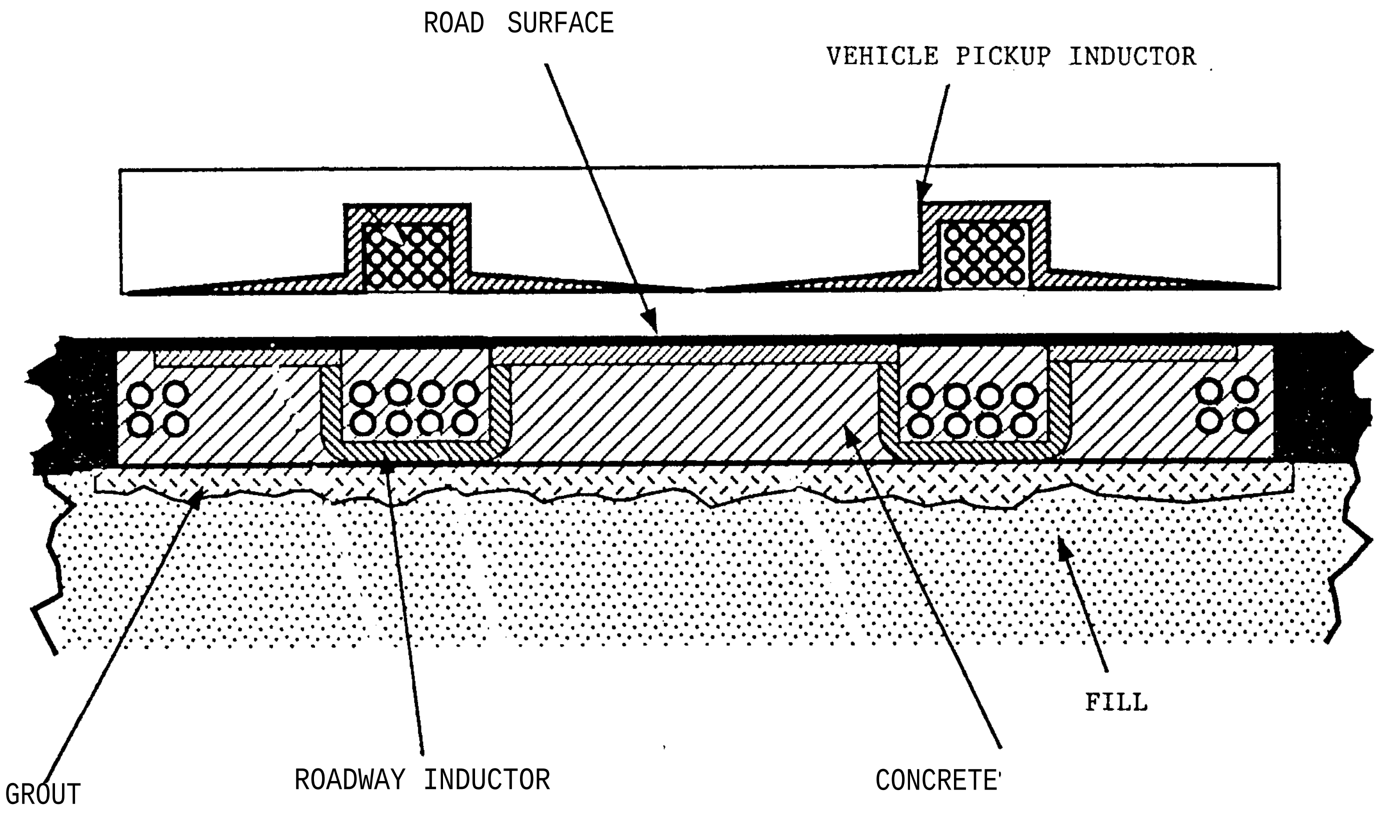


Figure 1: Inductive Coupling System (ICS)

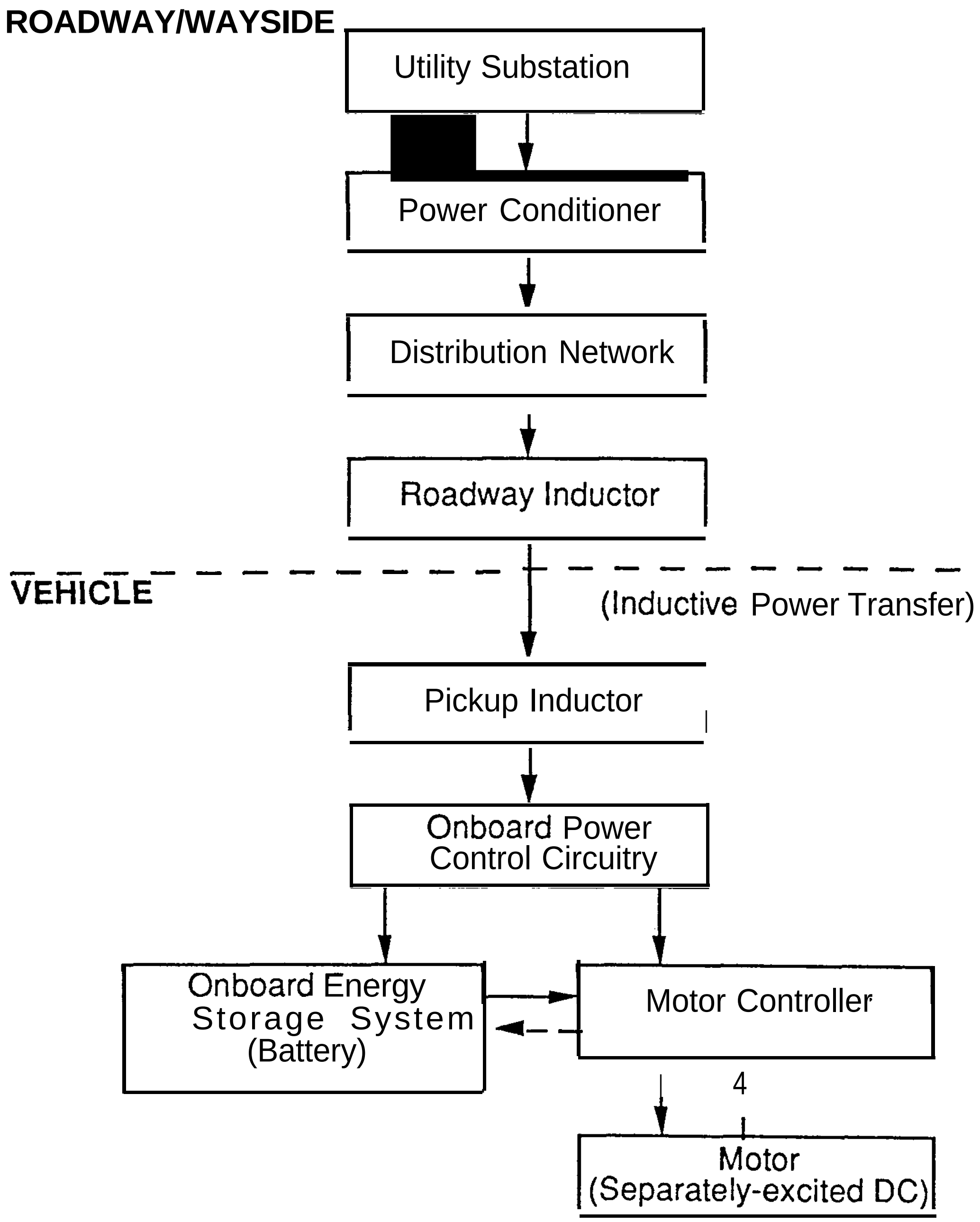


Figure 2: Components of RPEV and Power Flow

less important for-the RPEV.

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6. Develop a technology demonstration plan, and identify issues pertinent to the implementation
7. Estimate probable costs of the technology demonstration plan

ORGANIZATION OF THE REPORT

This report is organized into several sections, one for each task, as follows. Task 1 provides an overview of the current status of the technology development of the RPEV. Task 2 highlights the data collection efforts that culminated in the selection of El-Monte Busway in Los Angeles for a case study. Tasks 3 through 7 constitute the main analysis. Task 3 analyzes the electrification scale and level of the ICS power transfer required. In this regard, various electrification scale scenarios are developed and evaluated. Task 4 presents preliminary engineering specifications for the ICS to be implemented. Task 5 examines the daily use demand by the time-of-day due to this RPEV system. Task 6 presents a plan for implementing public demonstration of the RPEV, as well as identifying issues pertinent to the implementation. Finally, Task 7 describes costs of the RPEV system at large-scale production, as well as estimated costs of the proposed public demonstration plan.

In addition, potential emission benefits due to adopting roadway-powered electric buses, vans, and cars for California is also evaluated. The analysis of emission benefits due to the use of RPEV's is reported separately in Volume 2B.

Task 1

Overview of Current Status of RPEV Technology

Inductive energy transfer for road vehicles was first reported in the 1890's. During the oil crisis in the 1970's, Lawrence Berkeley and Lawrence Livermore National Laboratories conducted tests of a 6-kilowatt proof-of-concept system. In 1979, CALTRANS sponsored a feasibility study of a roadway-powered electric bus system for the City of Santa Barbara (Systems Control Technology, 1984), which included vehicle simulations, as well as laboratory tests of RPEV components and subsystems. Santa Barbara's project did not lead to the implementation of roadway power electric buses, because the RPEV technology was not yet ready for on-the-road applications. Nevertheless, interest and support in the project led to further RPEV research in both the public and private sectors.

Since the completion of Santa Barbara's study in the mid 1980's, two major R&D efforts have been ongoing at California PATH and the Playa Vista Project in southern California. The two efforts were independently initiated, but have maintained close cooperation in the sharing of research findings. These two programs have addressed both the technical and economic feasibilities of applying the RPEV on the highway. Research at the PATH program has included a major study focusing on the design, analyses, and tests to extend the range and driving cycles of the RPEV (SCT, 1992a), as well as a policy study examining the feasibility of large-scale deployment of the RPEV in the Southern California Association of Governments (SCAG) region (SCAG, 1992). A prototype roadway-powered bus was built as part of California PATH's research program. Research at the Playa Vista Project has focused on the design and testing of a prototype full-sized van (G-van), with R&D efforts to date devoted to reducing acoustic noise and electromagnetic fields (EMF's).

Results of the literature review are summarized below, in terms of the technical, economic, and utility-demand feasibilities of applying the RPEV in the highway environment.

1.1 Technical Feasibility of RPEV

Findings on the technical feasibility of the RPEV are primarily based on the prototype bus and G-van, both of which were retrofits of existing vehicles.

Testing of the prototype systems were conducted using the following system parameters.

Parameter	Prototype Bus	G-Van
Air-gap height	3 inches	2 inches
Power rating	60 kilowatts	40 kilowatts
Roadway frequency	400 Hz	8,500 Hz
Roadway current	1,200 amp-turns	240 amp-turns
Output current	400 amp	180 amp
Nominal voltage	128 volts	216 volts
Maximum voltage	154 volts	255 volts

Test results of the prototype bus were reported at three levels : component, subsystem, and overall system levels (Lechner et al 1990; and Systems Control Technology, 1991). Tests of components included the roadway cores, pickup cores, solid-state switches, and onboard controller inductors. Tests of subsystems were conducted to verify the first level of integration, and included the roadway inductor, pickup inductor, power distribution system, onboard controller, and accessory system. Tests of the overall system were conducted to provide information on the system performance, which included power coupling capability, closed loop control, mechanical clearance, static operation, dynamic operation, range, and vehicle performance. Results of the literature synthesis are presented below concerning the following: power transfer reliability, system efficiency, vehicle performance, safety, and environmental and health impacts, integrity of the pavement, robustness of the RPEV in all weather and operating conditions, and configuration of power supply and distribution systems for large networks.

1.1.1 Power Transfer Reliability

Evidence from tests of prototype systems (Lechner et al, 1990; and Systems Control Technology, 1991) indicates the following:

* The hardware developed and tested for the prototype systems is capable of transferring power while the vehicles are stationary and in motion.

- The systems are able to track commanded output current reasonably well.
- The power transfer is affected by the air-gap height, in that the power transfer capability decreases with increasing air-gap height, and rapidly declines as this height exceeds 3 inches.
- The power transfer is sensitive to the vehicle lateral offset from the roadway inductor. As vehicles are steered farther from the roadway inductor (i.e., the lateral offset increases), the maximum ICS power transfer declines. Results of tests of the prototype PATH bus indicate that it is usually difficult to maintain the output current beyond 150 amp when lateral offsets between the pickup and the roadway inductors are 6 inches or more. This implies that practical RPEV systems are likely to require the integration of some low-power automated steering assistance or control, to ensure that the pickup is centered along the roadway inductor while the vehicle is drawing energy from the electrified roadway.

1.1.2 System Efficiency

For RPEV systems, much of the energy (about 80 percent) transferred to the vehicle from the roadway is used immediately by the motor controller, and does not have to be stored in the onboard battery. This in turn helps to minimize losses in the battery.

Lechner et al (1990) reported that overall system efficiency of the prototype PATH bus in static tests was about 60-65 percent (at an output power level of 60 kilowatt, output current of 400 amp, and roadway frequency of 400 Hz). In dynamic tests, the efficiency could be 2-5 percent lower than static efficiency, possibly because the vehicle might not have been perfectly centered. Lechner et al (1990) also reported that the overall system efficiency of the RPEV could be enhanced through the use of high-frequency systems and low roadway currents. For example, RPEV systems with roadway frequency of 8,500 Hz and output currents of 250 amps could yield overall system efficiencies about 75 percent.

The Playa Vista Project has plans in the immediate future to build high-frequency RPEV systems with roadway current of about 240 amp-turns. Several tests are being planned to determine EMF effects, integrated lateral control systems, air gap control, energy storage, onboard control systems, and roadway design/construction (SCAG, 1991).

1.1.3 Vehicle Performance

RPEV systems could improve the range of pure electric vehicles. Further, relative to pure electric vehicles, the ICS of RPEV's could also improve vehicle acceleration by increasing the power available to the motor controller (Lechner et al, 1991).

1.1.4 Electric Shock Hazards

The energy transfer technique used in RPEV's does not present electric shock haz-ards to pedestrians or other non-electrified vehicles sharing the electrified roadway with RPEV's. Further, results from limited road tests of the prototype PATH bus have indicated that there is no appreciable difference in the driver responsibilities between driving the prototype bus and the conventional bus (Lechner 1992).

1.1.5 Environmental and Health Impacts

Concerns over potential effects of electromagnetic fields (EMF's) are not limited to just the RPEV. EMF's are also generated from other electrical systems and household electrical appliances. A number of ongoing studies are currently investigating biological and environmental effects of electromagnetic fields (EMF's). There is currently no conclusive findings concerning potential long-term health and biological effects of EMF's.

Measurements of magnetic flux were obtained in the Playa Vista study (Lechner et al, 1991), which reveal that magnetic flux at the height of 5 cm above the roadway inductor is less than 10 gauss. At 2.5 meters from the lane centerline, the flux density falls below 10 milligauss, regardless of the height above the roadway. In the vehicle, the flux density is much lower than above the roadway due to the vehicle's frame and body acting as a shield. For example, the flux density inside the prototype G-van is on the order of l-2 milligauss. The magnitude of these electromagnetic fields is below the magnitude experienced in the typical work or home environment (SCAG, 1991).

The EMF's generated by the RPEV could create noise and interference to nearby objects and infrastructures. Noise measurements obtained for the redesigned prototype G-van indicate that acoustic noise within the vehicles from the electrified roadway is about 40 dBA. This is not significantly different from the current noise level within the existing automobile population. Further research is needed to investigate noise inside nearby non-RPEV's due to the EMF's.

1.1.6 Integrity of Pavements

There is currently no documentation concerning potential impact of imbedding roadway inductors into the pavement on durability and integrity of the pavement. The literature also lacks information concerning how roadway inductor segments may withstand the rigors of the traffic load, and how pavement resurfacing should be carried out without the risk of damaging the roadway inductor segments.

1.1.7 All-Weather Robustness

The literature lacks information concerning effects of snow, mud, and sleet on the ICS power transfer. It is believed that standing water on wet pavement up to 3 inches would not affect the RPEV. However, thick snow buildup may make it necessary to raise the air-gap height, which in turn could affect the ICS power transfer capability.

1.1.8 *Power Supply and Distribution Systems for large network*

Power supply systems used on the prototype RPEV systems have some deficiencies that may make them unsuitable for real-world applications. There is currently no study addressing the design of power supply and distribution systems for large-scale operational RPEV networks, or their cost implications.

1.2 Economic Feasibility of RPEV

Systems Control Technology (1992) reported that the RPEV appeared to be economically competitive with internal-combustion-engine vehicles (ICEV's), in terms of the user cost per vehicle-mile of travel, when assuming that users will pay for the cost of the infrastructure. If users do not have to pay for the infrastructure cost, the cost per mile of travel for the RPEV could be lower than that for the comparable ICEV. This prior study assumed that there were 20,000 RPEV's per day, and that the roadway subsystem would last 25 years before replacement was needed. All costs used in their analysis were based on 1992 costs, with a real interest rate (nominal interest minus inflation) of 3 percent. It also went on to suggest that the "critical mass" for the RPEV in the SCAG region could be achieved when there are at least 500 miles of electrified roadways and about 200,000 RPEV's.

1.3 Impact of RPEV on Utility Demand

RPEV's draw energy from electrified roadways while operating on these facilities. The use of RPEV's could have impact on the utility demand and-capacity. On any given day, some RPEV's will use electricity supplied by the powered roadway; while some other RPEV's with low daily mileage may not need to draw electricity from the powered roadway, and could solely depend on the onboard battery. As the VMT of RPEV's increases, so could the electricity demand. One concern is that the use of RPEV's could add to the existing utility demand peak during the evening rush hours.

SCAG (1992) examined potential impact of large-scale use of the RPEV on the utility demand in the SCAG region. The study defined a use scenario for the SCAG region in the year 2025, in which the following was assumed:

- One lane in each direction of most freeways in the SCAG region is electrified, resulting in about 1000 lane-miles of electrified roadway being in operation (or about 10 percent of total freeway lane-miles in the SCAG region) by 2025.
- 15 percent of the daily VMT in the SCAG region is attributable to RPEV's.

SCAG (1992) estimated that the above RPEV use scenario could result in the utility company having to increase its utility capacity for the year 2025 by one percent, relative to the case in which the RPEV is not used. It noted that the utility company, without anticipating the use of RPEV's, is expected to have to increase the capacity by 90-95 percent between now and the year 2025 anyway in order to meet the rising utility demand within the region. Therefore, the use of the RPEV according to the assumed scenario would not-significantly affect the utility capacity for the SCAG region.

All the above evidence from the literature, taken together, indicates that RPEV systems can be designed for use on the highway. Since Santa Barbara's study in the mid 1980's, significant advancement has been achieved in the testing and design of RPEV systems. As a result, lower levels of the EMF's and acoustic noise have been achieved. However, the RPEV is still at a developmental stage, and design engineers believe that RPEV systems with higher frequency and lower roadway currents than the existing prototype systems are more suitable for the highway use. Such systems have yet to be built and tested, and most important, biological and health effects of the EMF's need to be well understood.

In the near term, the RPEV technology could initially be targeted for transit buses. This is because buses are likely to more readily adopt the RPEV than private vehicles, particularly when a critical mass of electrified roadway is not yet achieved. The public is also likely to support the use of roadway-powered electric buses, out of aesthetic and environmental concerns. Further, insight has already been gained from the analysis and testing of the prototype bus, which could result in the technology for transit buses becoming available soon.

Task 2

Site Selection and Data Collection

The overview of the RPEV technology in Task 1 indicates that it is a feasible technology for the highway use. Task 2 is aimed at selecting one high-occupancy-vehicle (HOV) facility in California, for use in a site-specific evaluation of preliminary engineering feasibility of early RPEV deployment. The use of the RPEV on HOV facilities is viewed as a stepping stone toward larger-scale deployment on the freeway system. Task 2 involves the following activities:

- Develop criteria for selecting a candidate HOV facility
- Compile information on all HOV facilities in California
- Collect data on the geometric and traffic characteristics of the selected HOV facility, for use in the preliminary design, specifications, and evaluation of an RPEV system to be implemented at that site

2.1 Site Selection Criteria

Early deployment of the RPEV could take place in existing HOV facilities. HOV facilities considered to be good candidates for such a purpose are those that generally meet the following criteria:

(a) It is desirable that the candidate HOV facility is located in an air-quality sensitive area of the state.

(b) HOV facilities currently in operation are preferred to those under construction, to assure that technology demonstration could take place in a timely manner.

(c) Longer HOV facilities are preferred to shorter ones, because the former could potentially provide greater range for RPEV's.

(d) Although benefits of RPEV systems would be more fully realized when adopted by both transit and non-transit vehicles, HOV facilities with higher daily numbers of transit vehicles are desirable for the initial technology demonstration. This is because transit vehicles are more likely to be early users of the technology than non-transit vehicles.

(e) HOV facilities with exclusive right-of-way and controlled access and egress are preferred, because construction of the roadway electrification within these facilities would result in minimal disruption to the traffic on the corridor. Further, the exclusive access offers maximum safety and ease of on-site tests prior to the deployment, if needed.

2.2 Candidate HOV Facility for Preliminary Engineering Feasibility Evaluation

In order to select an HOV facility for the evaluation of the preliminary engineering feasibility, all HOV facilities currently in operation, under construction, or being planned in California were compiled. Based on the above site-selection criteria, two HOV facilities were short-listed as candidate sites. They are El-Monte Busway in Los Angeles and the I-15 HOV facility in San Diego.

Please note that .El-Monte Busway is aa 3+ HOV facility and, contrary to its name, is open to private vehicles with at least three occupants onboard, in addition to buses.

Of these two short-listed facilities, El-Monte Busway offers a number 'of advantages over the I-15 HOV lane as follows:

- El-Monte Busway is a longer facility (over 11 miles long, compared to 8 miles of I-15 HOV lane).
- El-Monte Busway has a much higher number of transit buses than the I-15 HOV lane.
- With El-Monte Busway, there exist opportunities for installing electrification at the El-Monte Bus Terminal, and static chargers at downtown bus stops. This makes it possible to evaluate a large number of electrification scenarios.

Therefore, El-Monte Busway is selected as a site for the study of preliminary engineering feasibility for early RPEV deployment. Data required for the feasibility evaluation are highlighted below.

2.3 Geometric Layout of El-Monte **Busway**

El-Monte Busway is an exclusive-access HOV facility located on I-10 (San Bernardino Freeway). It is about 11.6 miles long, with a relatively high design standard. Figure 3 is a diagrammatic layout of El-Monte Busway. Its western end originates in downtown Los Angeles at Alameda Street. To the east, the HOV facility ends at the El-Monte Busway Terminal. It has one travel lane in each direction, with the two directions separated by permanent barriers.

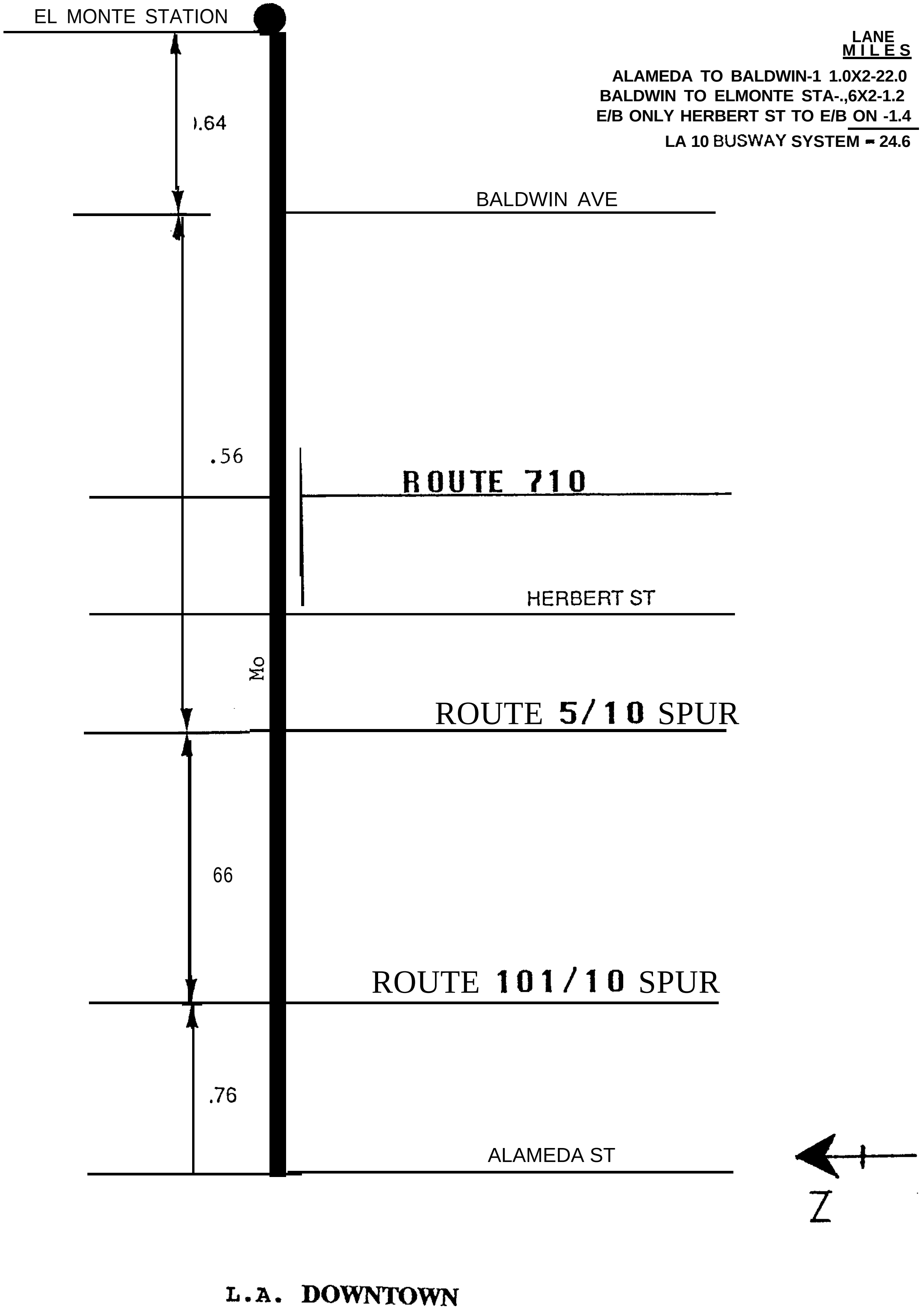


Figure 3: Diagram of El-Monte Busway in Los Angeles

For about four miles of the Busway on the western end, the HOV lane is separated from the freeway lanes by permanent barriers. For the remaining length, the HOV lane is separated from the freeway lanes by buffers of at least 4 feet wide. A breakdown lane is also providedalong most of this buffered section. Access and egress to El-Monte Busway are through exclusive ramps only.

2.4 Traffic on El-Monte **Busway**

El-Monte Busway is a 24-hour HOV facility, which opens to both transit and non-transit vehicles with at least three occupants. Peak-hour traffic volume on the Busway is over 1,200 vehicles per hour per lane, and there are over 500 bus trips per day for both directions combined. Information on existing bus lines currently using El-Monte Busway was compiled. For each bus line, its route, as well as scheduled travel time and stops, were obtained from the published schedules. The length of various road segments making up the route was obtained from detailed road maps. Parameters concerning bus operation (such as dwell time at bus stops and travel speeds) were estimated from published schedules.

2.5 Characteristics and Performance of Existing Buses

Information concerning the design, dimensions, and performance of existing diesel transit buses was obtained from Southern California Rapid Transit District (SCRTD). Similar information on existing trolley buses was also obtained from MUNI. This information and the Federal Transit Administration's (FTA)

performance specifications for urban buses are used in specifying performance characteristics of the hypothetical roadway-powered El-Monte bus.

Task 3

Scale of Electrification for El-Monte Busway

In Task 2, El-Monte Busway in Los Angeles was selected for the case study. Tasks 3 through 7 focus on the feasibility evaluation for early deployment of the RPEV in El-Monte Busway. Task 3 investigates the amount of roadway electrification and level of the ICS energy transfer required for El-Monte Busway. Task 4 focuses on the preliminary specifications of the ICS for the El-Monte system. Task 5 examines the utility demand by the time-of-day due to the deployment of the El-Monte system. Task 6 proposes a plan for public demonstration, and Task 7 describes cost estimates for this public demonstration plan.

Task 3 involves the following determinations:

- Functional requirements for the El-Monte system
- Scale of electrification required to meet these functional requirements
- Level of the inductive energy transfer system required to satisfy the functional requirements

3.1 Functional Requirements for El-Monte Design

The RPEV system for early deployment in El-Monte Busway could have the following functional requirements:

Vehicle Range

When roadway electrification is implemented on El-Monte

Busway, it will benefit all roadway-powered electric vehicles (transit as well as private vehicles). A decision on the extent of electrification and what locations to be electrified depends on the range requirement of the target vehicle population to be satisfied by this' system. Within the context of this study, the electrification of El-Monte Busway is aimed at providing adequate energy to enable transit buses to operate continuously for at least 15 hours a day before requiring overnight battery recharging.

The rationale for selecting transit buses as the target vehicle population lies in a general belief that, before a critical mass of electrified roadway is achieved, transit buses would be more ready to adopt the RPEV than private vehicles. There is likely to be good public support for roadway powered electric buses because these vehicles could significantly reduce pollutant emissions, noise, and odor relative to existing diesel buses. Further, the fixed routes of transit buses make it relatively easy to design an electrification system to assure that their daily range requirements are met. Assurance of adequate range is particularly important when introducing this new technology with no on-the-road experience.

Energy Transfer Mode

The system to be implemented on El-Monte Busway could make use of both the dynamic and static energy transfer modes. That is, while vehicles are running on El-Monte Busway, the electrified roadway would provide power to the vehicles through dynamic energy transfer. At bus stops and bus layover points, static chargers could be installed to provide quick battery recharging while vehicles are stationary atop the static chargers. Static charging could be an important energy supply source for buses because one minute of static charging could be equivalent to one-half mile of roadway power. Yet, static charging segments are expected to incur only 1 percent of the construction costs of the equivalent length of powered lanes. Therefore, a combination of dynamic and static chargers could assure that maximum power is available to the vehicles at minimum roadway costs.

Vehicle Performance

Roadway powered electric buses for the El-Monte system should have acceleration performance at least comparable with existing diesel buses, as well as meeting the FTA's specification for urban transit buses. Figure 4 shows the acceleration of the hypothetical El-Monte bus, which meets the FTA's specification. It also exceeds the acceleration of the prototype bus. However, the acceleration of the hypothetical bus is slightly lower than that of existing trolley buses, due to a very high power-to-weight ratio of the latter.

Average Energy Consumption

Average energy consumption of roadway-powered electric buses for El-Monte Busway should be approximately 2.5 kilowatt-hours per mile. We believe that this level of average energy consumption

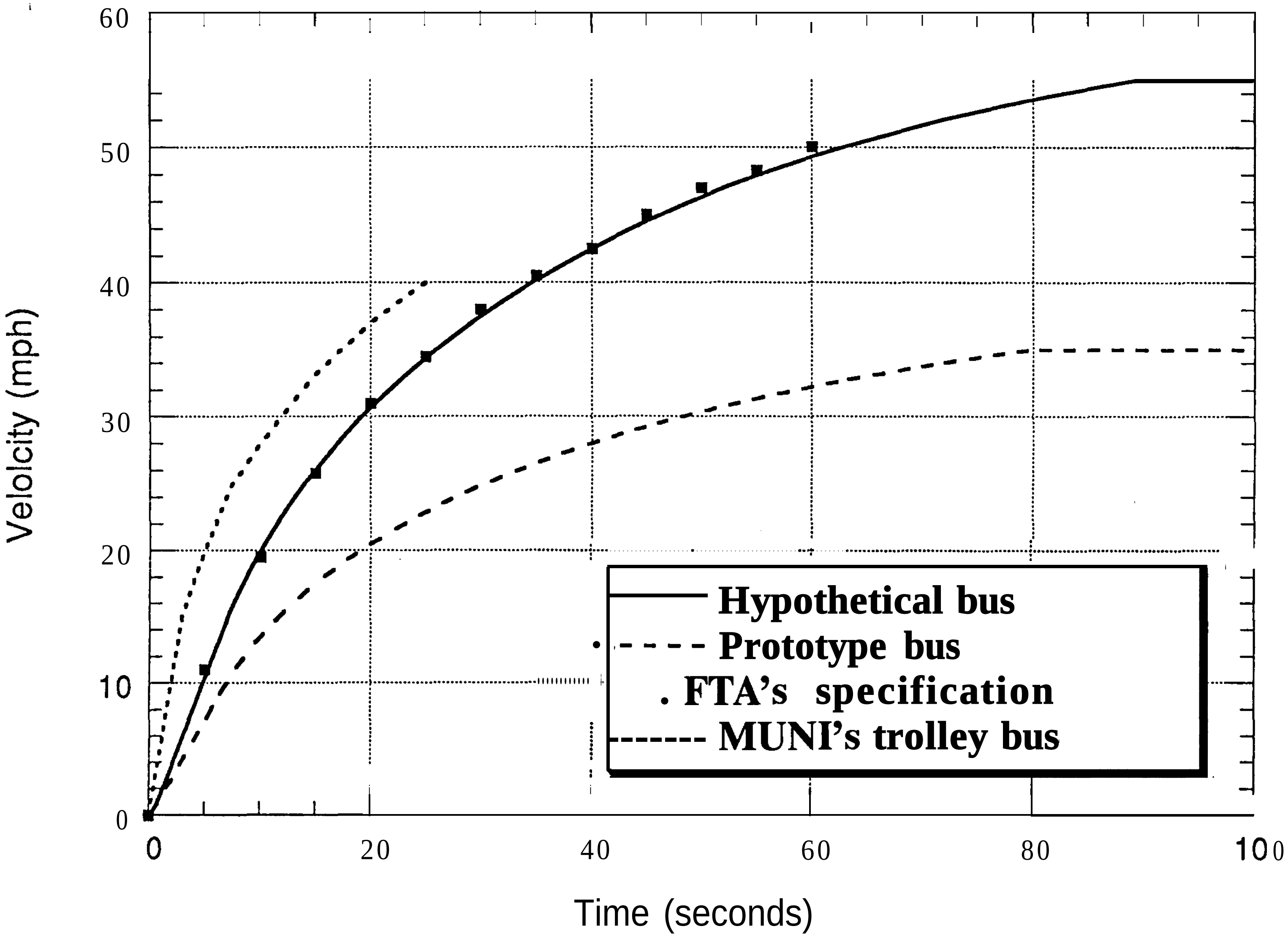


Figure 4: Performance of Hypothetical El-Monte Bus

could provide a good balance between the energy needed by the bus and the energy available from the battery and the ICS.

ICS Power Ratinq

The ICS for the El-Monte system should have a minimum power rating of 150 kilowatt, to enable transit buses to operate continuously for at least 15 hours between overnight recharges, without requiring roadway electrification outside the Busway (except static chargers to be provided at bus layover points and bus stops).

Net Battery Depth of Discharge (DOD) for Buses

One measure-of-effectiveness for determining whether a particular electrification scheme could satisfy daily range requirements of the buses is the level of discharge of the onboard battery. Other things being equal, a smaller battery discharge requires that a higher proportion of total trip time be spent on electrified facilities. This in turn implies that higher mileage of roadway power and/or more static-charging locations are needed. An ideal RPEV system is one that yields zero net battery discharge at the end of a round trip. For economical and practical systems, some amount of net battery discharge is acceptable. This is because the battery could easily be fully recharged overnight before the next-day's operation. In the absence of a specific policy guideline at this time, the onboard battery of the El-Monte buses should not be discharged below 80 percent at any time during normal daily operation. This would help maintain the service life of the battery, as well as provide reserved capacity for the buses to operate in case of power failure for a couple of hours on the battery power alone.

3.2 Alternative Electrification Scale Scenarios for El-Monte Busway

Other things being equal, more extensive electrification would provide more roadway power, and thus greater range for roadway-powered vehicles. For the El-Monte system, maximum electrification could be achieved by installing electrification along the entire length of the travel lanes of the busway (including bus stops along El-Monte Busway), as well as static chargers at the layover points for each bus line (i.e., the origin and destination of each bus line) and downtown bus stops. Electrification to be installed on the travel lanes of El-Monte Busway is capable of supplying power to the vehicles while they are in motion or standing still, and is referred to in this report as "dynamic roadway electrification." At bus stops or layover points, relatively short sections of static chargers could be used to supply power to vehicles while they are stopped atop the static chargers.

Three alternative electrification scenarios using electrification in the dynamic and static modes are defined for the El-Monte Busway system. All three scenarios involve, as a minimum, installing roadway power along the entire length of the busway's travel lanes. Preliminary engineering feasibilities of these three scenarios are then evaluated to determine whether they could satisfy the daily range requirements of bus lines currently using the Busway. These scenarios, listed in order from the most to the least electrification, are described below,. In the next section, additional electrification scenarios using static chargers exclusively will be evaluated.

Scenario A: Electrify El-Monte Busway Plus Install Static Chargers at Bus Stops and Layover Points

This scenario involves installing roadway electrification along the entire length of the travel lanes of El-Monte Busway. In addition, static chargers will also be installed at downtown stops used by El-Monte buses, as well as at layover points for each of the bus lines operating on El-Monte Busway.

Scenario B: Electrify El-Monte Busway Plus Install Static Chargers at Layover Points

Scenario B involves installing roadway electrification along the entire length of El-Monte Busway. In addition, static chargers will also be installed at layover points of all bus lines. However, static chargers will not be installed at downtown bus stops.

Scenario C: Electrify El-Monte Busway without Using Static Chargers

This scenario involves installation of roadway electrification along the travel lanes of El-Monte Busway only. No static chargers will be installed at layover points or downtown bus stops.

3.3 Methodology for Engineering Feasibility Evaluation

To be a viable scenario, the scenario under investigation has to enable buses to operate continuously for at least 15 hours a day, without the battery DOD exceeding 80 percent, with the ICS output current of no more than 300 amp. Based on knowledge gained from other ongoing R&D activities in California, design engineers generally consider the ICS output currents of up to 300 amp as being desirable. Higher ICS output currents could result in higher roadway losses and system costs.

Vehicle simulation is used to evaluate whether each of Scenarios A through C could meet the daily range requirements for all existing bus lines currently operating on El-Monte Busway. The simulation is accomplished through an electric-vehicle simulation model, EVSIM, developed by Systems Control Technology (1984). EVSIM can simulate many vehicle types along multiple routes. The model includes any number of blocks, in which each block is represented by acceleration, cruise, and deceleration. Parameters such as the route length, roadway grades, and speeds are set for each block. By selecting the appropriate number of blocks and the associated parameters, the driving cycles can be simulated. EVSIM also allows effects of the variation in many parameters such as mass, frontal area, aerodynamic and rolling resistance drag coefficients, vehicle voltage, battery capacity, motor ratings, and gear reduction ratio to be analyzed.

Bus lines currently using El-Monte Busway are listed in Table 1. Please note that the actual route numbers of buses shown in Column 1 are the numbers displayed on the buses. To facilitate the interpretation of simulation results, these bus lines are recoded and ranked in an ascending order of the route length as shown in the last column. For example, the shortest bus route (line 491) is recoded as "Line 1," while the longest route (Line 490) is recoded as "Line 9."

For simulation purposes, characteristics of the hypothetical El-Monte bus have to be defined. This is a full-sized bus (GVW of 31,200 lbs). It has the nominal voltage of 500 volts, which is typical voltage of electric trolley buses used in California. Other vehicle parameters are shown below:

* Maximum acceleration	10 feet per sec^2
* Drag coefficient	0.60
* Rated motor torque	254 ft-lbs
* Rated motor base speed	1,600 rpm
* Gear ratio	45 rpm/mph
* Battery amp-hour rating	400

The inductive coupling system assumed in the simulation has roadway excitation of 8,500 Hz.

3.4 Evaluation Results for Scenarios A Through C

Simulation results obtained indicate that Scenario A could

Table 1

Characteristics of Existing Bus Lines Using El-Monte Busway

Actual Route Number	Destination	Round Trip Length (miles)	Round Trip Time (including layovers) (minutes)	Total Layovers (minutes)	Average Velocity (including layovers) (mph)	Average Velocity (excluding layovers) (mph)	Recoded Bus Number*
480	Pomona Express	68.2	192	39	21.3	26.9	5
491	Sierra Madre	43.5	123	14	21.2	23.9	1
481	West Covina	52.0	157	25	19.9	23.6	2
497	Montclair	75.2	212	34	21.3	25.3	6
486	Puente Hills	53.6	180	23	17.9	20.4	3
482	Pomona	88.1	297	54	17.8	21.8	8
484	Ontario Airp.	87.0	318	60	16.4	20.2	7
488	Glendora	67.8	259	39	15.7	18.5	4
490	Fullerton	95.7	296	40	19.4	22.4	9

* Recoded bus number is in an ascending order of the route length

provide adequate power for all bus lines using El-Monte Busway to operate continuously for at least 15 hours a day with the ICS output current of 300 amp, without the battery DOD exceeding 80 percent at any time during the daily operation. Unlike Scenario A, Scenarios B and C are found to require more than 300 amp in order to satisfy the daily range requirement for a number of longer bus lines.

Differences in the ICS output current requirements among Scenarios A, B, and C can be illustrated by Figure 5. The figure compares plots of the hourly net battery discharge rate (percent per hour) versus the required ICS output current levels for Line 1 (the shortest bus route) among Scenarios A, B, and C. The hourly net battery discharge rate is defined as the difference in the battery discharge level between the end and the start of one round trip, divided by total round-trip time. Since the vertical axis is the battery discharge, a higher positive value indicates that the battery actually has less energy available. Figure 5 is based on a round trip for which the battery depth-of-discharge (DOD) at the start of the trip is 20 percent. Please note that for Bus Line 1, the percent of round-trip time spent on the powered facilities differs considerably among the three scenarios (42, 34, and 22 percent for A, B, and C, respectively). Figure 5 indicates that Bus Line 1 requires the ICS output current of 230 amp to maintain the hourly net battery discharge rate of 4 percent per hour under Scenario A. Under Scenario B, Line 1 would require an output current 295 amp to maintain the hourly net DOD rate of 4 percent

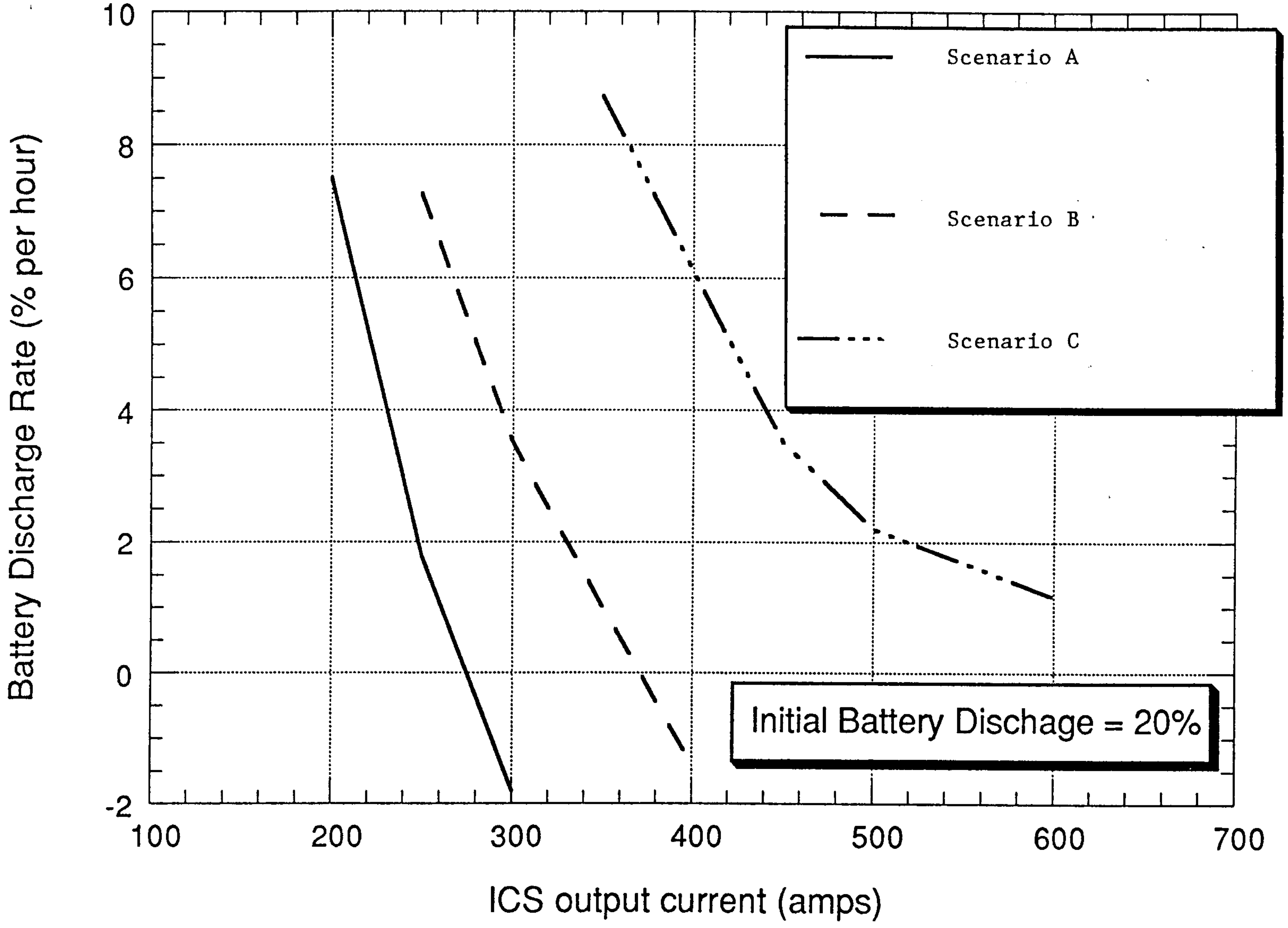


Figure 5: Hourly Battery Discharge Rate vs ICS Output Current for Bus Line 1

per hour. Under Scenario C, Line 1 would require an output current of 440 amp to maintain this same hourly average net battery DOD rate. Generally speaking, the hourly average net DOD rate increases with the length of the unpowered portion of the bus line.

Because Scenario A is a viable electrification-scale scenario, further simulation results for Scenario A are presented below. On the other hand, Scenarios B and *C* are excluded from further consideration.

3.4.1 Effects of Terrain on Battery DOD

Effects of the terrain (level versus roadway grades) on battery DOD are found to be similar for all individual bus lines. Line 1 is used to illustrate effects of the terrain on the battery DOD under Scenario A.

For Level Terrain

The speed profile for Line 1, assuming that the entire route is on level terrain, is shown in Figure 6. The figure indicates that the bus starts in the downtown area, and is outbound on the Busway from minutes 15 to 28. This is followed by a stop at the El Monte Terminal for two minutes, before proceeding onto the suburban portion of the route. As expected, the average bus speed is lower for the suburban portion than on the Busway. Figure 6 shows that top speeds for the suburban portion are 40-45 mph, compared with 60 mph on El-Monte Busway. There is a layover of seven minutes at the end of the line, from minutes 55-62. The bus then retraces itself

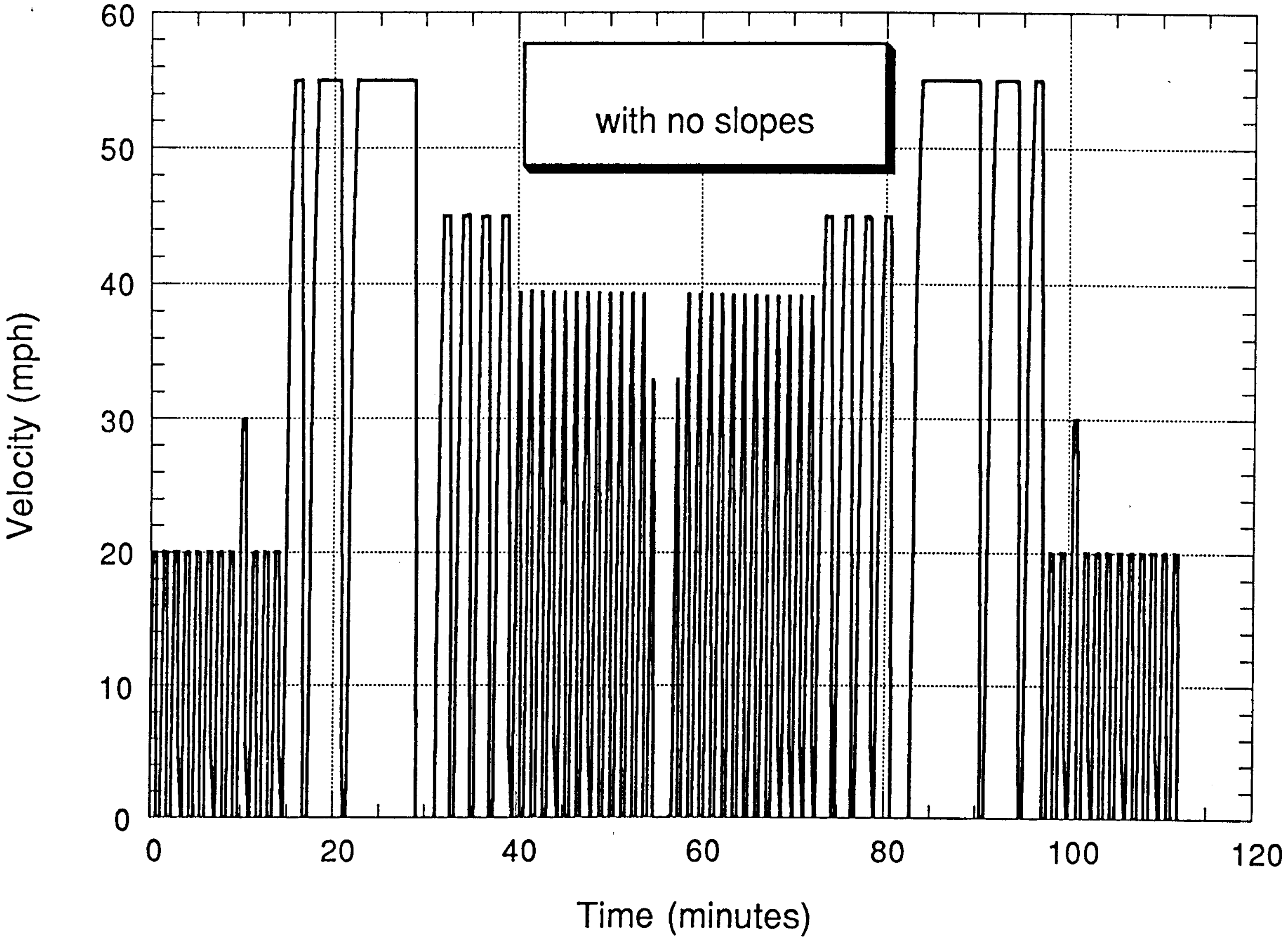


Figure 6: Speed Profile of Bus Line 1 for One Round Trip (Assuming Flat Terrain)

on the inbound journey. The round trip ends with a seven-minute layover in downtown, after which the bus is ready to start its next round trip.

The dc output from the ICS assumed in the analysis is 250 amp. The battery-DOD profile for Line 1 is shown in Figure 7. The solid curve represents the operation of Line 1 over a level-terrain route. The battery DOD at the start of a round trip is assumed to be 20 percent. There is slight charging of the battery both in the downtown area and on El-Monte Busway. This indicates that more energy is transferred to the vehicle at the bus stops in downtown than the energy required in driving. The battery charging continues as Line 1 travels outbound along the El Monte busway. There is battery discharge as the bus traverses the unpowered suburban portion of the route, from minutes 30-55. The battery DOD increases approximately 15 percent during this 25-minute interval. Figure 7 indicates that there are short intervals of battery charging (decreases in battery DOD) every block due to regenerative braking. The ripples in the curve are further apart in the suburbs than in downtown, indicating longer distances between stops for the former. During the layover between minutes 55 and 62, the battery receives a partial recharge. This is then followed by discharging through the suburbs and finally net charging on the Busway, the downtown blocks, and the downtown layover. For one round trip, the difference between the DOD at the end and the start of the trip is about 4 percent.

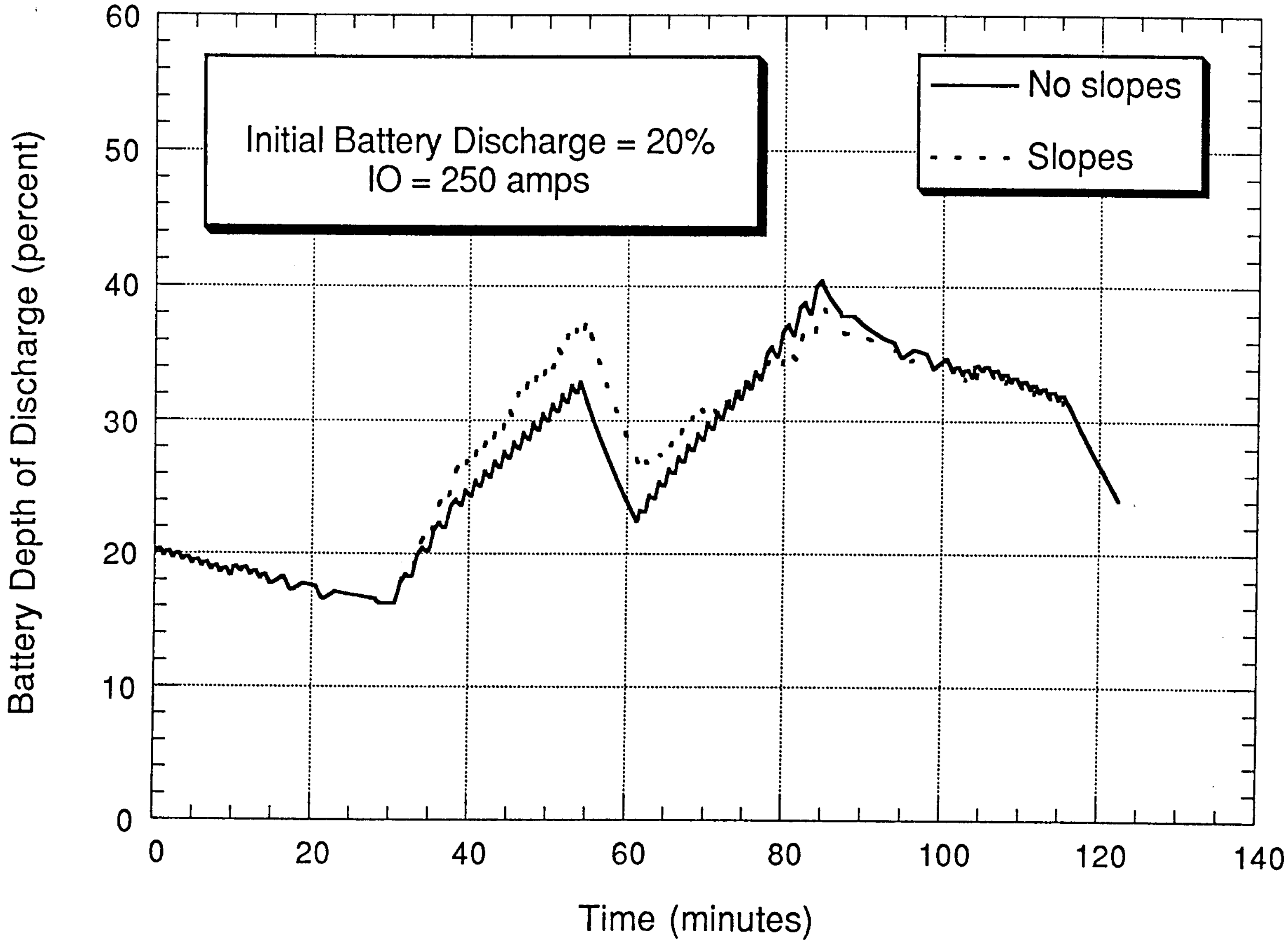


Figure 7: Battery Discharge Profile for Bus Line 1, With and Without Roadway Grade

For Routes With Actual Grades

There is significant elevation gain on the outbound half of the route of Line 1. Simulation results for Line 1 with actual roadway grades are shown as the dashed curve in Figure 7. The solid and the dashed curves for the outbound journey are identical until the bus reaches the uphill areas of the suburbs. Starting at minute 30, the dashed curve rises more quickly than the solid curve, representing more drain of energy from the battery as the bus goes uphill. On the return inbound trip, the dashed curve represents downhill travel, and the two curves finally converge. The dashed curve falls below the solid curve briefly, which is due primarily to the time constant of the battery. At the end of the round trip, the two curves converge, indicating that there is virtually no difference in the net battery discharge for one round trip between routes with upgrades and routes on the level terrain.

Figure 8 presents the velocity profile for Line 1 when actual roadway grades are included. On upgrades, the bus accelerates more slowly than on level ground. Nevertheless, even though the first three uphill blocks (minutes 30 to 39) are relatively long, the bus is still able to reach the 45 mph top speed. For the next 13 blocks of upgrades (minutes 39 to 54), the top speeds are reduced to about 35 mph (compared with 40 mph for the same time interval when assuming level roadways as shown in Figure 6). As was the case with the battery DOD, most of the time that is lost on the uphill portion is later regained on the downhill. As a result, the difference in total round-trip time between the level-terrain route

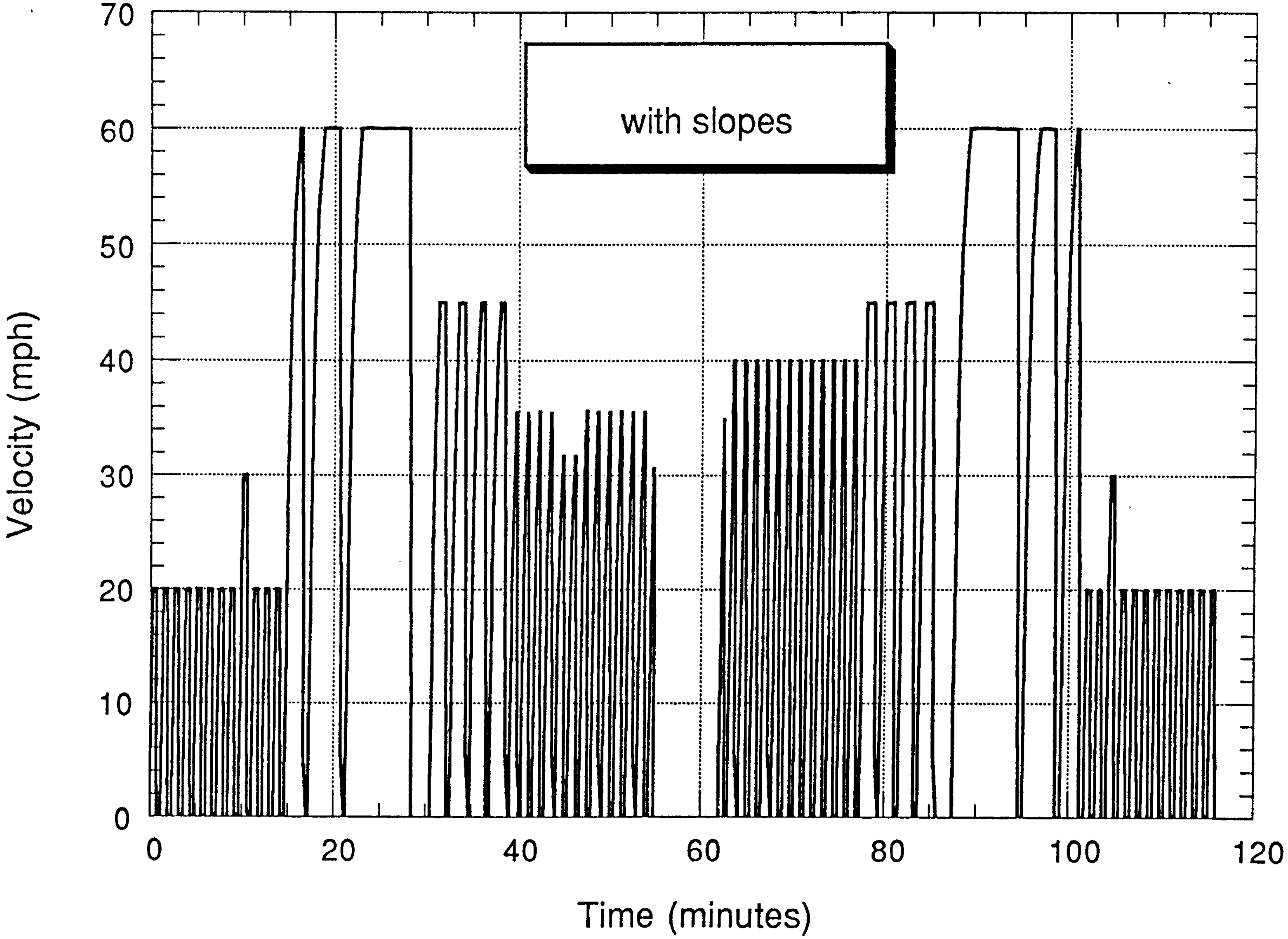


Figure 8: Speed Profile for Bus Line 1 in One Round Trip, With Actual Roadway Grade

and the actual route with grades is negligibly small (within one minute of each other over two hours).

3.4.2 Desired Initial Battery DOD

Batteries of all bus lines should be fully charged at the start of the day. This is in order to maximize their daily range, as well as to achieve full service life of the batteries.

During any one round trip, the battery could reach a peak DOD considerably higher than the DOD at the start of the trip. Therefore, it is important to assure that the battery DOD at the start of the last trip does not exceed a certain value so as to result in the peak DOD exceeding 80 percent during that trip. This point can be illustrated by Figure 9, which shows the battery DOD profiles for four bus lines, assuming an output current of 250 amp. Consider Line 1, in which the bus only has to travel off the powered facilities (i.e., relying solely on the battery power) for a relatively short time (30-40 minutes). The peak DOD during a round trip occurs at minute 80, which is about 20 percent higher than the DOD at the start of the trip. Therefore, the battery DOD at the start of the last trip of the day for Line 1 could be as high as 60 percent and the peak DOD reached during the last trip would not exceed 80 percent. At the other extreme, Line 8 is the second longest bus line and the bus spends a long time on the unpowered portion in the suburb. The peak battery DOD for Line 8 is reached at minute 242, which is 63 percent higher than the DOD at the start of the trip. Therefore, if the battery DOD for Line

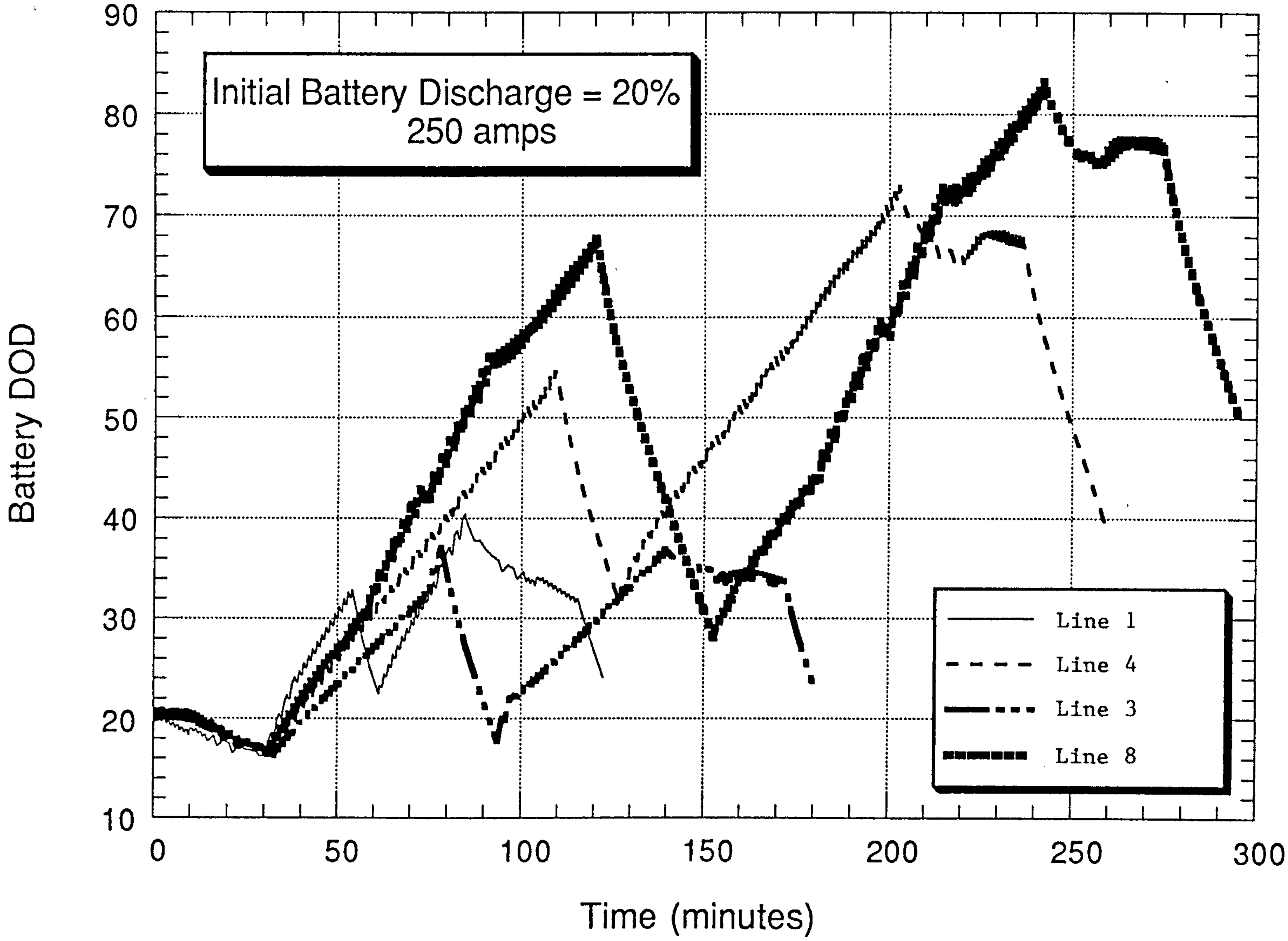


Figure 9 Profiles of Battery Depth of Discharge (DOD) for One Round Trip of Bus Lines 1,3,4, and 8 (Output Current of 250 Amp)

8 at the start of the last trip exceeds 17 percent, the battery DOD will exceed 80 percent at minute 242.

The above results indicate that longer bus lines have to maintain a higher state of the charge than shorter bus routes at the start of any one round trip, in order to have enough energy to negotiate the round trip successfully.

3.4.3 *ICS Output Currents Required for Individual Bus Lines*

Figure 10 shows plots of battery DOD for Line 3 with three levels of the ICS output current (250, 300, and 400 amp). For the output current of 250 amp, the peak DOD reached during one round trip is 37 percent (at minute 78), which is 17 percent higher than the DOD at the start of that trip. Further, the battery DOD at the end of the trip is 2.9 percent higher than the DOD at the start of the trip. Because Line 3 takes about three hours to complete one round trip, the hourly net DOD rate is about one percent per hour. Therefore, if Line 3 starts its daily operation with a fully-charged battery, its battery could reach 80-percent DOD during the 23rd round trip. This implies that Line 3 could operate on an output current of 250 amp for 22 round trips (or 66 hours) without its DOD reaching 80 percent. Therefore, an output current of 250 amp is more than adequate to meet the 15-hour daily range requirement for Line 3.

As the ICS output current increases, both the peak DOD reached during one round trip and the DOD at the end of the trip will decrease. For example, Figure 9 indicates that with 300 amp, the

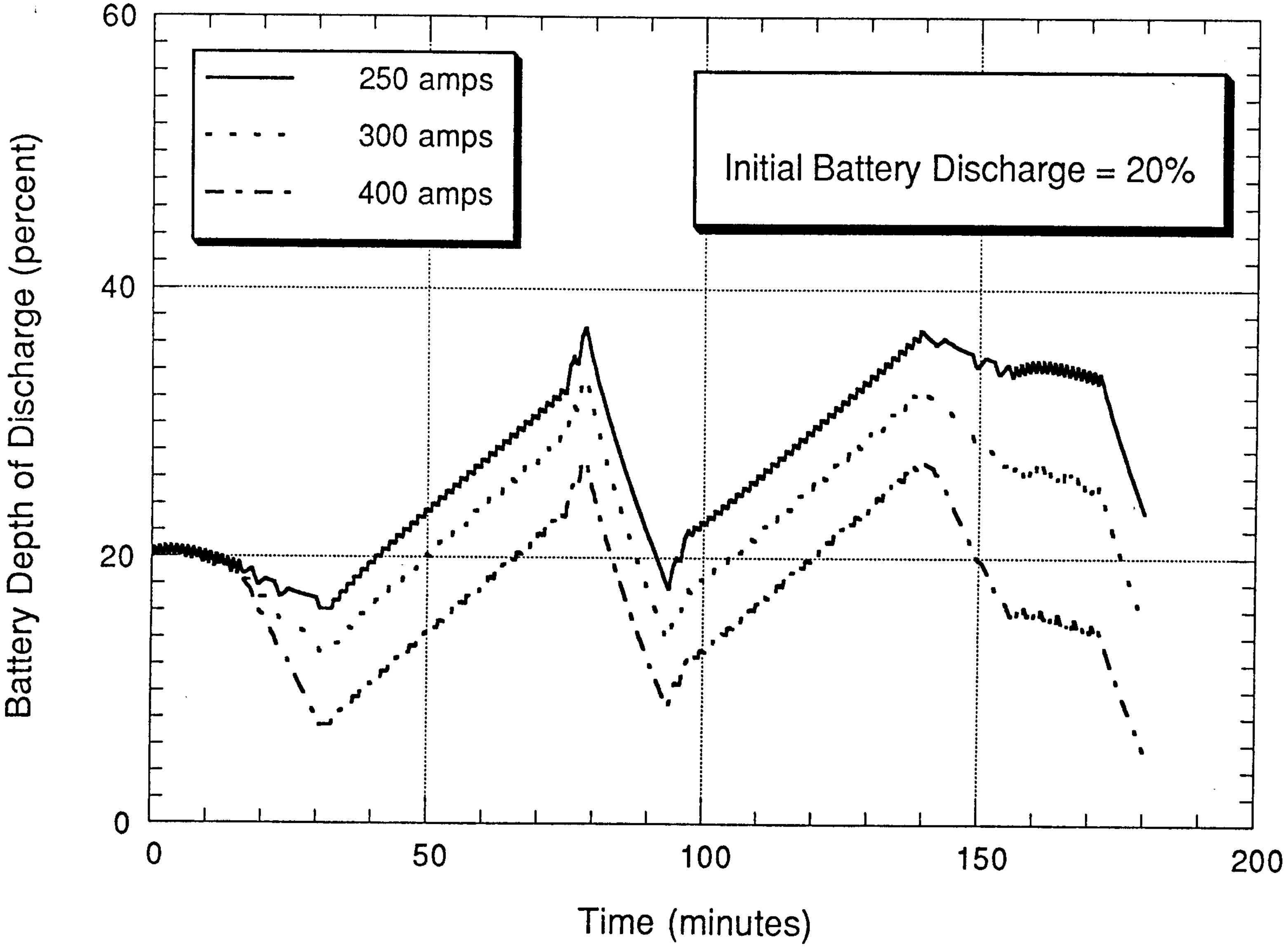


Figure 10 Battery Discharge Profiles for Bus Line 3 for Different Values of Output Current

battery of Line 3 actually experiences charging (as opposed to discharging) of 3 percent at the end of the trip. With 400 amp, the charging at the end of the trip is 14 percent. With battery charging for every one round trip completed, Line 3 will be able to operate indefinitely without reaching 80-percent DOD.

Hourly net battery discharge (or recharge) rates are plotted as a function of the ICS output current in Figure 11, for Bus Lines 1, 3, 4, 5, 8, and 9. These six bus lines essentially cover the entire range of route lengths for bus lines currently using El-Monte Busway. Figure 11 indicates that longer bus lines, which travel farther in the unpowered suburban portion of the route, would require larger ICS output currents than shorter bus lines. Bus Lines 1, 3, and 5 are similar in the level of the ICS output current required. Lines 4 and 8 are close together in terms of the ICS output current level requirement. Line 9 is clearly an "outlier" because it requires a much higher level of output current than the other bus lines.

Examinations of battery DOD profiles obtained from the simulation for all bus lines reveal the following:

(i) Output current of 250 amp would be adequate for 15-hour daily operation for Lines 1, 2, 3, and 5.

(ii) Bus Lines 4, 6, 7, and 8 require output current of 300 amp.

(iii) Line 9 (with the greatest round-trip distance) requires output current over 300 amp for the 15-hour daily operation. However, output current of 300 amp could be adequate for Line 9 if

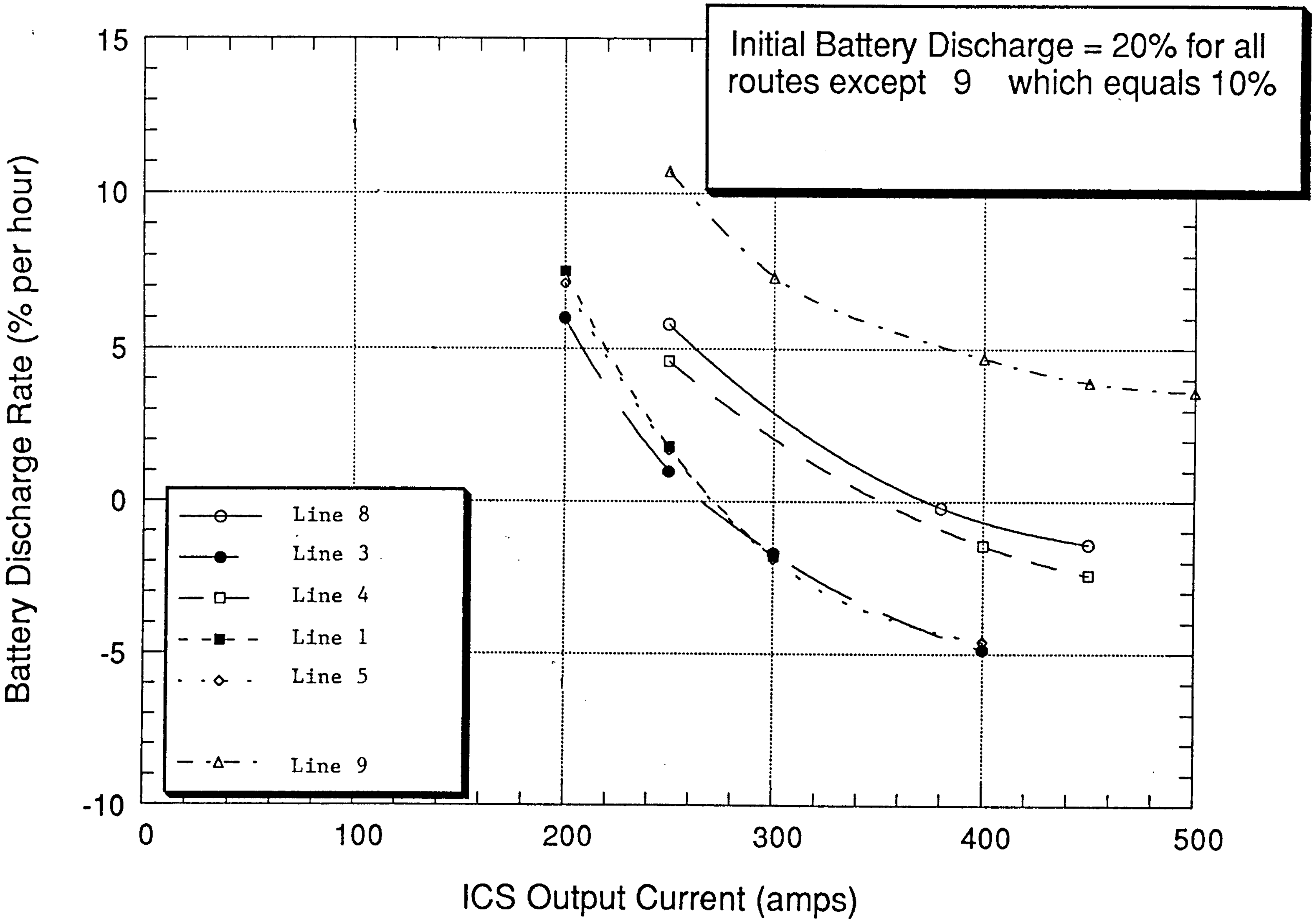


Figure 11 Hourly Battery DOD Rate vs. ICS Output Current for Various Bus Lines

one or more of the following relatively simple measures could also be implemented specifically for Line 9:

- Install static chargers at selected major bus stops in the suburban portion of Line 9.
- Adding layover time at existing layover points of Line 9.
- Create additional layover points (at which static chargers are installed) for Line 9.

Any one of the above measures is likely to be relatively easy to justify, as evidence from the statistics shown in Table 2. Table 2 indicates that Line 9 is a long route, and additional intermediate layover points in the suburban portion would probably be practical. Table 2 also indicates that Line 9 has by far the lowest percent of powered time (i.e., the fraction of round-trip time that is spent on the entire powered facilities) among all bus lines. This implies that there should be room for adding powered time for Line 9 at existing layover points or for installing static chargers at some major bus stops along the suburban portion of the route.

The above results suggest that Scenario A can be implemented with the ICS output current of 300 amp (at 500 volts).

Please note that while the buses are running on the electrified Busway, the motor controller is capable of drawing a large current from the roadway, and the battery could accept the balance of the current available from the powered Busway. During static charging at the layover points or at the downtown bus stops (through static chargers), however, essentially all of the power

Table 2

Percent of Round-Trip Time Spent on Layover Points and Powered Facilities (Scenario A)

Recoded Bus Number	Route Length (miles)	% Layover Time*	% Powered Time**
1	43.5	11	42.0
2	52.0	16	38.2
3	53.6	13	35.9
4	67.8	15	31.7
5	68.2	20	41.5
6	75.2	16	36.3
7	87.0	19	32.4
8	88.1	18	32.7
9	95.7	14	26.9

* This is the percent of total round-trip time that is spent at layover points.

** This is the percent of total round-trip time that is spent on the entire powered facilities.

from the roadway inductor goes to the battery. The battery's ability to accept charge could limit how much power could be drawn from static chargers. For example, when the battery is relatively fully charged (i.e., at a low DOD), less energy is transferred from a static charger to the vehicle. The ability of the bus to achieve peak power transfer during the dynamic and static modes of operation is illustrated in Figures 12 and 13. Figure 12 shows a situation in which the maximum output current is 250 amp, and this level of power transfer can be achieved by the bus at all times while on the dynamic or static powered facility. Figure 13 represents a situation in which the maximum coupled current is 400 amp, but this level of power transfer is only reached when the bus is running on the powered busway and the motor is drawing a large current. At the downtown bus stops (i.e., the first 15 minutes and minutes 155-172) in which the power mostly goes into the battery, the battery charge acceptance never exceeds 260 amp. During the mid-route layover (minutes 78-98) and again at the downtown layover (minutes 172-180), the power transfer level is reduced over time, according to the battery's ability to accept charge. This is another technical reason for limiting the ICS output current to approximately 300 amp, because output currents larger than 300 amp are likely to yield only marginal benefits, and at a risk of much higher roadway losses.

3.4.4 Energy Consumption Under Scenario A

Net energy flow into the motor controller (or energy

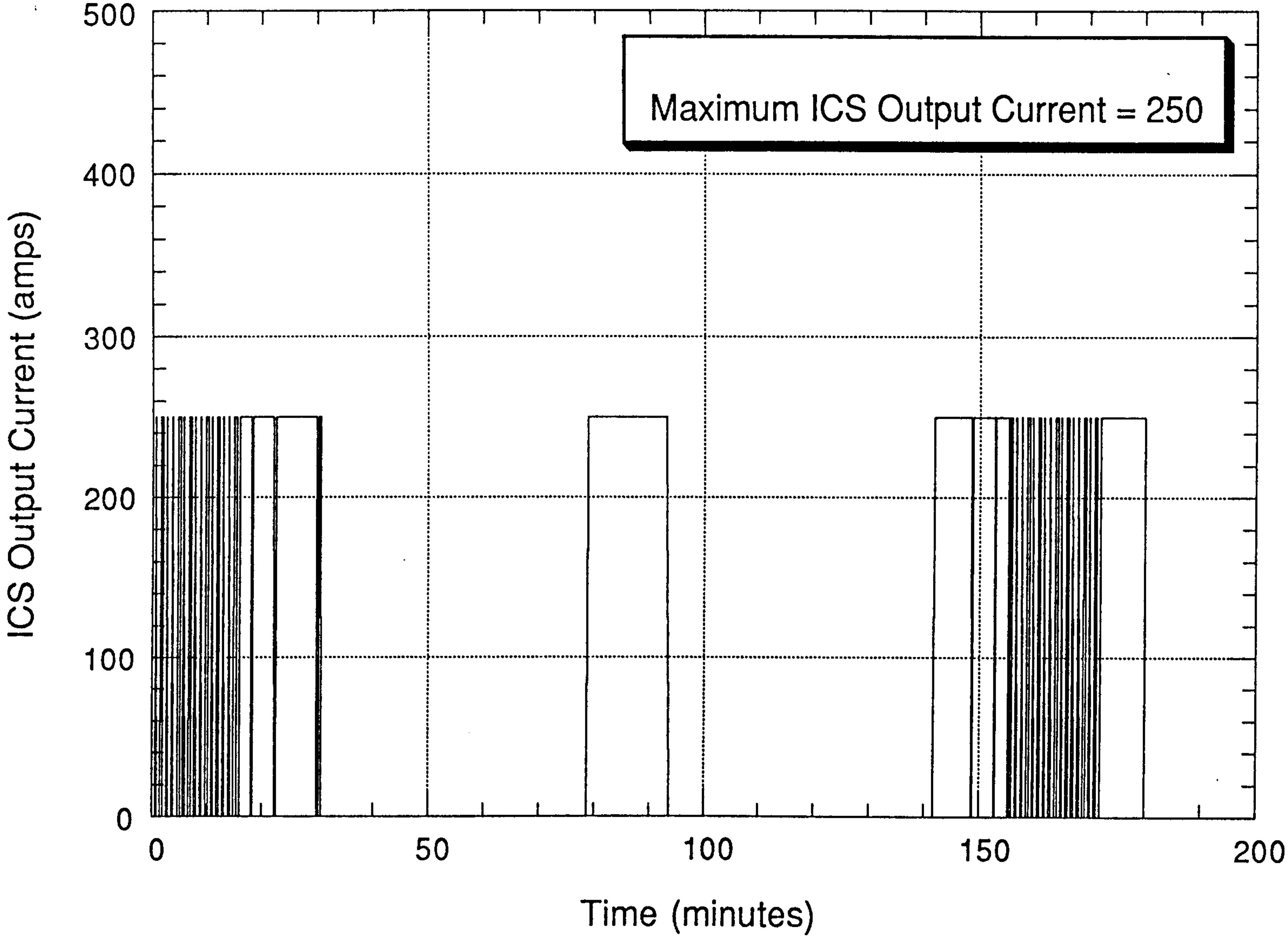


Figure 12 Charge Acceptance Profile for Line 3 in One Round Trip, Assuming ICS Output Current of 250 Amp

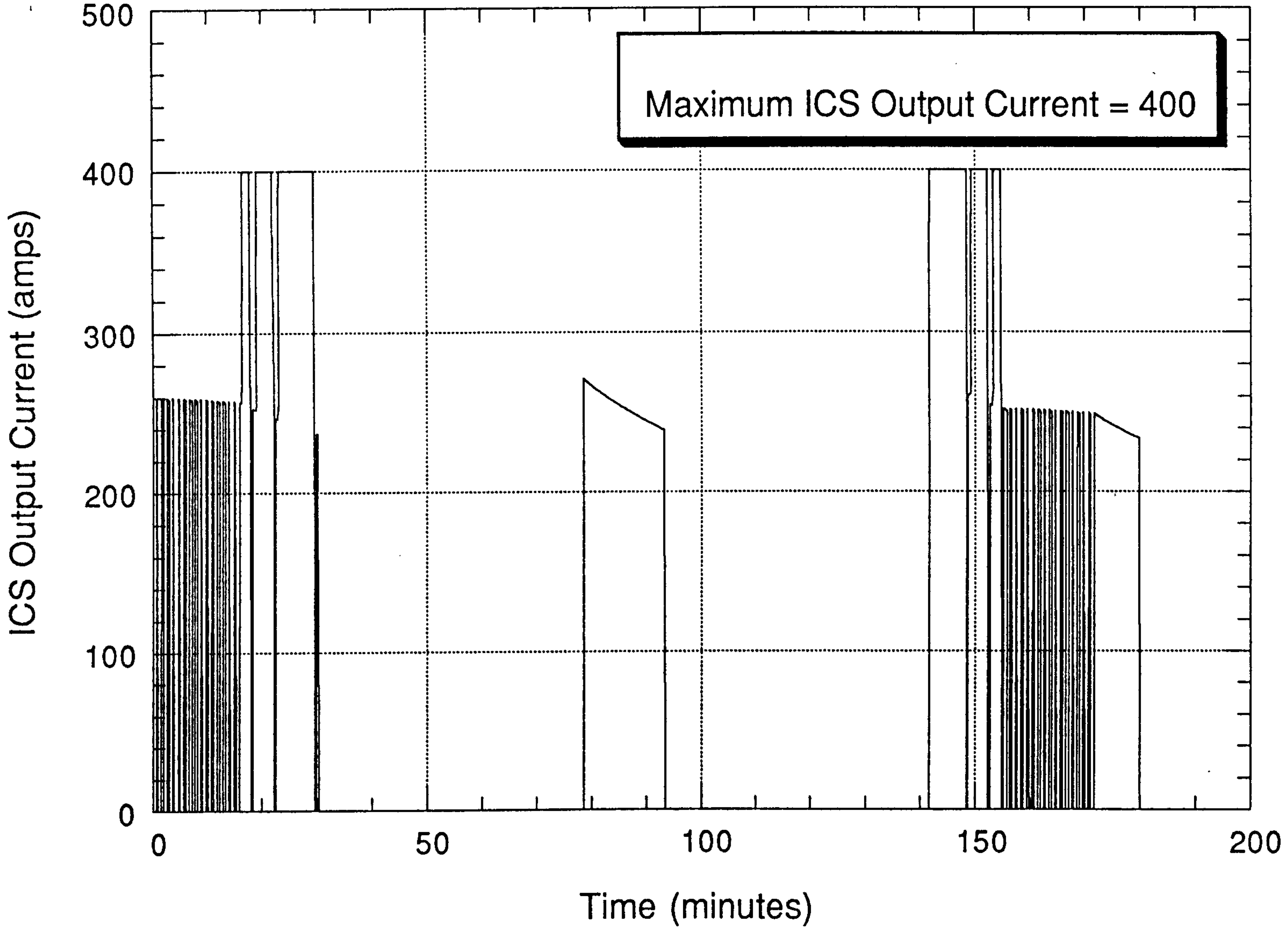


Figure 13 Charge Acceptance Profile for Line 3, Assuming ICS Output Current of 400 Amp

consumption) for all bus lines is determined through vehicle simulation using the EVSIM model. Energy consumption for all bus lines is found to range from 2.25 to 2.53 kilowatt-hours per mile, among the nine bus lines. This range of energy consumption values among the nine bus lines is small despite the wide variation in their route lengths and driving cycles. Energy consumption values and average speeds for five bus lines are plotted in Figure 14 for illustration. The figure indicates that average travel speeds among these bus lines could vary by as much as 50 percent (from 18 to 27 mph), while their energy consumption values varies only by 10 percent (from 2.25 to 2.53 kwh/mile). Generally, bus lines with higher average travel speeds tend to have lower energy consumption. This is because higher average speeds are usually associated with lower numbers of bus stops. Frequent stops require higher energy for frequent start-up accelerations. Regenerative braking could minimize the energy loss in a stop/start cycle, but it clearly does not entirely eliminate the loss.

3.4.5 Potential Range of RPEV's under Scenario A

The electrified El-Monte Busway could be used by all kinds of roadway powered electric vehicles (e.g., cars, vans, pickups, etc.), not just transit buses. This electrified roadway provides extended range to RPEV's in two ways:

(i) While on the electrified roadway, RPEV's do not have to draw or use energy from the onboard battery. Therefore, the unused battery energy can be saved for use in subsequent travel off the

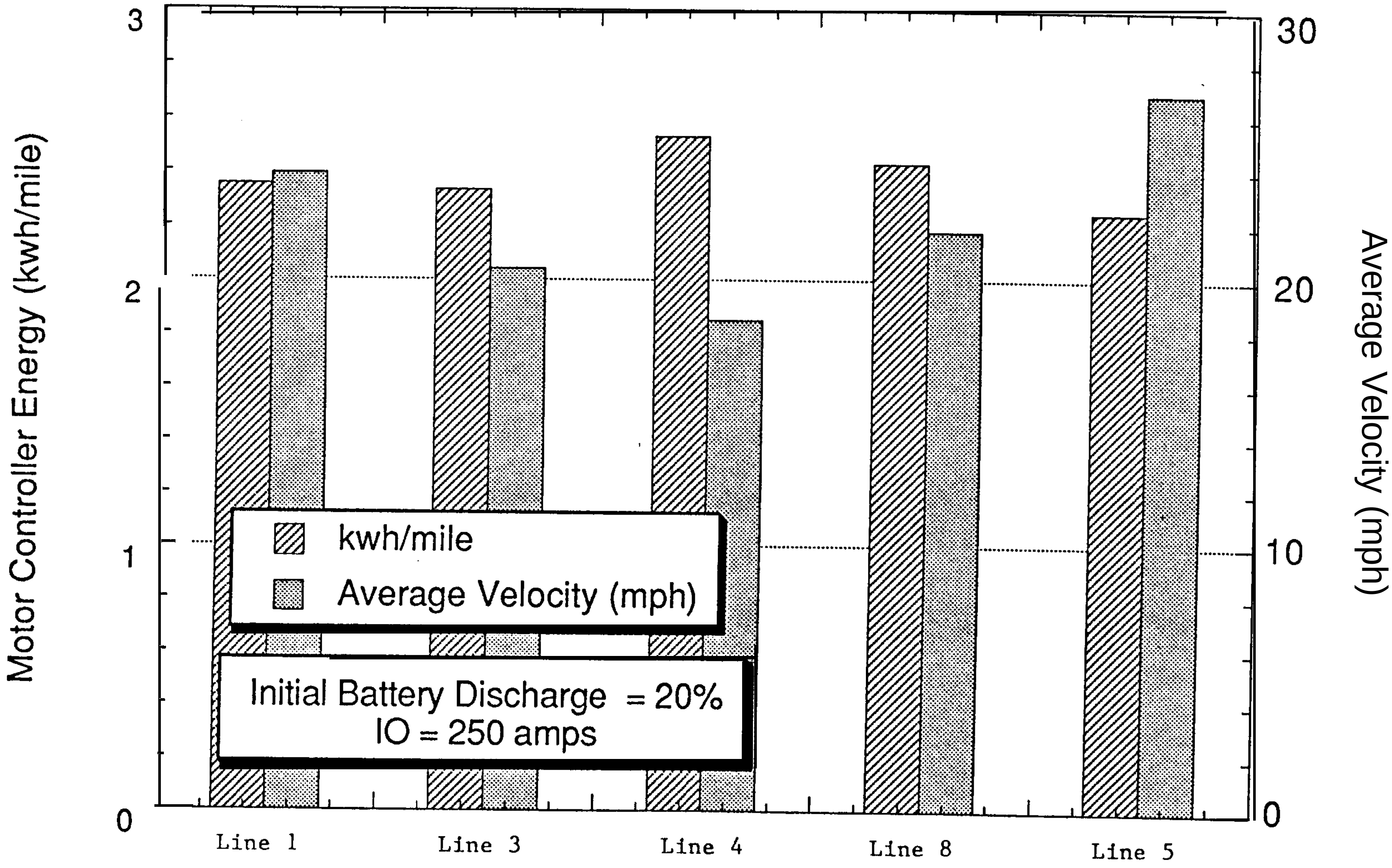


Figure 14: Average Energy Consumption Rates and Speeds of Various Existing El-Monte Bus Lines

electrified roadway. The 22-mile electrification of El-Monte Busway could provide reserved battery energy to allow RPEV's to travel another 22 miles off El-Monte Busway.

(ii) When RPEV is operating and drawing energy from the electrified roadway, about 80-85 percent of the roadway energy goes directly into the motor controller and the other 15-20 percent goes into the onboard battery. Therefore, as the vehicle leaves the powered roadway, its battery could have more energy than when it entered the roadway. For l-mile of the electrified El-Monte Busway, up to 0.25 miles of extra range off the electrified roadway could result this way. Thus, 22-mile of the electrified roadway could deliver up to 5.5 miles of extra range to RPEV's.

3.5 Electrification Scenarios Using Static Chargers Exclusively

The above Scenario A involves electrifying the travel lanes of El-Monte Busway in both directions. Existing bus lines using El-Monte Busway can maintain their current routing and scheduling; existing diesel buses would simply be replaced by new roadway powered electric buses.

There are other approaches for providing roadway power to transit buses on El-Monte Busway, some of which could involve a much smaller scale of electrification than Scenarios A through C. One approach is to use static chargers exclusively at locations where buses routinely stop (i.e., bus stops and layover points). With static chargers, the primary circuit of the ICS (which is a relatively short segment) is embedded below the street surface.

When vehicles equipped with the secondary inductor (or pickup) inductor stop directly atop the primary circuit, the pickup is lowered to a height of two inches or less. The circuit is then energized and the power is transferred to the vehicle through the magnetic'fields between the primary and secondary windings. As in dynamic roadway electrification, there is no contact between the primary and secondary windings, and thus no roadway apparatus is visible at or above the street level.

The use of static chargers exclusively has the following advantages and disadvantages:

(i) Power transfer for static charging occurs while the vehicles are stationary atop the chargers. This could allow the air-gap height to be reduced to a fraction of an inch during the energy transfer, thus significantly improving the energy transfer efficiency.

(ii) The pickup required for a static charger could be reduced in size, which in turn reduces the onboard equipment weight and costs. The roadway inductor section for a static charger has to be only as long as the pickup inductor.

(iii) Relative to dynamic roadway electrification, there is likely to be less environmental concern due to EMF's with static chargers due to the reduced length of the roadway inductor. Further, since static chargers are only energized when vehicles are stopped over them, stray magnetic fields are much less of a problem. The vehicle pickup essentially acts as a shield and absorbs almost all of the EMF's.

(iv) Due to the short roadway section required, infrastructure costs for static chargers will be much lower than those for dynamic roadway electrification.

(v) For static charging, essentially all of the power from the roadway subsystem goes directly into the battery (and not the motor controller as is the case with the dynamic power transfer). As a result, there is additional battery loss of up to 20 percent for static charging. This disadvantage, together with the advantages in (i) and (ii), yield the overall system efficiency for static charging of about 60-70 percent (compared with 70-80 percent for dynamic roadway power).

The low infrastructure cost of static chargers makes the use of static chargers particularly appealing. Exclusive use of static chargers could be a low-cost alternative for early technology demonstration, which could precede the demonstration of (more expensive) dynamic roadway electrification. Real-world data on energy consumption, as well as performance of the ICS and the battery, can be collected from the demonstration on exclusive use of static chargers. These data can be used to refine simulation models and the design of the RPEV. Further, public and driver acceptance of the RPEV technology can be evaluated from the demonstration on exclusive use of static chargers.

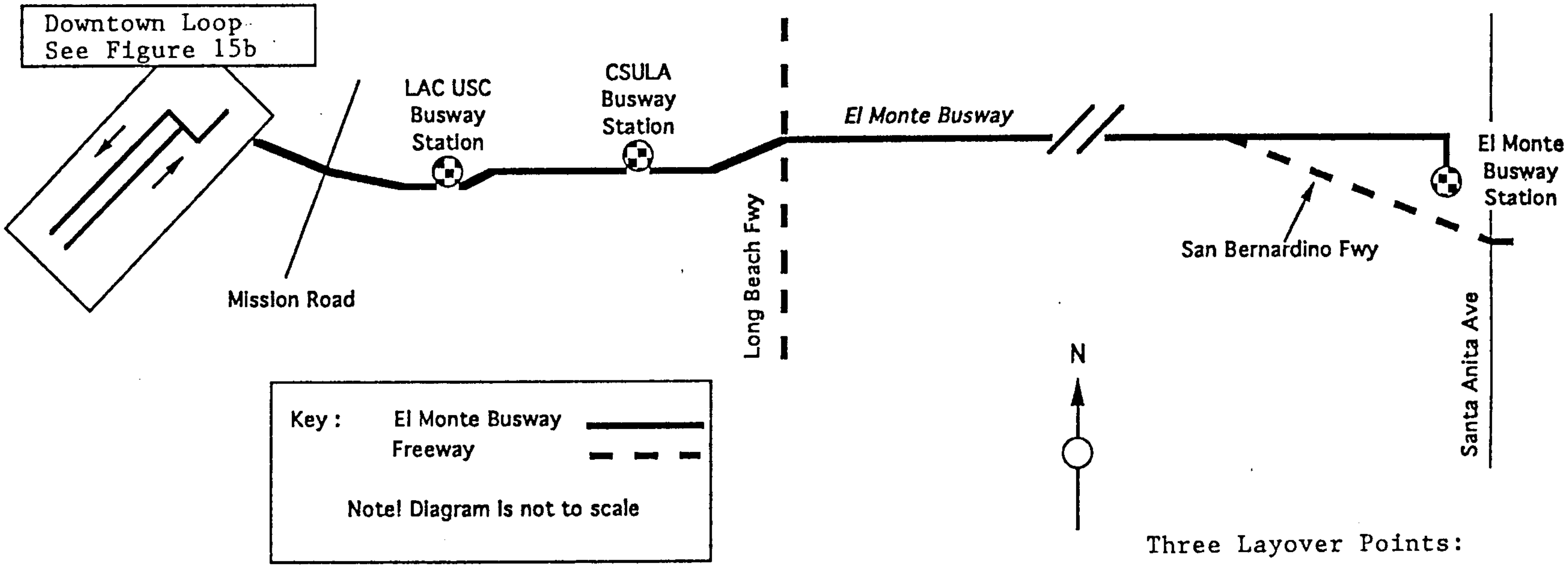
Three more scenarios which make use of static chargers exclusively, without electrifying El-Monte Busway, are described below:

3.5.1 *Downtown/El Monte Shuttle Bus Service (Scenario D)*

Scenario D provides a *Downtown/El Monte Shuttle bus service* between the downtown area and the El-Monte Bus Terminal, using static chargers exclusively. The route of this *Downtown/El Monte Shuttle* service essentially consists of two connecting loops -- the El-Monte Loop and the Downtown Loop (Figures 15a and 15b). The Downtown Loop as shown in Figure 15b is similar to the existing downtown DASH bus service currently operated by the LADOT. The *Downtown/El Monte Shuttle bus* will be a roadway-powered electric bus, which starts from Venice Boulevard (in the downtown). It then proceeds to Union Station, before getting onto El-Monte Busway and proceeding toward the El-Monte Terminal. Under Scenario D, three layover points are designated -- at Venice Boulevard, Union Station, and El-Monte Bus Terminal. Total round-trip time for this shuttle service is on the order of 75 minutes or longer, depending on the scheduled layover time.

Scenario D involves installing static chargers at the above-mentioned three layover points, as well as at downtown bus stops along the Downtown Loop.

Vehicle simulation using the EVSIM model is used to evaluate whether Scenario D could provide adequate energy to enable the *Downtown/El Monte Shuttle bus* to operate continuously for at least 15 hours a day (i.e., between overnight recharging). Please note that the role of static chargers in Scenario D is to assure that the shuttle bus can continue to operate for at least 15 hours a day, without the battery DOD exceeding 80 percent. These static



Three Layover Points:

- at El-Monte Terminal
- at Union Station
- at Venice Bl.

Figure 15a: Route Layout of Downtown/El Monte Shuttle Bus Service (Scenario D)

Two Layover Points for Downtown Loop:

- at Union Station
- at Venice Bl.

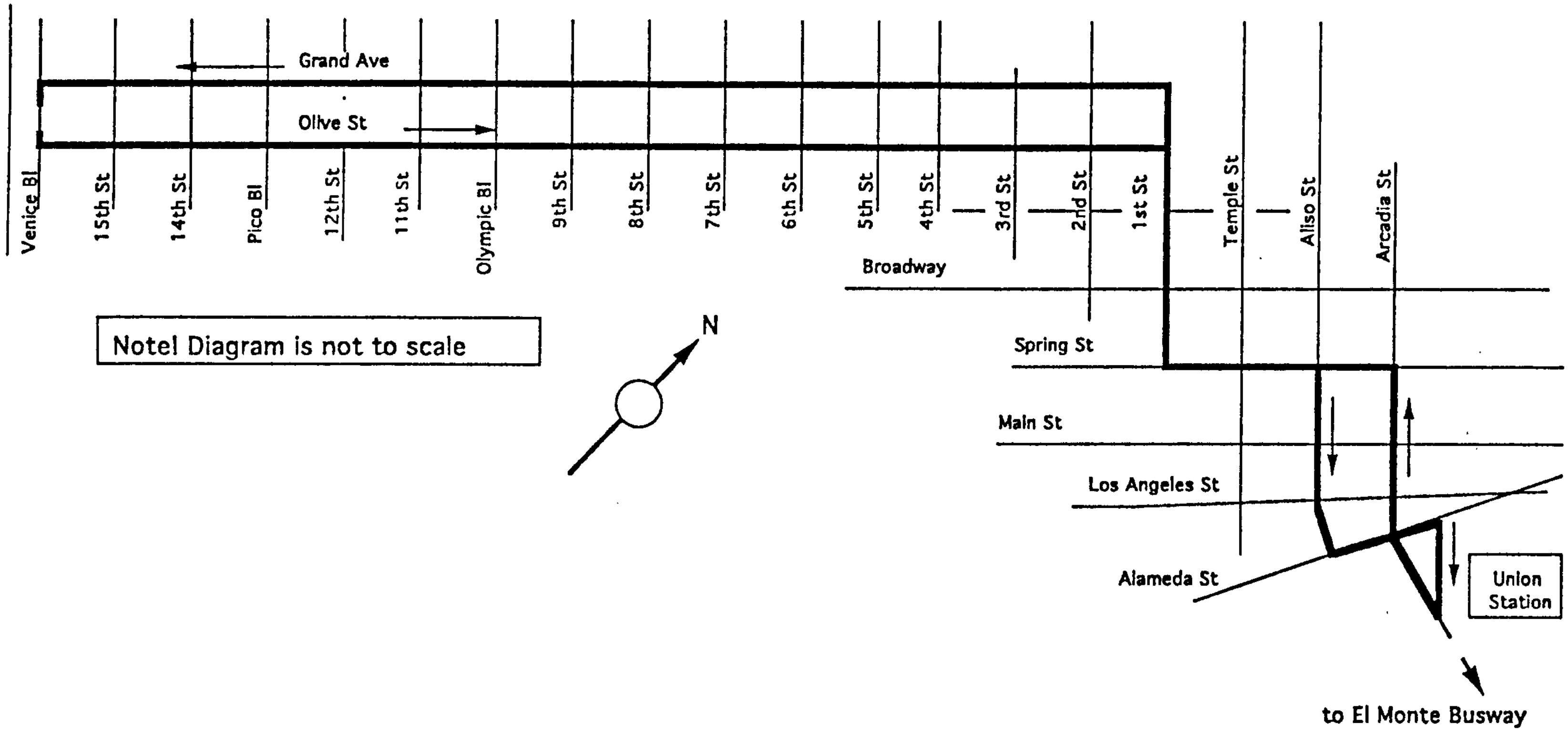


Figure 15b: The Downtown Loop of the Downtown/El Monte Shuttle Bus Service (Scenario D)

chargers are not meant to keep the battery fully (or close to fully) charged at all times while the bus is in operation. Rather, by providing regular battery charging (i.e., short-duration charging at bus stops and longer-duration charging at layover points), it is possible to prevent the battery from being discharged below 80 percent during the daily operation.

Figure 16 shows the hourly net battery discharge rate versus the ICS output current required for Scenario D, for four different values of the round trip time (75, 80, 85, and 90 minutes). Different values of the round-trip time reflect different amounts of time the ***Downtown/El Monte Shuttle*** bus spends at the three designated layover points. Higher round-trip time implies that more time is spent at the layover points, and thus more time is available for battery recharging from static chargers. Longer layover time also implies that more buses will be required in order to maintain the same level of service headway.

Figures 16 indicates that the hourly net battery discharge rate decreases with increasing values of the ICS output current up to 300 amp, beyond which no further decline in the discharge rate is expected. This implies that ICS output currents larger than 300 amp are of no value for Scenario D. This is because the battery would not be able to accept more charge. This suggests that it is feasible to implement Scenario D with the ICS output current of 275-300 amp, and the round-trip time of 80 minutes. Of these 80 minutes, about 15 minutes are total layover time.

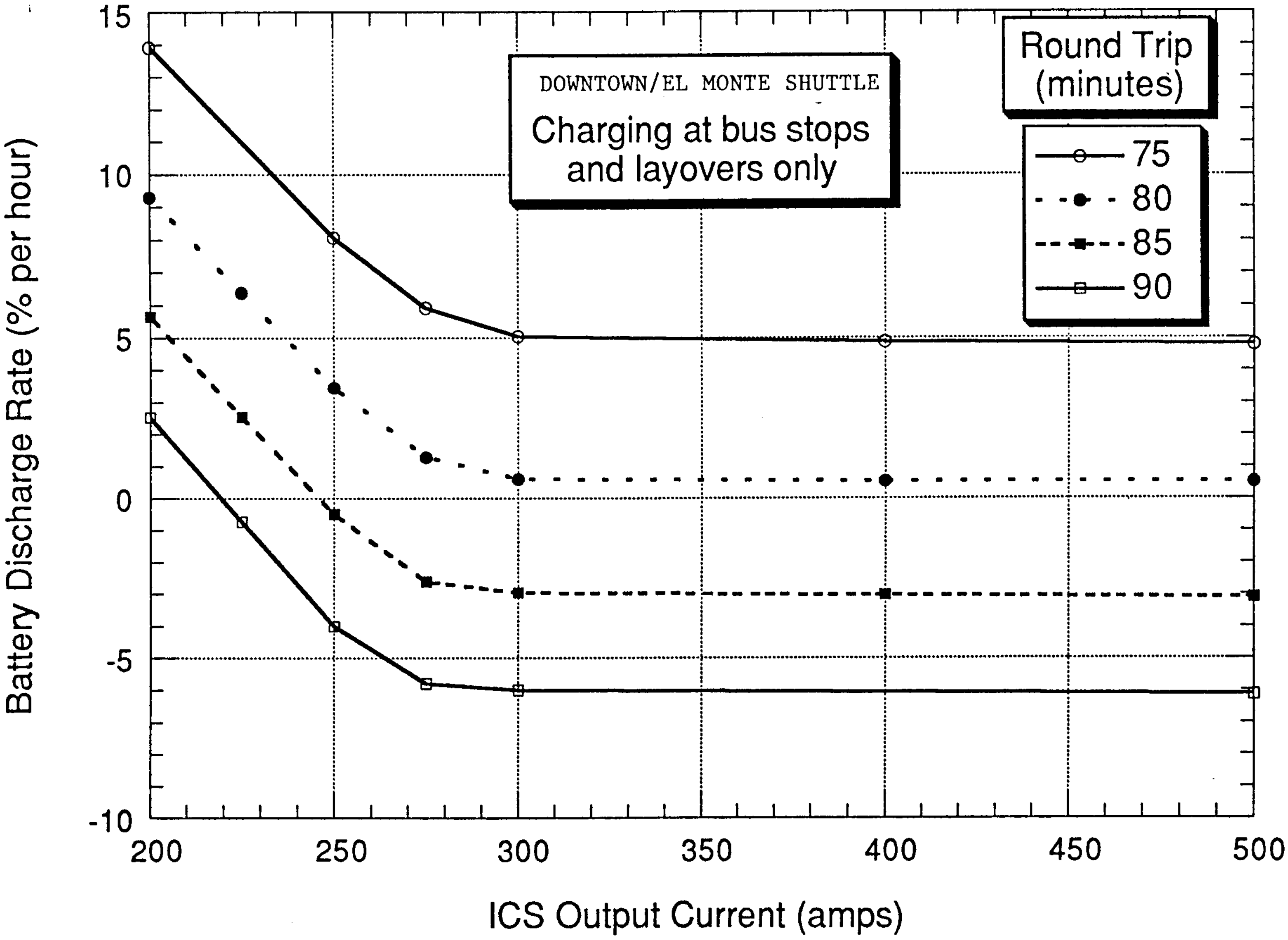


Figure 16: Hourly Battery Discharge Rate vs. ICS Output Current for Downtown/El Monte Shuttle (Scenario D)

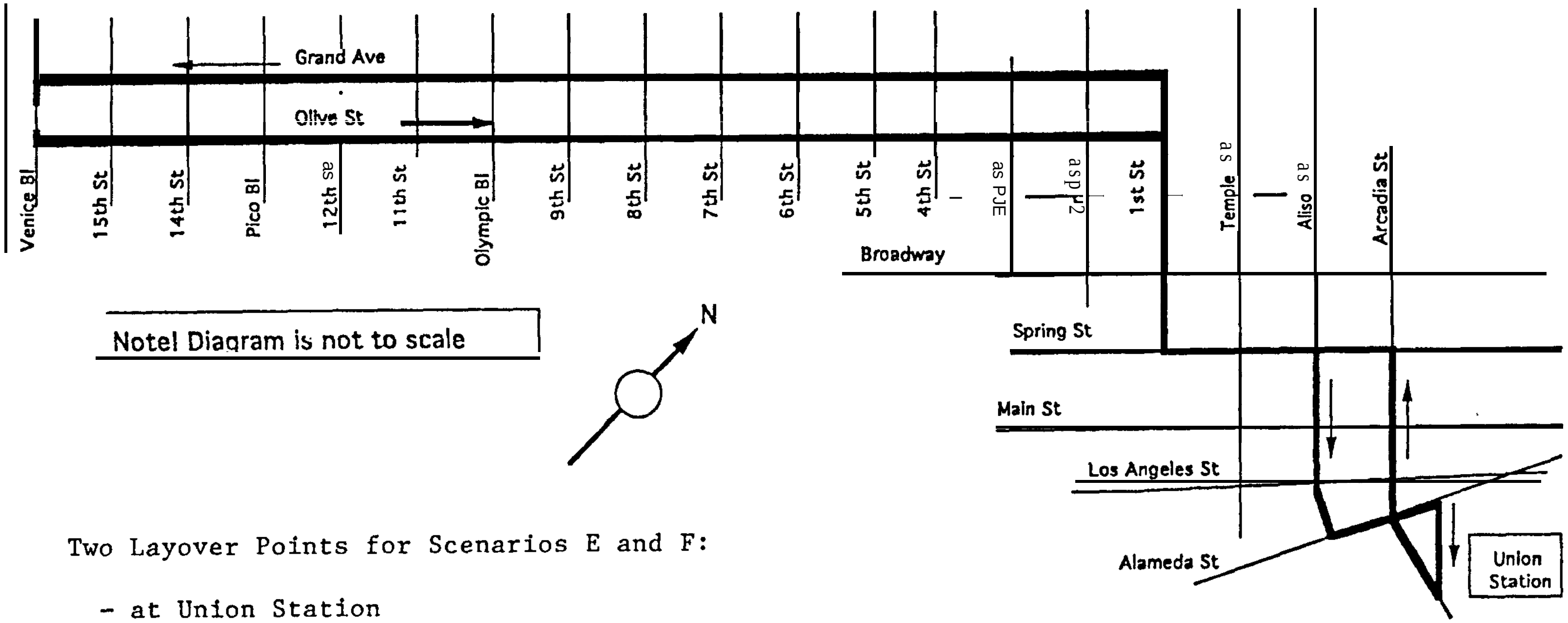
3.5.2 Downtown Shuttle Bus Service (Scenarios E and F)

A limited case of Scenario D is to have shuttle bus service serving the downtown area only, by using static chargers exclusively. One possible route for this downtown shuttle bus service is shown in Figure 17, which is essentially the Downtown Loop of Scenario D. This service will be called the ***Downtown Shuttle bus service.*** Two layover points are designated for the ***Downtown Shuttle bus --*** one located at Union Station and the other at the southern end of the Downtown Loop at Venice boulevard.

Two scenarios are defined and evaluated for this ***Downtown Shuttle bus service.*** Scenario E proposes to install static chargers only at the two designated bus layover points. Scenario F proposes to install static chargers at the two designated layover points, plus some bus stops along the loop. Energy transfer feasibilities for these two scenarios are evaluated by vehicle simulation using the EVSIM model, and the results are presented below.

Scenario E

Figure 18 shows simulation results for Scenario E, assuming that static chargers are installed at the two bus layover points, for three values of the round-trip time (35, 40, and 45 minutes). Higher round-trip time implies that more time is spent at the layover points, and thus more time for battery recharging from static chargers. The figure indicates that for 35-minute round-trip time (two minutes of which are layover time), the ICS output



Two Layover Points for Scenarios E and F:

- at Union Station
- at Venice Bl.

Figure 17 Route Layout of Downtown Shuttle Bus Service (Scenarios E and F)

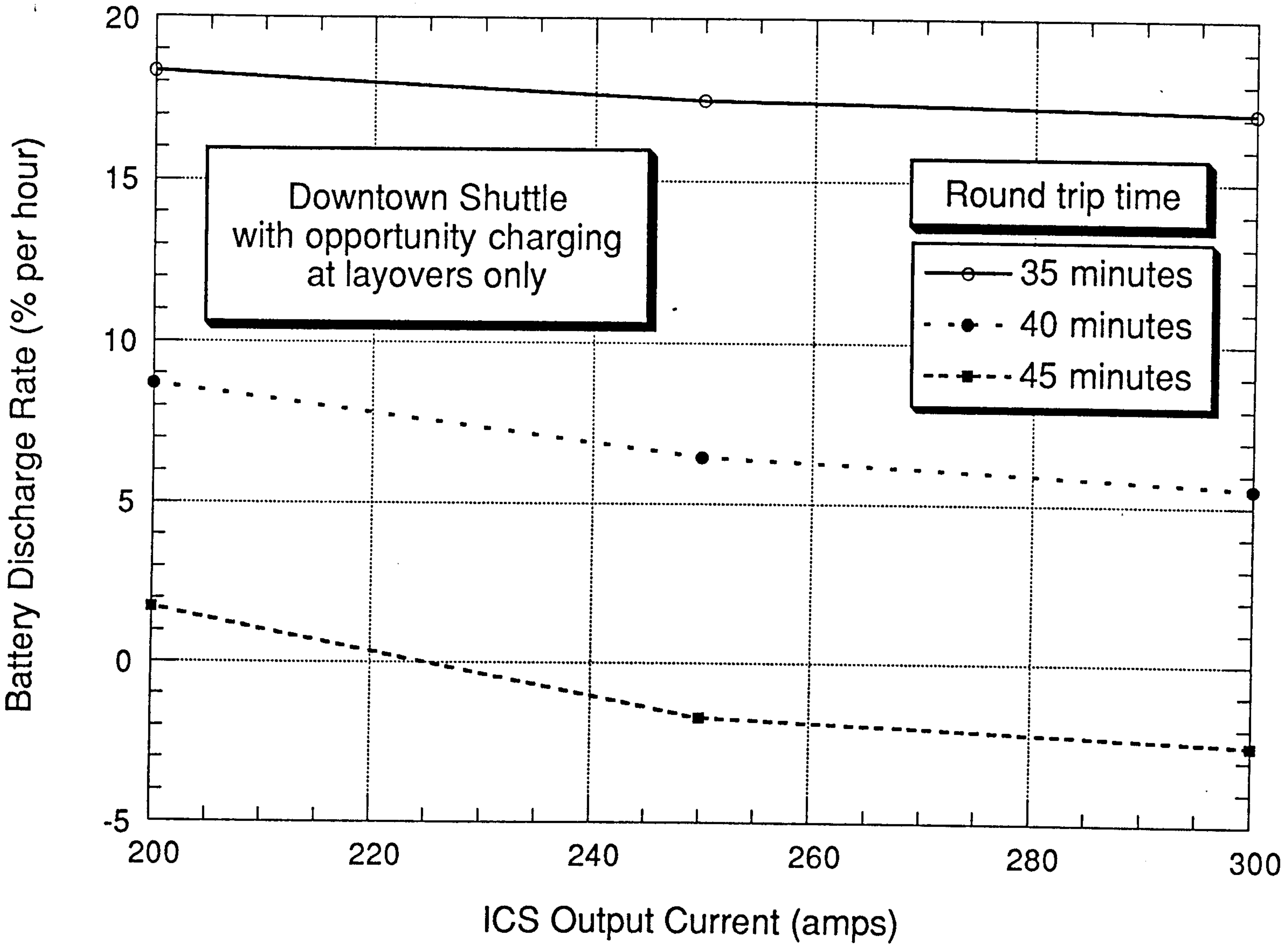


Figure 18: Hourly Battery Discharge Rate vs. ICS Output Current for Downtown Shuttle Bus Service With Static Chargers at Layover Points Only (Scenario E)

currents of 250-300 amp would yield hourly net battery DOD of 17 percent or more per hour. This would make it impossible for the *Downtown Shuttle bus* to provide continuous service for more than 4-5 hours. If the round-trip time is increased to 40 minutes (7 minutes of which are layover time), the ICS output current of 300 amp would yield an hourly average net battery DOD of 6 percent per hour. This would enable the Downtown Shuttle bus to operate continuously for 12-15 hours without the battery DOD exceeding 80 percent. The 40-minute round trip time would require 8 buses to provide 5-minute service headway. The 45-minute round trip time would actually result in battery recharge (as oppose to discharge), and thus the shuttle bus would be able to operate indefinitely without the need for overnight recharging. However, for the 45-minute round trip, 12 minutes (or 27 percent of the round-trip time) are layover time, which may be excessive.

The above results suggest that it may be desirable to also install static chargers at some bus stops along the downtown loop, in addition to the two layover points, as described in Scenario F.

Scenario F

Figure 19 shows plots of the hourly net battery discharge rate versus the ICS output current required to operate the *Downtown Shuttle bus service,* in which static chargers are installed at the two designated bus layover points as well as at all bus stops along the route (i.e., a total of 39 bus stops). Figure 19 shows plots for two values of the round-trip time (35 and 40 minutes). Please

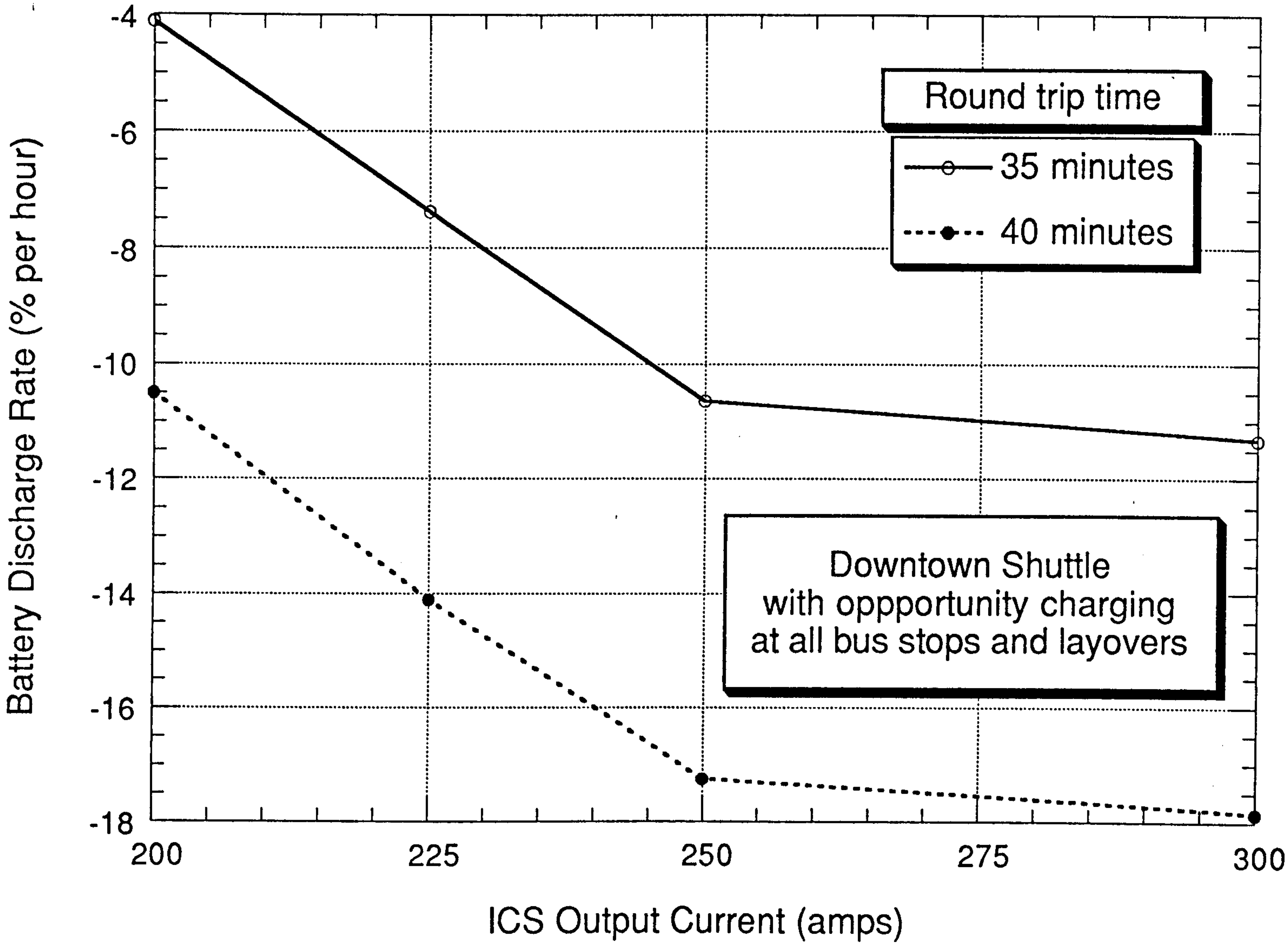


Figure 19: Hourly Battery Discharge Rate vs. ICS Output Current for Downtown Shuttle Bus With Static Chargers at Layover Points and Bus Stops (Scenario F)

note that the minus sign on the vertical axis indicates battery recharge (as oppose to discharge). Figure 19 indicates that, for ICS output current of at least 200 amp, the downtown shuttle bus could run indefinitely without the need for overnight battery recharging, as evidenced by the battery charging during the round trip. This is true for both values of the round-trip time. Therefore, 41 static chargers are more than adequate.

Further simulations performed indicate the following:

- It is feasible to operate the *Downtown Shuttle bus service* (with the round-trip time of 35 minutes), by installing static chargers at about 50 percent of the bus stops along the downtown loop (i.e., about 19 bus stops) in addition to the two layover points. This would provide at least 15 hours of continuous operation with the ICS current of 250 amp, without the battery DOD exceeding 80 percent. The battery would have to be recharged overnight after each daily operation.
- It is feasible to implement the *Downtown Shuttle service* with the round-trip time of 40 minutes (i.e., by having about 7 minutes for layover), by installing static chargers at about one-third of the bus stops (about 13 bus stops) along the downtown loop in addition to the two layover points. This would provide at least 15 hours of continuous operation per day with 250 amp.
- Finally, it is feasible to install static chargers at 4-5 bus stops along the downtown loop in addition to the two

layover points, if a roadway current of 300 amp is used with 40-minute round trips.

3.5.3 Potential Usefulness of Scenarios D and F to Non-Transit Vehicles

Unlike Scenario A in which the electrified El-Monte Busway could be used by all kinds of roadway-powered electric vehicles, the use of static chargers exclusively in Scenarios D and F is targeted for transit buses. Roadway powered private vehicles are likely to have no real use of the static chargers installed at bus layover points and bus stops. This is because private vehicles are not likely to stop at downtown bus stops and/or bus layover points for the purpose of recharging their batteries from static chargers. From the bus operation's standpoint, it is also undesirable for buses to have to share bus stops and layover points with private vehicles. Therefore, the use of static chargers exclusively should be viewed as a possible low-cost technology demonstration step preceding the ultimate installation of more-expensive electrified roadways.

3.6 Task Summary

Several electrification-scale scenarios are evaluated. A viable scenario is one that could satisfy daily range requirements of roadway powered electric buses, by allowing them to operate continuously for at least 15 hours per day without the battery DOD exceeding 80 percent. Principal findings of Task 3 include:

1. One viable scenario (Scenario A) involves installing roadway electrification along the entire length of the travel lanes of the busway in both directions. In addition, static chargers are also installed at the layover points for each of the bus lines and at downtown bus stops used by these buses (Scenario A). The ICS output current required for this system is 300 amp (at 500 volts). Existing bus lines using El-Monte Busway can maintain their current routing and scheduling; roadway-powered electric buses would simply replace existing diesel buses.

2. Another viable scenario (Scenario D) is to provide the *Downtown/El Monte Shuttle bus* service that operates between Venice Boulevard (in the downtown area) and the El-Monte Bus Terminal. Scenario D proposes the use of static chargers exclusively at three designated bus layover points and at bus stops in the downtown area. The route for this *Downtown/El Monte Shuttle bus service* consists of two connecting loops -- the Downtown Loop (which is similar to the existing downtown DASH bus service operated by the LADOT), and the El-Monte Loop. The shuttle bus will draw energy from static chargers as it is stopped atop the chargers. The ICS output current required for Scenario D is 275-300 amp, which would enable the *Downtown/El Monte Shuttle bus to* operate continuously for at least 15 hours between overnight recharging without the battery being discharged below 80 percent. This shuttle service would operate with total round trip time of 80 minutes.

3. As a limited case of Scenario D, it is feasible to use static chargers exclusively to operate the *Downtown Shuttle bus*

service, which runs between Venice Boulevard and Union Station (Scenario F). The route for this *Downtown Shuttle service* is the above-mentioned Downtown Loop (which is similar to the existing DASH service currently operated by the LADOT). As a minimum, static chargers should be installed at the two designated bus layover points (Venice Boulevard and Union Station), as well as at *4-5* bus stop along the loop. This *Downtown Shuttle bus* could operate with the round trip time of 40 minutes, with the ICS output current of 300 amp. If static chargers are installed at a larger number of the bus stops along the loop, total round-trip time and/or the ICS output current can be reduced.

Task 4

Preliminary Design of RPEV System for El-Monte Busway

One functional requirement of the RPEV system to be implemented in El-Monte Busway is that the electrification installed should provide adequate energy to enable roadway powered electric buses to operate continuously for at least 15 hours between overnight battery recharges, without the battery depth of discharge (DOD) exceeding 80 percent. Simulation results from Task 3 indicate that the ICS for El-Monte Busway could have the output current of 300 amp, at 500 volts.

This task describes preliminary specifications for an RPEV system proposed for EL-Monte Busway. Engineering judgments and experience gained from the design of the prototype systems were used to guide these preliminary system specifications.

4.1 Inductive Coupling System

The design of the ICS for the El-Monte Busway application builds upon the Playa Vista design (Lechner et al, 1991). Figure 20 shows the cross section of the ICS for the El-Monte system. This ICS could operate at a power frequency of 8,500 Hz. To prevent possible "skin effect" (or the tendency for large currents to flow near the conductor surface at higher frequencies), a large number of small conductors (e.g., 10-30 conductors) is used for both the pickup and roadway. Also, to minimize core losses due to the use of a high frequency, the pickup cores are made of 0.002-

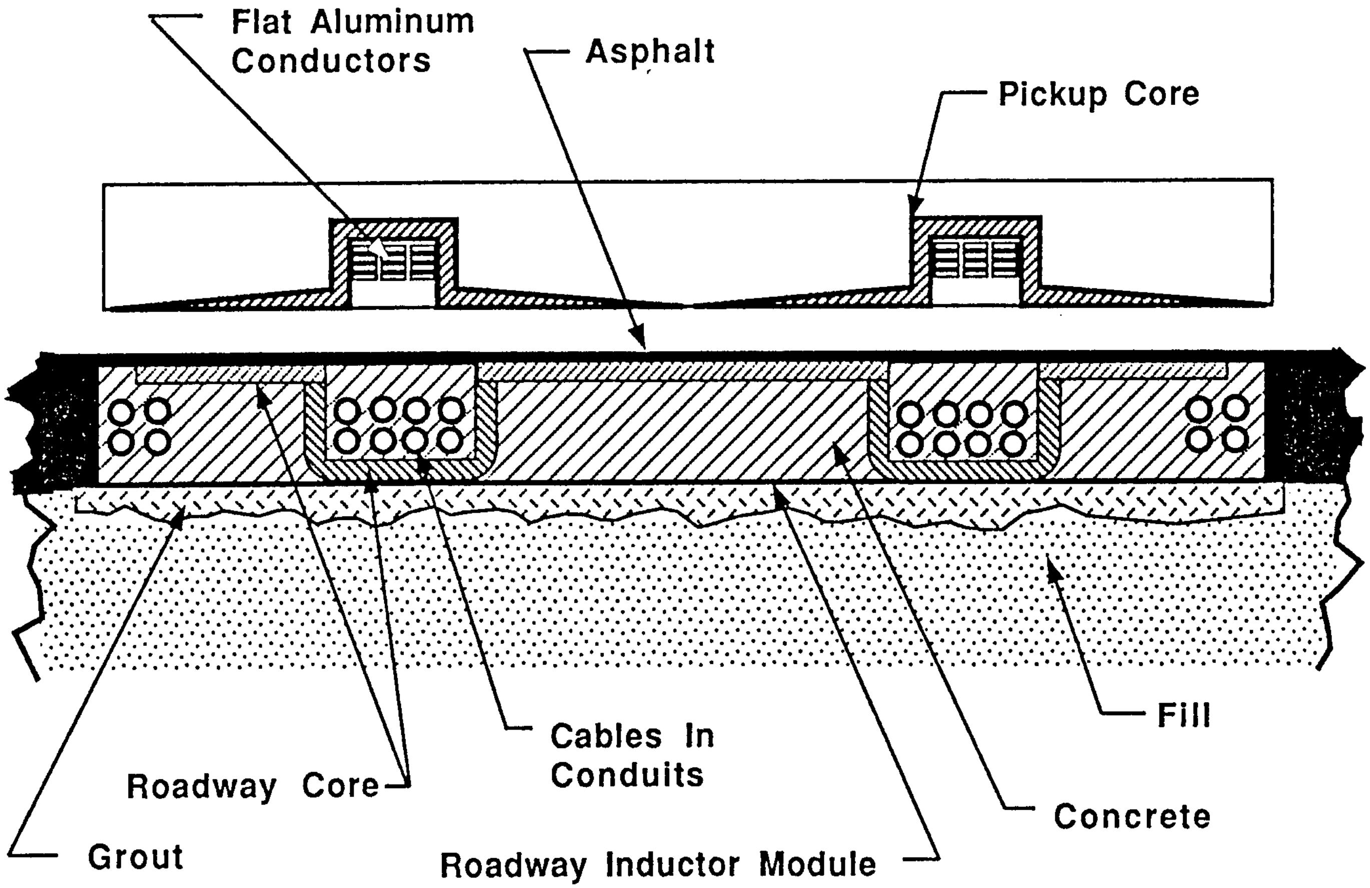


Figure 20: Typical Cross Section of the ICS for El-Monte System

inch laminations and roadway cores made of 0.011-inch (or thinner) laminations could be thickened. Two pickups in parallel are used to double the output current.

Nominal operating point of the El-Monte's ICS has a roadway excitation of 250 amp-turns. At 500 volts, this yields an output current of 150 amp for one pickup (assuming 3-inch air gap). Therefore, two pickups in parallel will provide an output current of (2 x 150) or 300 amp, as needed. Relative to existing prototype ICS's, which operate at a lower frequency (400 Hz) and a higher roadway current of 1200 amp-turns, this higher-frequency system proposed for El-Monte Busway could reduce: (i) stray magnetic fields, (ii) acoustic noise, and (iii) resistive losses in the roadway inductor.

Figure 21 shows a plot of the output current versus the power frequency for a roadway current of 250 amp-turns, obtained from the simulation. The figure indicates that the output current increases with the frequency up to about 7,500 Hz, then levels off at just under 160 amp, and stays at that level until 50,000 Hz. Therefore, the frequency of 7,500 Hz would have been sufficient for the El-Monte design, and the recommended frequency of 8,500 Hz airs on a conservative side.

4.2 Roadway Subsystem

This includes roadway cores and power conditioner/distribution systems.

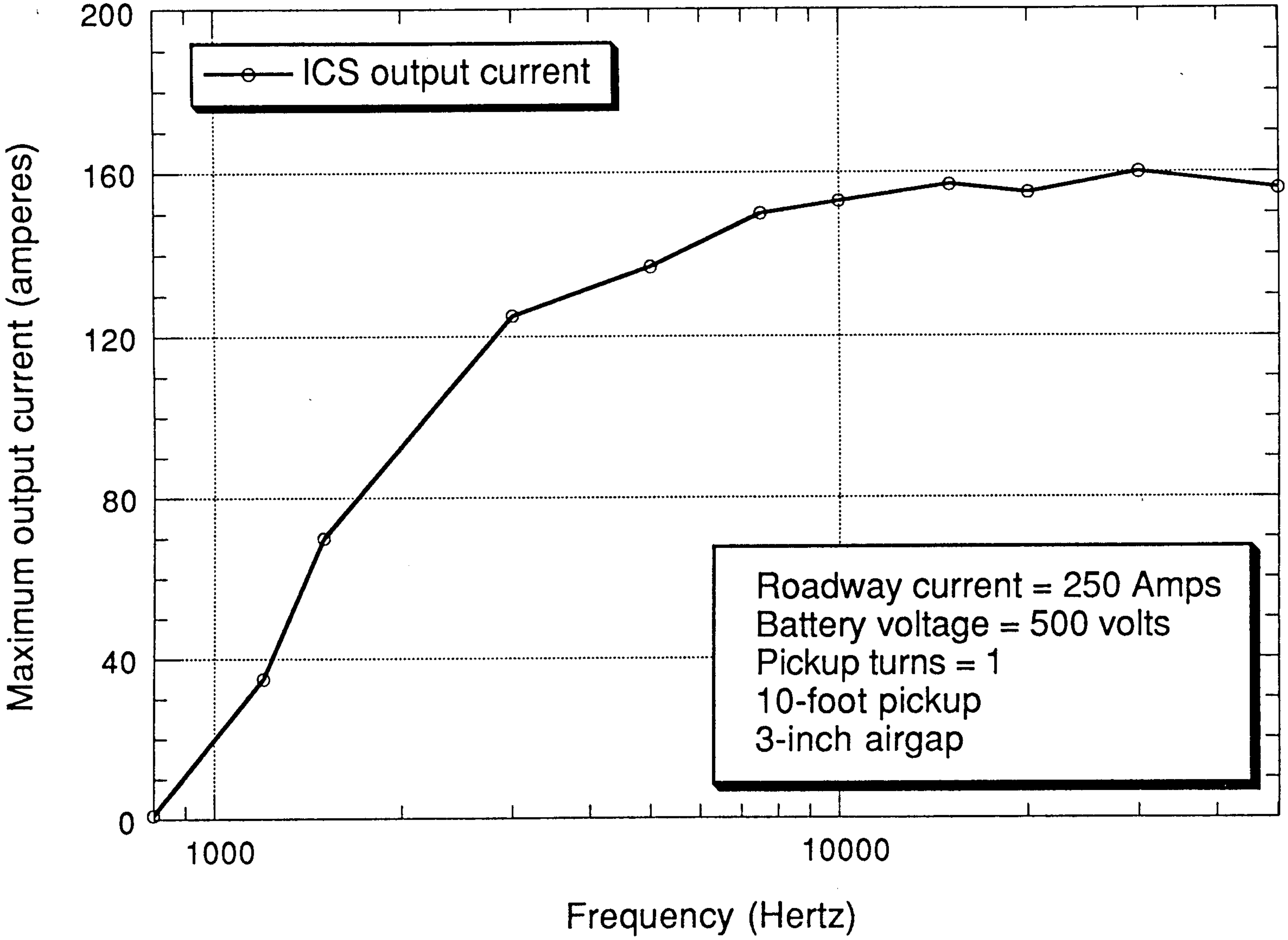


Figure 21: ICS Output Current vs. Roadway Frequency for El-Monte System

4.2.1 Roadway Cores

The roadway core modules proposed for the El-Monte system are 48 inches wide, 120 inches long, and 10 inches deep (Figure 22). The module is cast as a single W core (instead of two separate U cores), which will reduce the number of modules that must be installed by 50 percent. The cost'of the roadway, on a per-foot basis, is also reduced because it is less expensive to cast one W module than two U modules. Components of the module will also cost less, because a single long pole piece can be used between the two C-cores instead of two shorter poles of the U design. These modules are cast with built-in lifting points to allow easy attachment to the lifting equipment used during transportation or installation.

Experience obtained during the construction of a roadway section at Richmond Field Station of the University of California at Berkeley suggests that a single multiple-conductor cable (as opposed to multiple cables) installed in each conduit should be used for the El-Monte system. This could save construction time, particularly as the roadway length increases substantially. Such multiple-conductor cables have to be specially made-to-order for the El-Monte system, due to the amperage and inductance requirements.

The laminated steel cores will be the same three-piece design used in the Playa Vista prototype (Lechner et al, 1991). Figure 22 shows the core, which features a 0.75-inch section made of 0.011 to 0.014 inch laminations. One advantage of this type of core is that

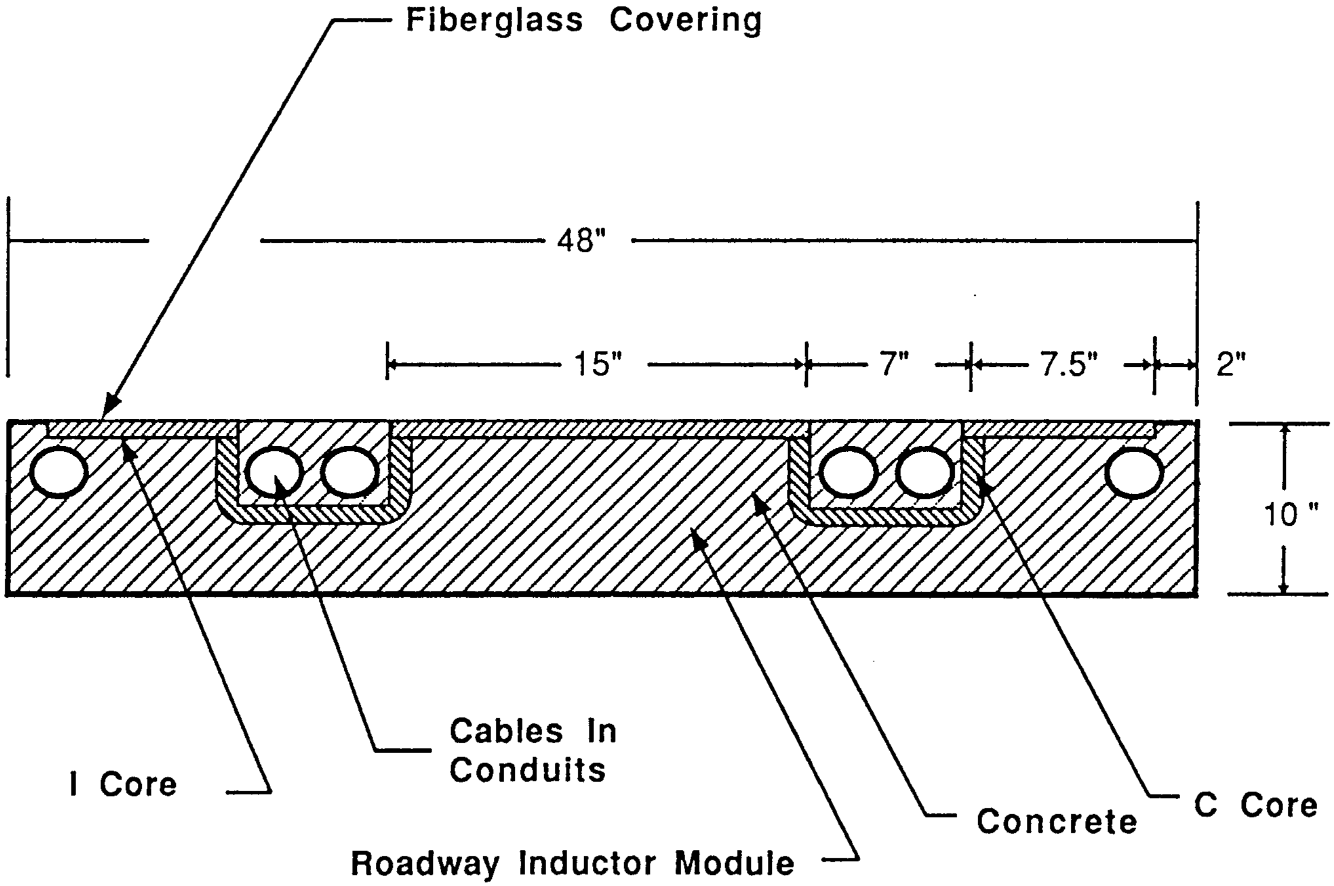


Figure 22: Roadway Core Module for El-Monte System

the C-shaped throat section and the I-shaped pole piece (both are turned on their sides) are standard transformer shapes. Therefore, they are easier and less costly to obtain.

The roadway core module is made by embedding the core pieces, along with conduits for the conductors, into a concrete matrix. This technique is inexpensive and produces strong, easily handled modules. A layer of fiberglass cloth and epoxy or polyester resin is applied over the cores to protect the steel of the cores exposed at the top surface of the module.

4.2.2 Power Conditioner and Distribution System

The power distribution system carries power from the power conditioners to individual roadway inductor segments. These segments are energized individually and activated only when an RPEV is present. The power distribution system senses the presence of vehicles equipped with ICS, and then switches the segment on and off accordingly. On the average, power conditioners are sized to provide energy for approximately one lane-mile of roadway. For El-Monte Busway, each power conditioner can be used to power one-half mile of travel lanes for both directions. Conductors to connect the power conditioners with individual segments can be installed along the electrified roadway, possibly on the pavement edge or in the median.

4.3 Vehicle Subsystem

This includes vehicle pickups, the vehicle, onboard battery, and automated vehicle steering assistance systems.

4.3.1 Vehicle Pickups

The design of the vehicle pickup is shown in Figure 20. To reduce the pickup weight, aluminum conductors for the conductor packs could be used, instead of copper which has been used in the prototype systems. Flat bars, instead of tubular conductors, could be used since they have a better aspect ratio. This makes them ideal for use in the pickup in which the magnetic field tends to force the current to flow in the portion of the conductor farthest from the core. Flat bars also have better current distribution than a tube, thus lower resistivity for a given cross-section area of aluminum. One disadvantage of using flat bars is that it is more difficult to attach the cables carrying the current from the pickup to the onboard controller. This is because the cable cannot be crimped or soldered into the ends of a bar as they can with a tube. The conductor packs are encapsulated in fiberglass-reinforced epoxy to form a structural beam as well as a conductor assembly.

The vehicle's pickup cores are the standard "hat section" type, made from hydraulically formed and oven-annealed laminations. Silicon-iron material of 0.002 inches could be used for such a system with a high frequency of excitation. The very thin laminations would reduce eddy current losses in the cores. Ongoing research on more advanced core design is underway to further reduce the core weight without degrading magnetic performance. However, results from these.efforts are not available at this time.

For transit buses, split pickups with two lo-foot long sections are used. Split pickups offer greater flexibility in mounting and wiring than a single pickup. Pickups for roadway powered electric vans and cars have the same geometry and configuration, but their lengths can be reduced from 120 inches to 100 and 60 inches, respectively.

The pickup is designed to be retractable to allow for maximum ground clearance between the vehicle and the pavement when the vehicles are running on non-electrified roadways. Pending results from new road tests, design engineers generally feel that the 3-inch air gap should not present problems when the vehicles are running on electrified roadways. This is because powered roadways call for the construction of relatively even road surface, and regular maintenance to keep the surface free of debris. In the event that the 3-inch air gap is judged to be too small for operational purposes, a number of modifications are possible. For example, the ICS can be designed to have a larger air gap; or secondary suspensions (e.g., air cushions) can be incorporated to support the pickup so that the pickup can deflect around "bumps" on the powered roadway.

4.3.2 Vehicle Design

The roadway powered El-Monte bus would be a full-sized bus with GVW of 31,200 lbs and the power train rating of 240 horsepowers (180 kilowatt). These buses would have performance comparable with that of existing diesel buses. The motor can be mounted below the floor level and the battery mounted under the seats along the entire length of the bus. This would allow the entire bus to be used for passengers. This yields a better front-to-rear weight distribution, relative to existing diesel buses. Vehicle parameters for El-Monte buses are shown in Table 3. The table also gives parameters for the prototype PATH bus for comparison. Drivetrains that are already available from several suppliers could be used to meet the power requirement of the El-Monte bus.

Vehicle parameters for roadway powered electric vans and cars are shown in Table 3. Figure 23 shows velocity versus time profiles for these vehicles.

*4.3.3 Onboard **Energy Storage***

The analysis and simulation performed in Task 3 assume that the El-Monte bus uses a lead-acid battery, with a capacity of 400 amp-hours at 500 volts. More advanced batteries should be investigated. Sodium-sulfur and nickel-metal hybride can offer potentially better specific power and energy than lead-acid. However, neither is commercially available at this time. Nickel-cadmium cells are available and their performance closely matches nickel-metal hybride. Although nickel-cadmium batteries would not be desirable for long-term use due to their cost and the cadmium toxicity, they could be considered for use on an interim basis. The charge acceptance of these batteries is superior to lead-acid

Table 3: Vehicle Parameters for Various Types of RPEV's

	El Monte Bus	PATH Bus	G-Van	TEVan	Impact
Weight (lbs)	31,200	31,200	8,600	6,670	2,550
Drag Coefficient	0.60	0.75	0.45	0.35	.019
Maximum Acceleration (ft/sec$^{2)}$	10	10	10	10	20
Rated Motor Torque (ft-lbs)	254	254	106	95	75
Rated Motor Speed (rpm)	1600	1033	2000	3000	5300
Gear Ratio (rpm/mph)	45	66	100	200/100	158
Battery Voltage	500	128	216	168	320
Amp-hour Rating	400	600	205	206	42.5

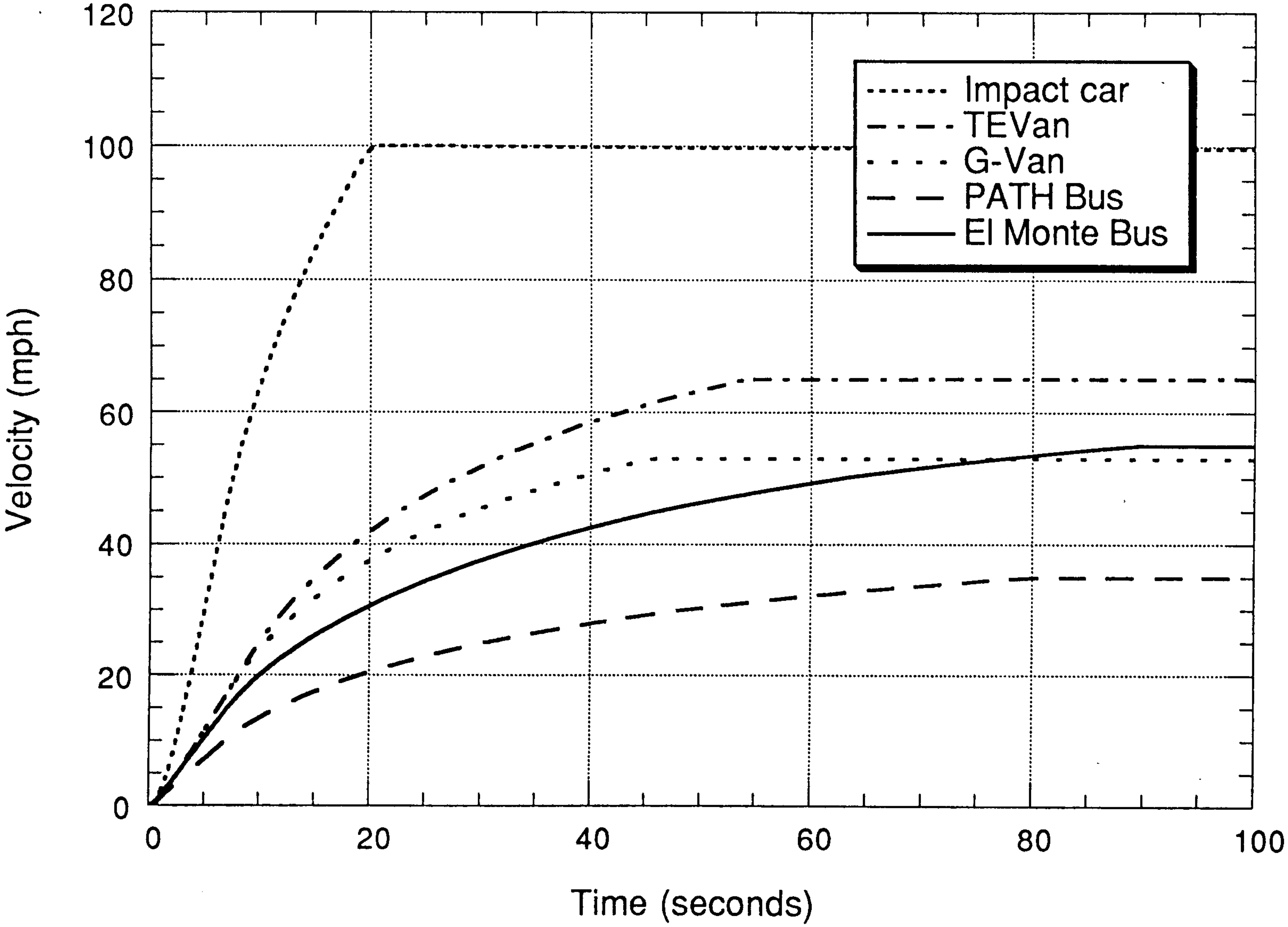


Figure 23: Performance of Various Types of RPEV's

batteries, and the battery weight for the transit bus is under 6,000 lbs.

4.2.4 Low-Power Automated Vehicle Steering

To maximize the energy transfer capability of the ICS, it is necessary to keep the vehicle well centered over the powered roadway when transferring power. This could be accomplished through automated low-power vehicle steering assistance systems. In this regard, the magnetic field generated by the roadway readily serves as the roadway reference. A detector system has already been designed and used on the prototype PATH bus to receive the magnetic fields. Signals could be transmitted to a low-power actuator that steers the vehicle. This actuator provides input to the steering system under normal driving conditions, which can be easily overridden by the driver's own steering input in lane-changing or emergency situations. In this way, the driver will be in control of the vehicle, with just enough input from the steering assistance system to keep the vehicle centered without requiring constant steering adjustments by the driver.

Further R&D are needed to integrate all components of the automated vehicle steering technology into RPEV's.

4.4 Onboard Equipment

This includes the onboard controller and onboard control computer.

4.4.1 Onboard Controller (OBC)

The onboard controller consists of the capacitance bank and rectifier circuit. The capacitance bank modulates the output of the ICS and prevents overcharging of the battery while maximizing the energy transfer from the powered roadway. The rectifier circuit converts the high-frequency AC current from the pickup to DC current for the motor or battery. Technologies necessary for manufacturing the OBC are readily available, and thus most components of the OBC are relatively easy to obtain. A notable exception is the switch for the capacitance bank, which needs further developmental work.

4.4.2 Onboard Control Computer (OBCC)

The OBCC controls the OBC, and the processor in the OBCC can also be used by the automated vehicle steering system. The OBCC can be obtained from available technologies.

4.5 Roadway Inductor for Static Chargers

For static chargers, relatively short sections of the roadway inductor (10-15 feet) could be installed at bus stops and layover points to provide a quick charge while the bus is stopped atop the inductors. In static charging, the pickup of the stopped vehicle acts as a shield against stray magnetic fields. One benefit of this shielding effect is that it may not be necessary to limit the excitation current to 250 amp-turns, and that up to 400 amp-turns or more could probably be used. Further, because the vehicle has to be stopped in order to draw power from a static charger, an air gap considerably smaller than 3 inches could be adopted. All these suggest that it is possible to achieve output current of up to 400 amp in static charging, which is not possible in dynamic roadway electrification's current of 250 amp-turns and the practical air-gap height constraints previously identified.

4.5 A Note on Power Frequency, Onboard Voltage, and Output Current

The analysis results obtained in Tasks 2 and 3 are based on onboard voltage of 500 volts. Knowledge gained during the course of this study indicates that 600-650 volts could be even a better choice. This 25-percent increase in the operating voltage would not invalidate previously obtained results concerning the viability of particular electrification-scale scenarios for El-Monte Busway. An increased voltage could proportionally reduce the ICS output current, which is desirable from the standpoint of minimizing roadway losses. Since power is the product of voltage and current, the 25-percent increase in the voltage (given a fixed power level) could result in a corresponding 25-percent decrease in the output current. Therefore, if the El-Monte design employs 650 volts (instead of 500 volts), the output current required would be about 225 amp (instead of 300 amp).

When the voltage is increased to 650 volts, it may be necessary to increase the roadway excitation frequency by 25 percent to obtain a flux level in the pickup cores suitable for supplying a higher output current. A 25-percent increase in the frequency will result in a new frequency of 10,000 Hz. This represents a relatively small change from the previously suggested frequency of 8,500 Hz.

Task 5

Utility Demand for El-Monte System

The time-of-day utility demand is an important consideration for implementing a RPEV system on the highway. In operating an RPEV system, vehicles draw energy from the utility while using the electrified facilities. The use of RPEV's during the afternoon rush hour could, therefore, add to the existing peak utility demand. RPEV's will also use a significant amount of energy for overnight recharging. These include those vehicles using the electrified roadway on any given day, as well as those operating on their batteries only because of low daily mileage. This task investigates the utility demand due to the adoption of Scenario A, which is the most critical utility load compared with the other viable Scenarios D and F.

5.1 Analysis Approach

This study determines the time-of-day utility demand (or demand profiles) for each vehicle type. This profile is then multiplied by the projected number of vehicles of that particular type, and total demand is then derived by summing across all vehicle types. Four demand profiles for four groups of vehicles are determined, as follows:

- A demand profile for buses that operate all day, for 15 hours a day.
- A demand profile for optional rush-hour "helper" buses

that operate only during peak periods, for 8 hours a day.

- A demand profile for private vehicles (cars and vans) that draw energy from the electrified roadway.
- A demand profile for private vehicles operating from the battery exclusively, due to their relatively low daily mileage.

It is assumed that about 60 El-Monte buses are required to operate at 30-minute service headway under Scenario A. The first group of private vehicles are assumed to involve a typical driving cycle of two trips totalling 60 miles per day, with 22 miles on the electrified El-Monte Busway. The second group of private vehicles involve 30 miles of driving per day. Because of their relatively low daily mileage, this second group of private vehicles is assumed to complete their journey solely by energy from the onboard batteries.

5.2 Analysis Results

5.2.1 Demand Profile for Buses

Demand profiles for buses are split into two categories -- those operating on standard shifts of 15 hours ("regular" buses), and those operating during morning and afternoon rush hours only (rush-hour "helper" buses) to provide more-frequent service during rush hours.

Figure 24 shows a demand profile for the 60 "regular" buses,

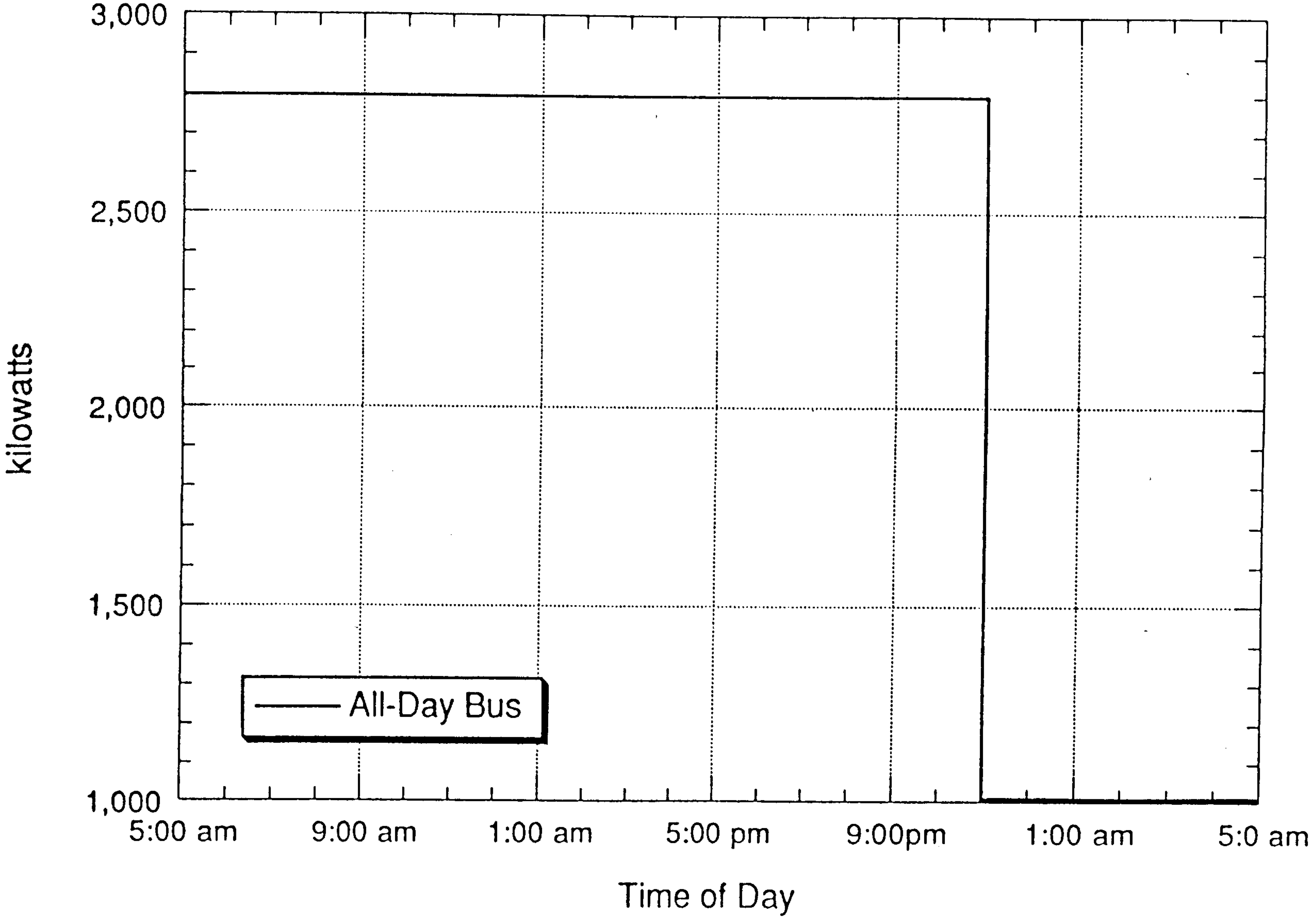


Figure 24: Utility Demand Profile by Time-of-Day for "Regular" All-Day Buses

which are required to provide 30-minute service headway. Utility demand for these buses totals 2,800 kilowatts during the day, and 1,000 kilowatts for overnight battery recharging.

Figure 25 shows a utility demand profile for rush-hour "helper" 'buses. Sixty of such buses are assumed operating so that the service headway during rush hours can be reduced from 30 to 15 minutes. During peak-hour operation (5:00 - 8:30 a.m. and 3:00 - 6:00 p.m.) and overnight recharging, the demand profile is similar to that of the regular buses.

Figure 26 shows the combined utility demand for both the "regular" and rush-hour "helper" buses. This combined demand profile exhibits two peaks during the morning and afternoon rush hours of about 5,600 kilowatt.

5.2.2 Demand Profile for Private Vehicles

There are uncertainties associated with predicting the demand profile for private vehicles, due to the usage variability by the time-of-day. For this analysis, vehicle-miles of travel (or VMT) of private vehicles are split into three time intervals -- morning peak, afternoon peak, and the rest of the day. VMT during the rest of the day is assumed to be uniformly distributed by the hour, except between 11:OO p.m. and 5:00 a.m. when battery recharging takes place.

Unlike the El-Monte buses, there is no good basis for predicting the number of private vehicles that will adopt the RPEV once El-Monte Busway is electrified. The utility demand analysis

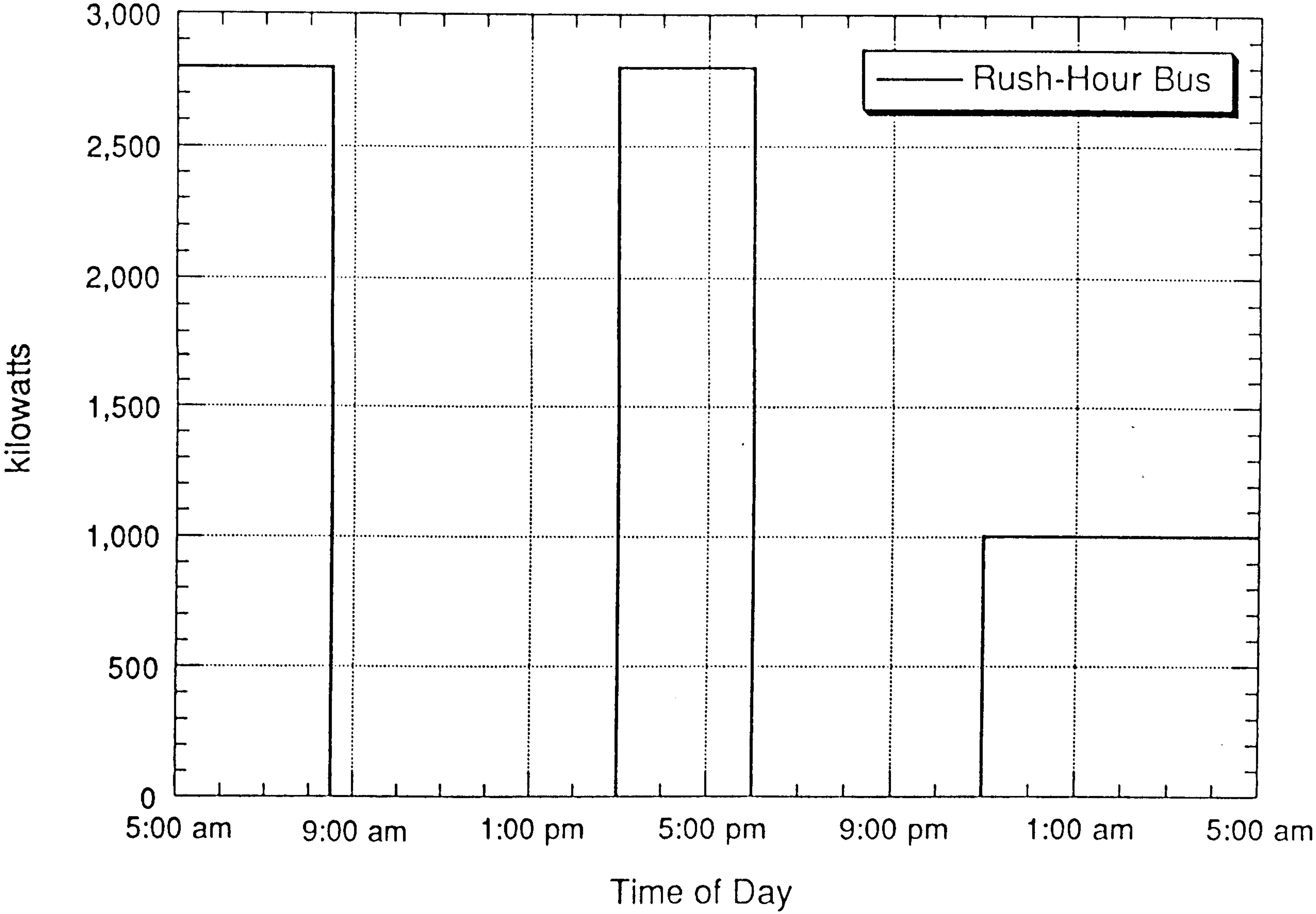


Figure 25: Utility Demand Profile by Time-of-Day for Rush-Hour "Helper" Buses

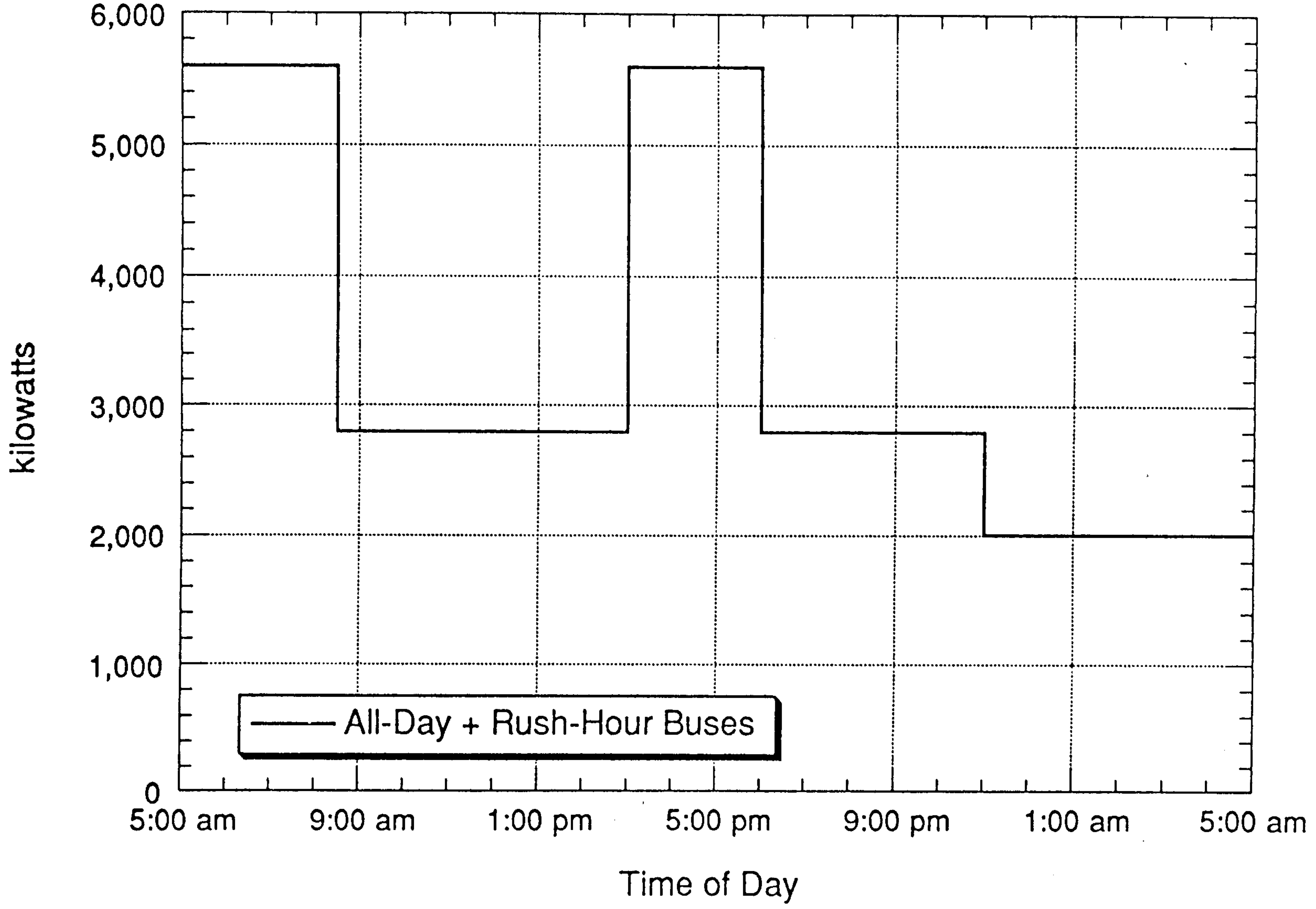


Figure 26: Utility Demand Profile by Time-of-day for All-Day and Rush-Hour Buses Combined

is thus performed assuming that 5 percent of the VMT on El-Monte Busway is due to private vehicles that adopt the RPEV. Figure 27 shows the utility demand profile for these private vehicles. It indicates that the highest peak load occurs overnight, with smaller peaks occurring during afternoon and morning rush hours.

On any given day, it is also conceivable that some private RPEV's (particularly those with relatively low daily mileage) would also operate solely on their batteries. The energy required by these private vehicles will be used strictly for overnight recharging. Figure 28 shows a utility demand profile for these vehicles.

5.2.3 Total Utility Demand

The total utility demand for all vehicles combined can be obtained by summing the above demand profiles of all individual vehicle types, as shown in Figure 29. The figure indicates that, if Scenario A is adopted, the utility demand could be increased by 7,000 kilowatts (or 7.0 megawatts) for battery recharging overnight (between 11 p.m. and 5 a.m.). Peak utility demand for morning and afternoon rush hours could add about 6.0 to 6.2 megawatts. This additional utility demand is negligibly small, since it represents less than 0.1 percent of the existing utility demand supplied to the SCAG region by Southern California Edison. Therefore, the deployment of Scenario A is not likely to have an impact on the electricity demand and capacity within that region.

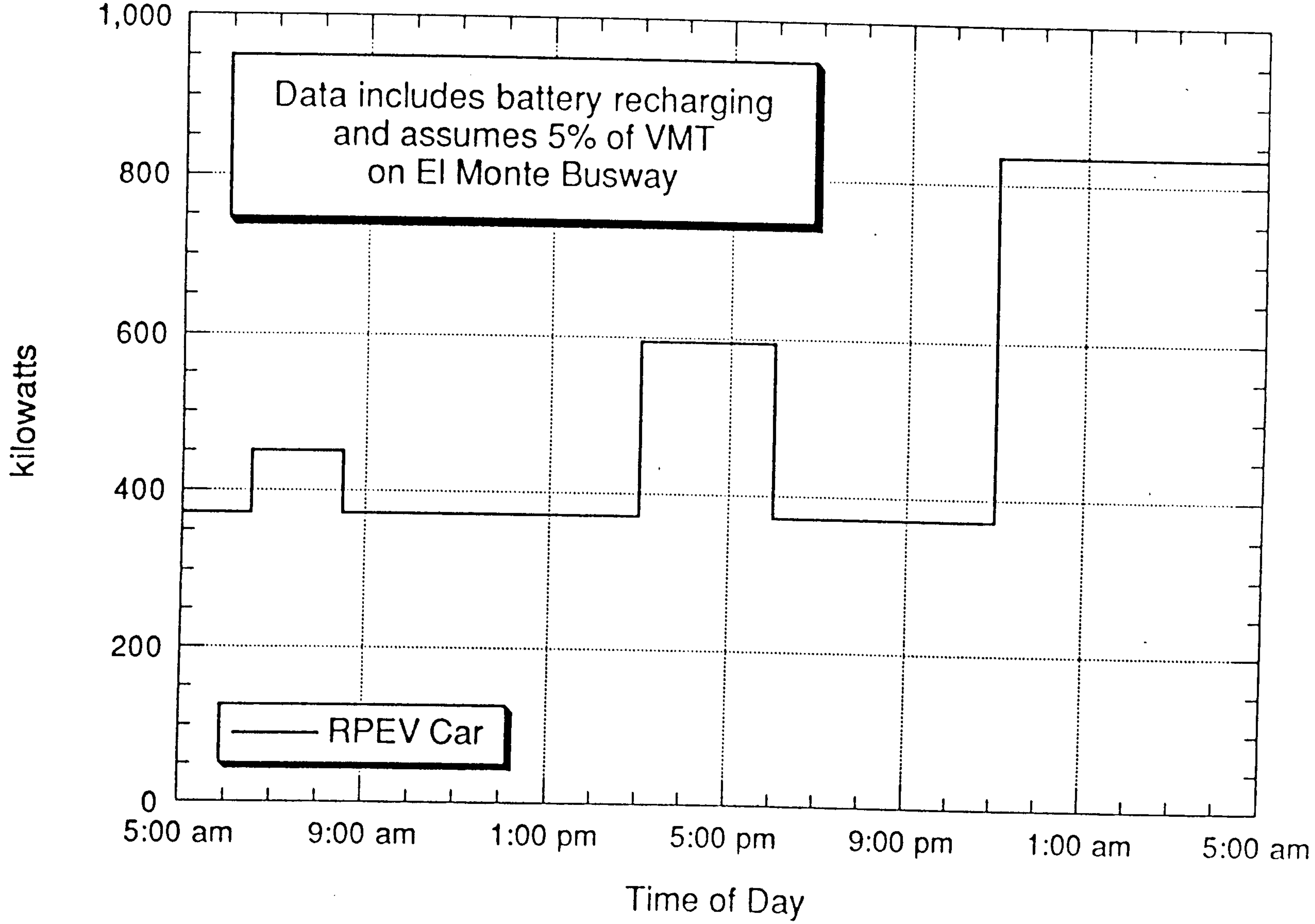


Figure 27: Utility Demand Profile by Time-of-Day for Private Vehicles (Which Utilize Electrified Roadway for 50% of Their Distance)

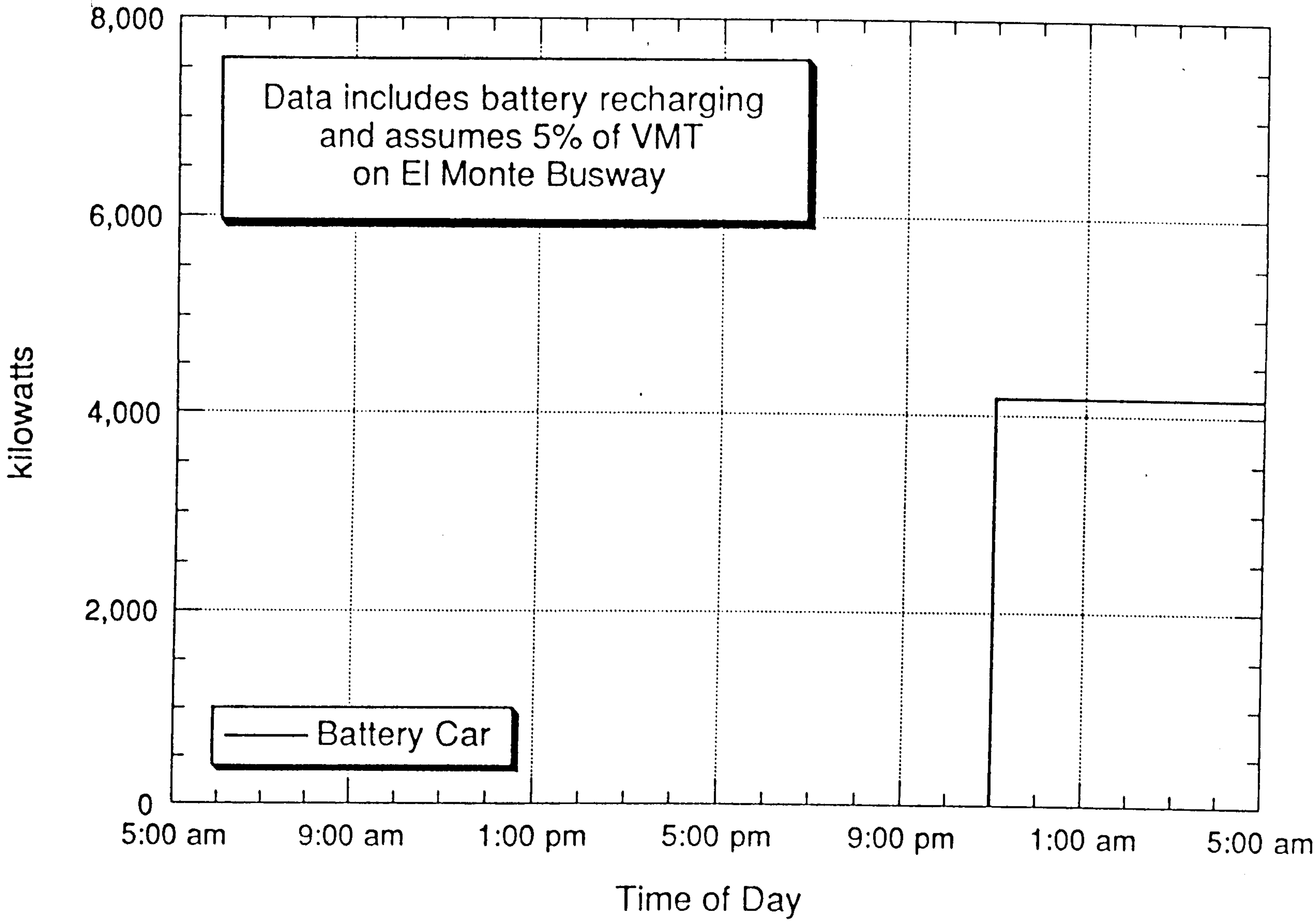


Figure 28: Utility Demand Profile by Time-of-Day for Private Vehicles Operating on Battery Exclusively (Due to Low Daily Mileage)

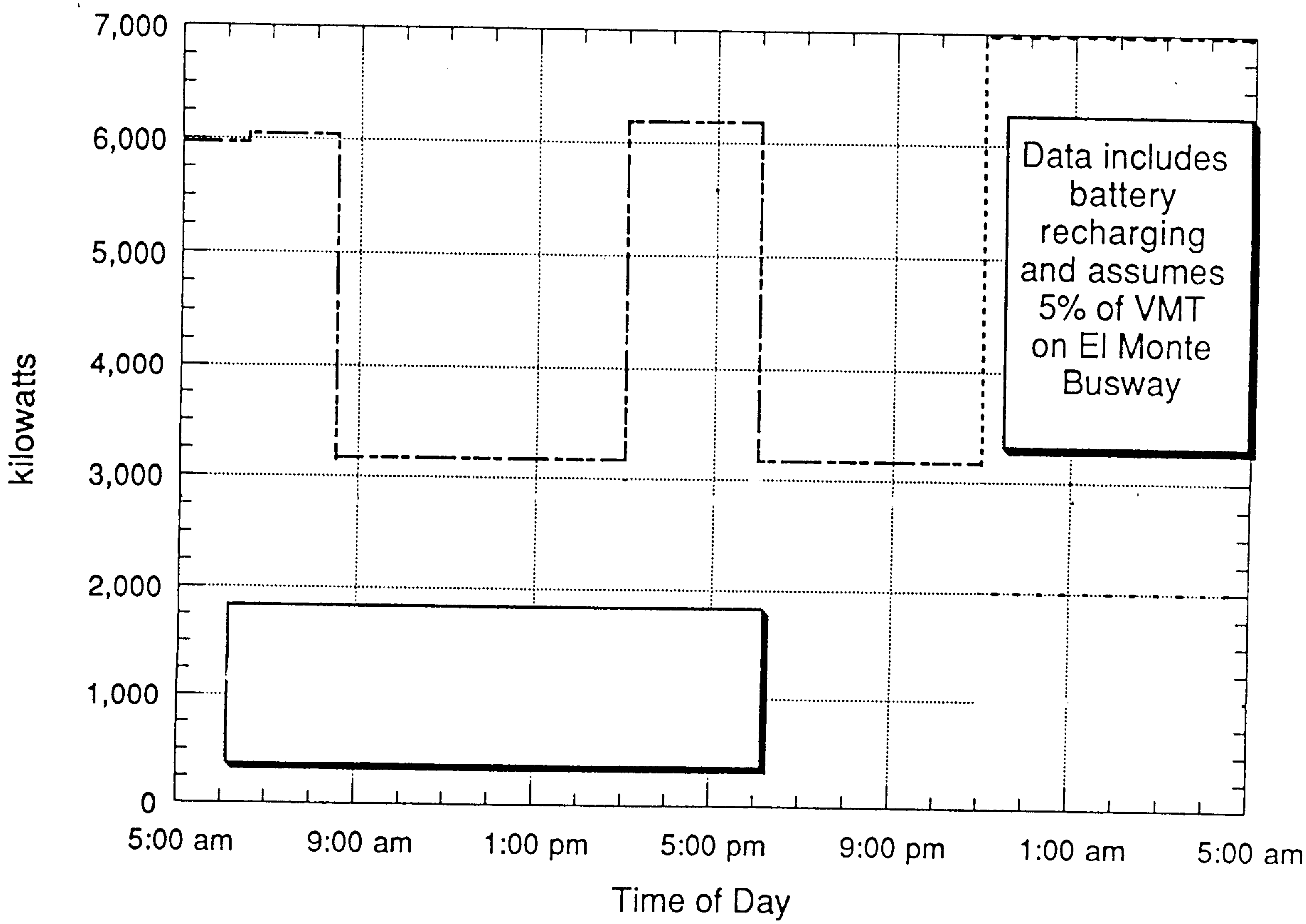


Figure 29: Total Utility Demand Profile by Time-of-Day for all RPEV's Combined

Task 6

A Plan for Technology Demonstration

Results of the preliminary engineering feasibility evaluation from Tasks 3 through 5 indicate that it is feasible to design RPEV systems for early deployment in El-Monte Busway. These systems could use static chargers exclusively, or a combination of static chargers and electrified travel lanes of El-Monte Busway. This task describes how the RPEV technology could be carried from its current state through to the technology demonstration. In this regard, a plan for technology demonstration of the RPEV is developed. It includes the implementation strategy, system concepts, project steps, and activity schedule. In addition, important implementation related issues are also identified.

6.1 A Plan for Technology Demonstration of RPEV

Implementation of the RPEV on El-Monte Busway can take place in three incremental phases, with each subsequent phase built upon the system(s) already deployed in the preceding phase(s). These three phases are described below.

Phase I: Implement Downtown Shuttle Service Using Static Chargers Exclusively

Demonstration of the RPEV technology could start with implementing the ***Downtown Shuttle bus*** service (Scenario F), which uses static chargers exclusively. The route for this ***Downtown***

Shuttle bus service is similar to the existing downtown DASH bus service currently operated by the LADOT (Figure 30). This ***Downtown Shuttle bus service*** would involve only city streets, with a total route length of about 5.3 miles. The shuttle service starts at Venice Boulevard and ends at Union Station. The shuttle bus will be roadway powered electric bus. . Two static chargers would be installed at two layover points -- one at the Venice Boulevard end and the other at the Union Station end. In addition, static chargers would also be installed at 4 bus stops along the loop.

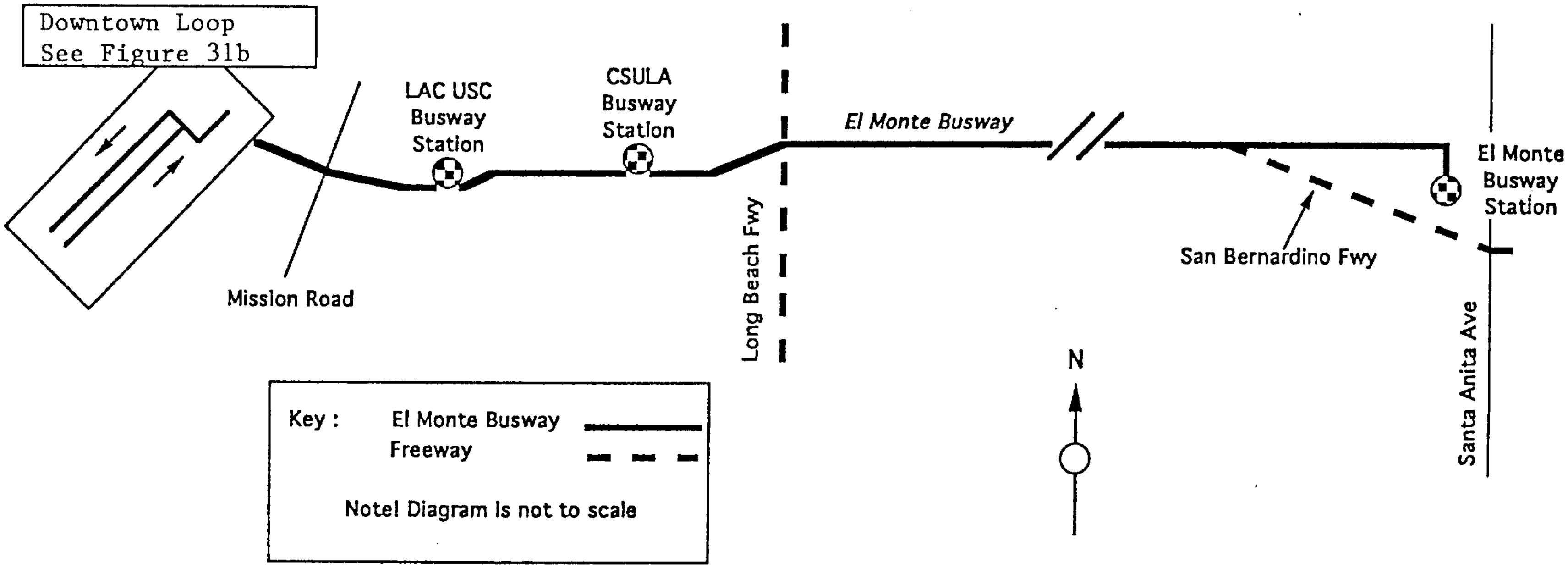
This ***Downtown Shuttle bus*** would have a relatively low average speed due to frequent stops and prevailing traffic conditions on surface streets. The round-trip time of this ***Downtown Shuttle service*** could be 40 minutes, about 7 minutes of which (or 18 percent of the total round-trip time) would be spent at the two layover points. The ICS output current of 300 amp would enable the shuttle bus to operate continuously for 15 hours, without the battery DOD being discharged below 80 percent during the daily operation. To maintain service headway of five minutes, at least 8 buses will be required.

Phase II: Implement Downtown/El Monte Shuttle Service Using Static Chargers Exclusively

In Phase II, the shuttle service implemented in Phase I could be extended eastward onto El-Monte Busway toward El-Monte Bus Terminal, or the ***Downtown/El Monte Shuttle bus service*** (Scenario D). As in Phase I, only static chargers will be used exclusively. This *Downtown/El* ***Monte Shuttle service*** connects the downtown area with the El-Monte Bus Terminal, and essentially consists of two connecting loops -- the Downtown Loop and the El-Monte Loop (Figures 31a and 31b). The Downtown Loop is identical to the Phase-I route, while the El-Monte Loop connects Union Station to El-Monte Bus Terminal.

In addition to static chargers already put in place in Phase I. the ***Downtown/El Monte Shuttle*** bus ***service*** in Phase II calls for additional static chargers to be installed at El-Monte Bus Terminal, as well as at all bus stops along the Downtown Loop. A total of 41 static chargers would be requires for Phase II, three at the three layover points, and the remainder at bus stops. With the ICS output current of 275-300 amp, the Downtown/El ***Monte*** Shuttle could operate with round-trip time of 80 minutes (about 15-16 minutes of which would be total layover time). This would allow the shuttle bus (roadway powered electric buses) to operate continuously for at least 15 hours a day without the battery being discharged below 80 percent. Service for the Downtown Loop could be made more frequent than service for the El-Monte Loop, depending on the demand. Less frequent service for the El-Monte Loop could also help to enhance the onboard energy balance, since the simulation results indicate that the battery discharges while on the El-Monte Loop and actually recharges while on the Downtown Loop.

The ***Downtown/El Monte Shuttle*** in Phase II will be more expensive than the ***Downtown Shuttle*** in Phase I, because many more



Three Bus Layover Points for Phase II:

- at El-Monte Terminal
- at Union Station, downtown
- at Venice Bl., downtown

Figure 31a: Route Layout for Downtown/El Monte Shuttle Bus Service in Phase II (Using Static Chargers Exclusively, at Bus Stops and Layover Points)

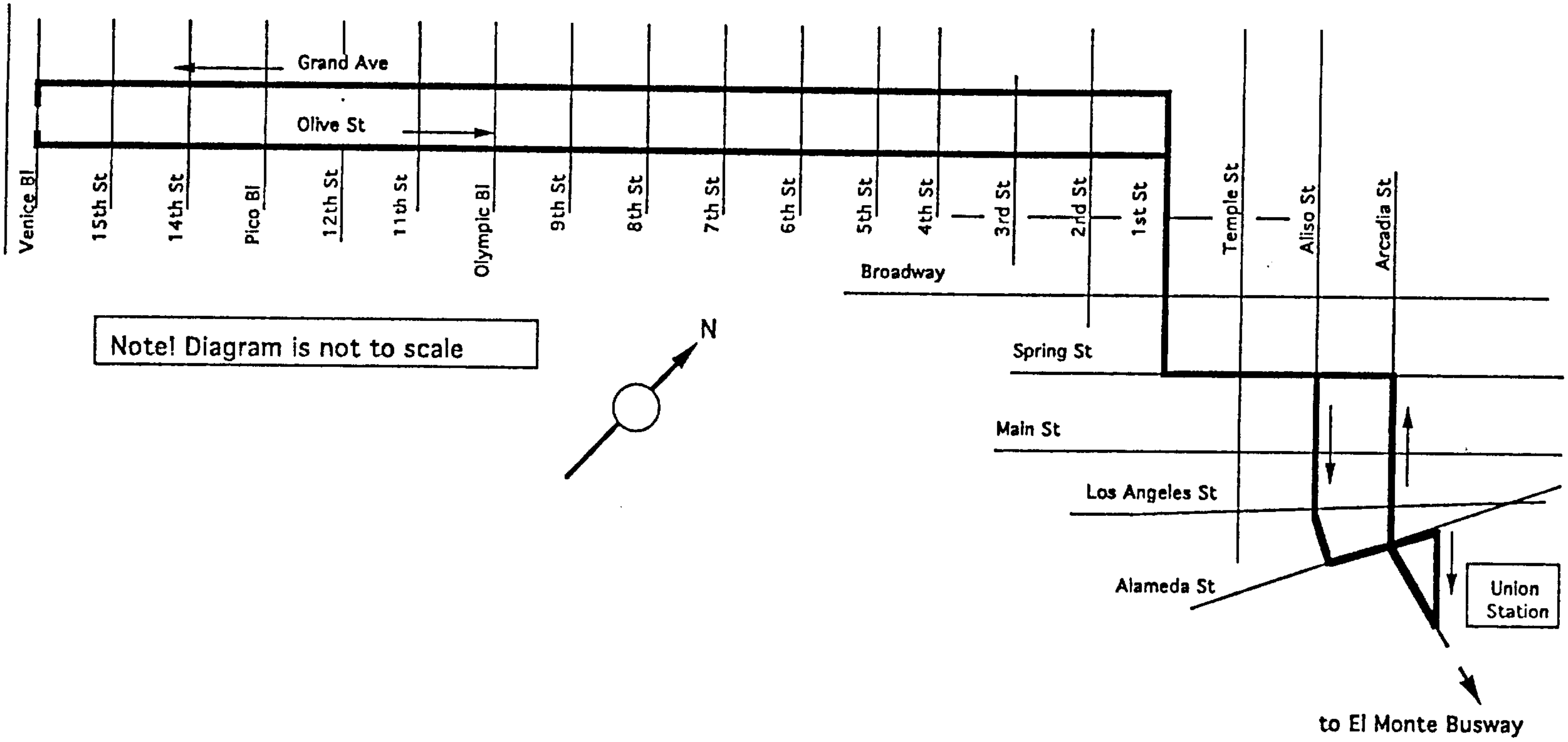


Figure 31b: The Downtown Portion of Downtown/El Monte Shuttle Bus Service to be Implemented in Phase II

static chargers and additional buses would be required. The number of buses required in Phase II depends on the service frequencies to be provided for the Downtown Loop and the El-Monte Loop.

Phase III: Electrify Travel Lanes of El-Monte Busway

In Phase III, Scenario A could be implemented by electrifying the travel lanes of El-Monte Busway in both directions, plus installing static chargers at the layover points for each of the bus lines currently using El-Monte Busway. Static chargers already in place from Phase II will become an integral part of the Phase-III system. Phase III would allow existing bus lines using El-Monte Busway to maintain their current routing and scheduling; new roadway powered electric buses will simply replace diesel buses. The Phase-III system could be implemented with the ICS output current of 300 amp. To provide an average of 30-minute service headway, a minimum of 68 roadway powered electric buses would be required.

The deployment of Phase III could eliminate about 68 diesel buses per day from the road (or roughly 5 million vehicle-miles of travel by diesel buses per year). This could begin to reduce vehicle emissions and improve air-quality in the region. If Phase III could also lead to some private vehicles adopting the roadway powered electric propulsion, greater air-quality benefits could be realized. Volume 2B of this study presents detailed emission impacts due to the use of roadway-powered electric buses, vans, and cars for California.

The 22 lane-miles of roadway electrification in El-Monte Busway is well below a critical mass required to yield practical market penetration of non-transit RPEV's. Nevertheless, the electrification of El-Monte Busway could be a significant first step toward achieving a sizable network of roadway electrification for the Los Angeles Basin. It is conceivable that, this early deployment of roadway electrification, once proven in El-Monte Busway, could be extended, possibly by electrifying one lane in each direction of I-10 eastward toward San Bernardino. If this happens, the number of electrified roadway mileage will increase substantially, and commuters using private vehicles on this corridor may be more willing to adopt RPEV's.

The installation of electrification along the travel lanes of El-Monte Busway in Phase III will involve the removal of a portion of the existing pavement and the placement of roadway inductor core modules in the pavement. This will require closing the travel lanes until the core modules have been put into place. Other tasks, such as the installations of the power conditioners, conduits, and conductors, will be much less disruptive to the traffic flow. The power conditioners, to be located adjacent to the right-of-way, are not likely to pose much of a problem. Similarly, installations of the conduits and power distribution system will involve work primarily along the side of the travel lanes. Pulling cables in the roadway inductor can be accomplished quickly, possible during an overnight shutdown of the Busway.

One possible scenario for installing the roadway core modules in the travel lanes of the Busway could involve closing the travel lane in one direction over a weekend, section by section. With appropriate core module design, specialized equipment, and installation procedure, it may be possible to install the core modules in each one-half mile of the busway on each weekend. Eventually, it may be possible to accomplish this task during an overnight lane shutdown once the construction crew has gained experience in the installation, and customized equipment for installing the RPEV modules is available. Alternatively, if such quick installation of the core modules is not possible, El-Monte Busway could be closed in one direction at a time during the installation period, while the other direction is temporarily used as a reversible lane. In this way, the disruption to the traffic flow within El-Monte Busway would be alleviated.

6.1.1 Project Steps for Technology Demonstration

Technology demonstration of each of the three incremental phases involves several project steps. These steps can be chronologically summarized as follows.

1. Detailed system design and specifications
2. Development and testing of prototype
3. Acquisition of property and approvals
4. Construction of operational facility and fabrication of vehicle
5. Shakedown and testing
6. Public demonstration

7. Evaluation

Details of these project steps are presented below. Those common to all three phases are described only once.

Step 1: 'Develop Detailed System Desian and Specifications

This step involves the determination of the location of powered roadway segments, route schedules, vehicle type, energy consumption, battery size and type, ICS output current rating, roadway excitation (frequency and current), and air-gap height. These determinations would have higher accuracy and greater details than previously achieved in the preliminary engineering feasibility evaluations of Tasks 3 through 5. The output will be used for establishing detailed component and system specifications. These determinations could be accomplished through the verification of the preliminary results obtained in Tasks 3 through 5, by using more up-to-date or accurate data input. This would help to improve the fidelity of the analysis results and increase confidence in the specifications of the system design. Examples of these activities are as follows:

(i) The number of bus stops and maximum travel speed for individual bus lines, which are input for analyses of Tasks 3 through 5, were estimated from available published bus schedules. More detailed and up-to-date data input could be obtained, as they become available, to verify these earlier results. Further, no mid-route layover points were assumed for any of the bus lines in the engineering feasibility evaluation of Scenario A (Task 3), even though longer bus routes clearly present opportunities for identifying extra layover points along the route.

(ii) The use of vehicle air conditioning, which includes variations in the thermal loading by time-of-day, could be modelled more accurately. (iii) Some aspects of the simulation models used to generate the outcome of Tasks 3 through 5 could be refined, as more knowledge about the technology becomes available through ongoing research and testing. This is particularly true for the modelling of the battery charge acceptance.

(iv) The analyses performed in Tasks 3 through 5 assume the use of lead-acid batteries. More advanced batteries with higher specific power ratings could significantly improve performance of the RPEV system. The battery duty cycle for an RPEV application, especially in static charging systems, is significantly different from conventional duty cycles of EV's. At this time, there is virtually no data available on any battery for the RPEV duty cycle. As part of this project step, an analysis of battery types that are likely to be available within the next five years has to be performed to identify an appropriate battery type for RPEV applications.

Once the detailed system design and specifications are completed, the feasibility of obtaining the right-of-way and adequate electric power at all required locations could be determined. Detailed analyses on important systems trade-offs are then performed to determine whether the overall system can be further improved. The development of plans for the construction of operational facilities and vehicle fabrication can then be initiated.

Step 2: Develop and Test Prototype Hardware

Fabrication of the prototype hardware takes place in this step. The hardware is then tested to measure performance characteristics of individual components, and to compare them against the design specifications. The source of discrepancies are then determined and resolved. Individual components are then combined into assemblies, and the subsystems formed are tested. Finally, the entire prototype system is assembled and tested.

A prototype ICS to be fabricated for the El-Monte system will also include the onboard controller, pickup inductor, roadway inductor, power conditioners, and communications and controls. Power conditioners for static chargers needed for applications in all three phases will be developed first. Later, power conditioners for operation in the dynamic mode for use in Phase III will be developed. The power conditioner is the one system component that requires significant further development beyond the hardware already tested at the Richmond Field Station, University of California, Berkeley.

The prototype ICS has to be tested both in a static mode (for Phases I and II), and later in a dynamic mode (for Phase III). Static testing of the energy transfer of the ICS is to:

- Measure output current under nominal conditions, as well as its sensitivity to the vehicle lateral offset and air-gap height.

- Verify controllability of the ICS output current.
- Record the position of vehicles at a static charging station to determine effects of various visual aids on the driver, as well as variations of these effects among different drivers.

Testing of the prototype ICS in the dynamic charging mode will be performed at various speeds, power levels, and duty cycles to determine the average current available from the ICS, as well as the pickup heating.

The control system will be tested, which includes the onboard control computer (OBCC), onboard controller (OBC) or power electronics, as well as communications equipment that automatically lowers/raises the pickup, energizes and de-energizes the roadway, and provides all safety interlocks. The OBC functions in the same way in both the static and dynamic modes. The function of other control equipment could differ significantly between the two modes of operation, and thus has to be tested in both modes.

Duty-cycle testing of the selected battery type is required to determine battery heating, cycle life, as well as specific power and energy under the required duty cycle. Charge acceptance is one key measure-of-effectiveness for the battery.

At this time, there exists a preliminary design of full-sized transit buses that appears to meet the requirements of the El-Monte bus. A prototype El-Monte bus will be built in this step, after which it will be tested to determine performance characteristics, such as acceleration and energy consumption.

Step 3: Obtain Approvals

This step involves an environmental evaluation of the El-Monte system to obtain necessary approvals and permits to proceed with the project. Acquisitions of properties, right-of-way, and utility interfaces are arranged. Some portions of this step can also be carried out concurrently with the development of the prototypes in Step 2.

Step 4: Construct Operational Facility and Fabricate Vehicle

This step involves construction of the roadway subsystem hardware, as well as vehicle fabrication. Testing of the operational hardware during intermediate stages of completion would be much more difficult than with the prototypes. Therefore, testing may be much more limited in this step.

Step 5: Perform System Shakedown and Testing

Testing of the operational hardware is necessary before a public demonstration of the system takes place, to identify and remedy any shortcomings within the system. This involves exercising all system functions, verifying that the performance of the operational hardware matches that of the prototype hardware. Discrepancies between actual performance and expected results have to be rectified.

The vehicle has to be tested both while powered by the battery only and after the ICS is installed. Testing of the vehicle on the operational duty cycle is needed to determine variations in the range with various charging patterns, battery heating, and likely battery life. Verification of the ground clearance of the pickup could be'done by driving the bus on the intended routes with a dummy pickup.

Step 6: Implement Technology Demonstration

Work on the technology demonstration should be initiated as soon as the prototype testing has verified the viability of the project. Public opinion surveys should be an integral part of these early activities, as well as during various stages of the project. The purpose is to pave the way for widespread support and use of the system.

Once the system is in operation, an important activity of this step is to collect data concerning technical performance, as well as public acceptance, of the system. Examples of data needed for the evaluation include the ICS energy transfer rates, dwell time at bus stops, energy consumption, and bus ridership.

Step 7: Perform Evaluation

Evaluation and documentation of the technology demonstration of any one phase is important for guiding future work in the next phase. For example, knowledge on the performance of Phase-I and Phase-II systems will be essential for the design of the operational equipment of Phase III. Proper documentation and interpretation of results in an earlier phase would help to reduce technical risks in a subsequent phase, as well as to avoid unnecessary costs.

6.1.2 Technology Demonstration Schedule

A schedule for the technology demonstrations of the three phases, together with a timetable for the various project steps within each phase, are presented in Figure 32. Activities for the technology demonstration of Phase I could start as early as 1993, and the system could be ready by 1995. Activities in Phase II could start in 1995, and the system could be ready for demonstration by 1998. Finally, Phase III could be initiated in 1996, and the technology demonstration of the system could be ready by 2000.

6.2 Implementation Related Issues

There are a number of important implementation related issues that need to be addressed and resolved before the technology demonstration in El-Monte Busway can take place. They are issues concerning important technical uncertainties for which further research is required, organization arrangements, and training needs. They are presented below.

6.2.1 Technical Uncertainties for Which Further Research is Needed

There are key technical issues that have to be resolved before the planned technology demonstration of the RPEV in El-Monte Busway

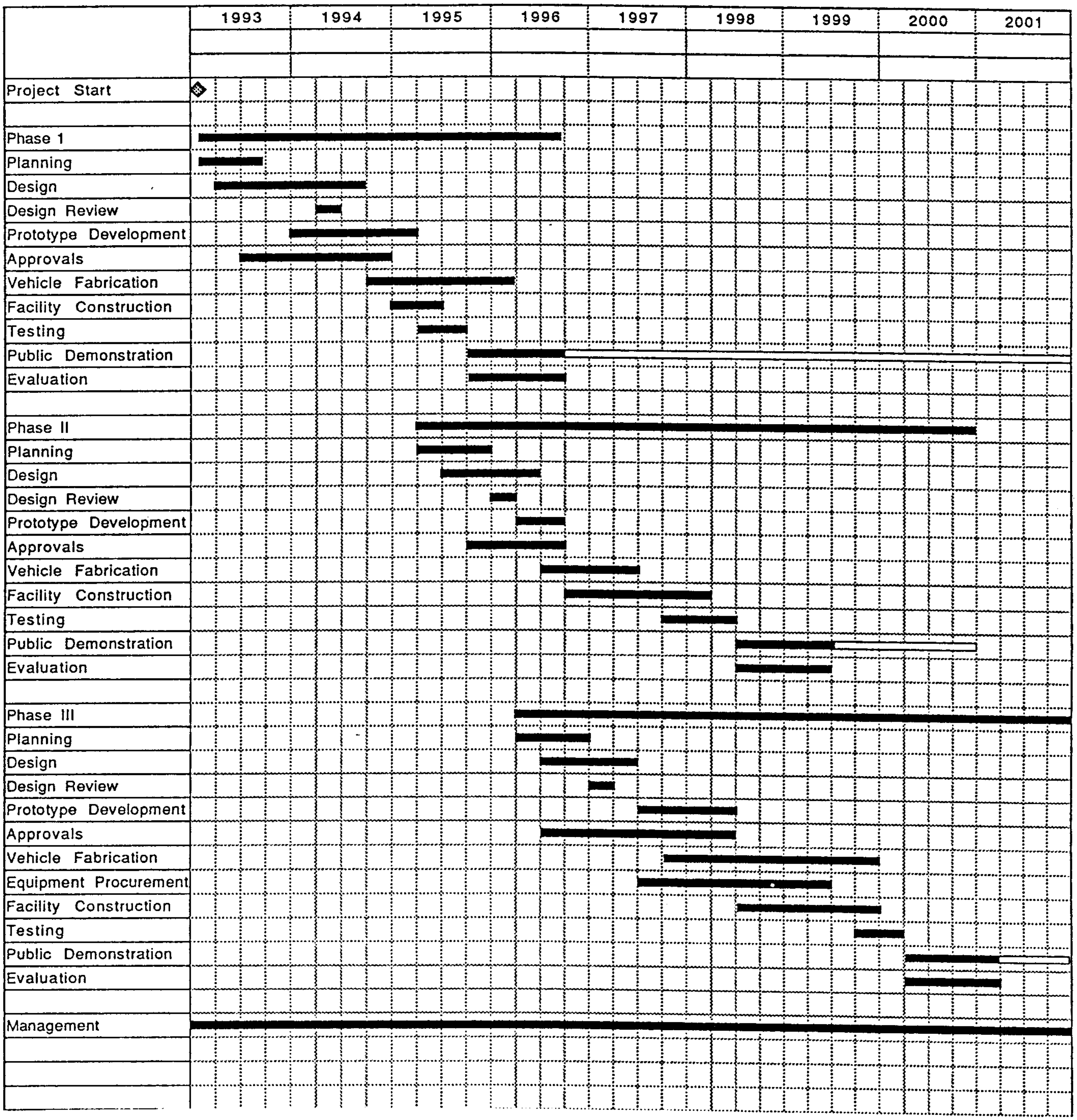


Figure 32: Public Demonstration Schedule and Project Activity Timetable

can take place. They include the following:

1. Research is needed in the development of prototype power conditioner and distribution systems for operation in the dynamic and static modes. Such prototypes do not exist at this time. Prototypes to be developed will help to address uncertainties concerning the following:

   - Switching capability required for supplying power from each power conditioner to multiple roadway segments.
   - Speed of the switching in the dynamic energy transfer mode.
   - Costs of power conditioner and distribution systems for large-scale applications; the power supplies purchased to date for the existing prototype RPEV systems are likely to be inadequate for use in an operational system.

2. Research is needed to investigate the battery charge acceptance and service life under dynamic and static modes of operation. For static charging systems, there are particular uncertainties that have to be resolved concerning the following:

   - Because most energy from static chargers goes directly into the battery and relatively little into the motor controller, research is needed to determine whether the battery will be able to absorb this amount of energy from static chargers.
   - Research is needed to determine the operational service life of the battery under this duty cycle.

3. The roadway cores under the dynamic mode of operation will

be subjected to continuous and repeated traffic load. Research is needed to determine how long the roadway cores would last. This is an issue that has not yet been adequately investigated.

4. There is currently ongoing research investigating potential impacts of EMF's on the environment, health, as well as interference with other communication media and onboard electronics (antilock brake systems, radios, etc.). However, no conclusive findings on these impacts have been reported to date. These are key determinants of the feasibility of deploying the RPEV on the highway.

5. Research is needed to determine how to best install dynamic roadway electrification in the pavement as a retrofit, so as to minimize costs and traffic disruption. Activities involved in the installation includes excavating existing pavement, placing the cores in the pavement, and sealing the pavement.

6.2.2 Organizational Arrangements

The likelihood and success of the technology demonstration of the RPEV in El-Monte Busway depend on coordination and cooperation from many agencies and organizations. Many organizational issues have to be resolved. They include, but are not limited to, the following:

Roadway Ownership and Maintenance Responsibilities

Agencies or organizations to be responsible for installing and maintaining the electrified roadway and facilities have to be identified from the outset of the project planning. It is conceivable that a consortium of agencies and organizations could be formed to share these responsibilities and work towards a common goal. In this regard, CALTRANS, LACTC (Los Angeles County Transportation Commission), LADWP (Los Angeles Department of Water & Power), and SCE (Southern California Edison) are key organizations.

Cooperation Among Agencies and Organizations for Operating the System

As early as possible in the project planning, cooperation among agencies and organizations must be obtained to assure smooth operation of the new system. Coordination and cooperation among the following agencies and organizations are essential: CALTRANS, SCRTD (Southern California Rapid Transit District), LADOT, SCE, LADWP, LACTC, SCAQMD (South Coast Air Quality Management District), CTC (California Transportation Commission), CEC (California Energy Commission), CARB (California Air Resources Board), SCAG (Southern California Association of Government), and local private transit operators.

An Oversight Committee

At the earliest possible date, consideration should be given to forming an oversight committee, to be charged with the following:

- Seeing the plan through implementation

- Assuring. good cooperation among agencies and organizations for the construction, maintenance, and smooth operation of the system
- Monitoring the system performance and making recommendations for future improvements

Use of Electrified Facility by Private Vehicles

For the El-Monte project, there are several issues concerning the use of the electrified roadway by private vehicles that need to be addressed as early as possible. Examples of these issues are as follows:

(i) Should users be charged the costs of the infrastructure, in addition to the utility charge ?

(ii) To whom will users pay these charges, and what is the user billing method ? There are two sources of electric energy used by RPEV's -- energy drawn from the roadway while the vehicle is in use, and energy for overnight battery recharging. Research on billing methods for utility drawn from the roadway is needed for both transit and private vehicles.

(iii) During the deployment of the RPEV in El-Monte busway when a "critical mass" of electrified roadways is not yet achieved, incentives may be needed to encourage private vehicles to adopt the clean-propulsion RPEV. These may include tax credits, licensing and insurance benefits, free electric energy drawn from the roadway while the vehicles are in use, etc.

Legal and Liability Issues

Potential legal and liability issues surrounding the deployment of this new technology have to be addressed and resolved. Some examples of these issues are possible health risks due to the magnetic fields; inadvertent heating of the roadway; and interference with the working parts of vehicles that may culminate in safety risks. Legal and liability implications relevant to the RPEV deployment on the highway have not been studied, and they need to be initiated soon.

6.2.3 Training Needs

The operation and maintenance of the electrified facilities could differ from those for existing highways. Personnel of the responsible agency have to be trained to operate and maintain the power distribution network, keep the roadway sealed so that corrosion of the roadway cores will not occur, inspect the roadway for possible corrosion of the roadway cores, and apply necessary remedies.

Electric vehicles also require different maintenance from internal-combustion-engine vehicles. This maintenance includes the battery, motor, and electrical system. In addition, drivers of electric vehicles should be educated about driving, as well as performance and behavior of, electric vehicles. It is desirable to educate the public about the operation of electrified roadways and electric vehicles, as well as their potential impacts on users and on air-quality.

Task 7

Cost Estimation

In Task 6, a plan for the public demonstration of the RPEV technology in El-Monte Busway is presented. This plan calls for a three-phased implementation, each ‘of which would build on the system in the preceding phase. This task examines possible costs of such a plan.

The RPEV technology has not been deployed on the highway; neither has it achieved full maturity. Therefore, it is difficult to estimate the hardware cost accurately at this time. Furthermore, hardware costs for large-scale production are likely to be different from those for initial deployment in which a relatively small number of electrified facilities and vehicles are deployed. Cost estimates presented in this task should be viewed as the best available estimates at this time.

Estimated costs for the roadway subsystem at large-scale production are presented, followed by the cost estimates for the static and dynamic modes of operation. This is followed by estimated costs for the vehicle subsystem at large-scale production. Finally, cost estimates for the three public-demonstration phases are presented.

7.1. Costs of Dynamic Roadway Subsystem for Large-Scale Production

Costs of the roadway subsystem include initial capital cost, as well as recurring operation, maintenance, and administration costs, as follows:

7.1.1 Initial Capital Cost

Initial capital outlay is a one-time expense in the year of construction. For dynamic roadway electrification, this includes costs of the roadway inductor, power conditioners, and distribution system. In addition, there is also an engineering cost associated with the development, as well as site-specific design. Total capital cost of the installed roadway electrification at large-scale production is projected to be $1.95 million per lane-mile. A breakdown of this capital cost is given in Table 4. Components of the capital cost are described below.

The largest capital cost component is the cost of the roadway core modules, which is expected to be about half of the total capital cost. The roadway cores are currently made of grain-oriented silicon steel laminations, with a projected cost of $900,000 per lane-mile.

Roadway conductors are assumed to be custom made for the RPEV application. They consist of multiple-conductor cables that are pulled through conduits cast into the core modules. The cost of the conductors (including associated equipment such as connectors), is projected to be $100,000 per lane-mile.

The projected cost of the power conditioners and distribution network has more uncertainty, because the power supplies purchased to date for existing prototype systems have deficiencies that have to be remedied for an operational system. Further, the length of

Table 4 Projected Costs of Roadway Subsystem (Large Scale Production)

	Conservative Cost $/lane-mile
Core Modules	900,000
Conductors	100,000
Power Conditioner	500,000
Engineering	100,000
Installation	350,000
Total	1,950,000

roadway that could be supplied by a single power conditioner is not known with certainty, and could vary from site to site, as well as by the roadway segment. Nevertheless, we believe that a single power conditioner could, on the average, power approximately one lane-mile of roadway. A power conditioner may have a peak power rating of 0.5 to 1.0 megawatts. The cost, which includes the sensing/communications and distribution equipment, is projected to be $500,000 per lane-mile.

The estimated cost of engineering associated with the roadway installation shown in Table 4 assumes that component standardization exists. Components can be designed to allow for relatively simple mechanical and electrical interfaces. A conservative projection of the engineering cost is $100,000 per lane-mile (or 5 percent of the capital cost).

Finally, the installation cost of the roadway electrification is projected to be $350,000 per lane-mile. This cost also has uncertainty.

The projected capital cost of $1.95 million per lane-mile does not include the capital cost of bringing the electricity to the site (i.e., running power lines from the nearest utility station to the site). This capital utility cost is not included in the above estimate, because it is expected that such a cost will be absorbed by the utility company and subsequently reflected in the utility charge.

All hardware components of the roadway subsystem are expected to have useful lives of 25 years, after which replacements will be required.

7.1.2 Operation, Maintenance, and Administration (OMA) Costs

Operation, maintenance, and administration (OMA) costs of the roadway subsystem are annually recurring costs. These expenditures cover work performed on the roadway subsystem between a period of initial construction and replacement 25 years later. Annual OMA costs for the roadway subsystem are modeled as the percent of the cumulative capital cost, using the actual capital outlays data from CALTRANS between 1970 and 1990. It is projected that annual OMA costs for the roadway subsystem are 1 percent of the total initial capital cost of the roadway subsystem. This percentage applies to both the dynamic roadway and static charging. Even though there are uncertainties surrounding this estimate, we believe that this value is likely to represent a conservative estimate.

7.2 Costs of Roadway Subsystem for Static Charging

7.2.1 Initial Capital Cost

Static chargers to be installed at bus stops or bus layover points are expected to be 10-15 feet long. The initial capital cost of each static charger for large-scale production is projected to be $45,000 per charger. Table 5 shows the breakdown of cost components of static chargers for large-scale production. Unlike the dynamic roadway electrification in which the major cost component is the core modules, the major cost component of static

Table 5 Projected Costs of Static Chargers
(Large Scale Production)

	Cost $/static charger
Core Modules	5,000
Conductors	—
Power Conditioner*	25,000
Engineering	5,000
Installation	10,000
Total	45,000

*Assumes one power conditioner at $50,000 that supplies two static chargers, perhaps two bus stops on opposite sides of the street. The number of static chargers supplied by a single power conditioner generally will be site specific.

chargers is the power conditioner.

7.2.2 Operation, Maintenance, and Administration (OMA) Costs

The OMA cost for static chargers is projected to be one percent of the capital cost.

7.3 **Cost of Vehicle Subsystem**

The cost of the vehicle subsystem includes initial capital, maintenance, and energy costs.

7.3.1 Initial Capital Cost

The capital cost of the vehicle subsystem includes the onboard power electronics, pickup (core and inductor), battery, other onboard controls (e.g., computer, communication, sensors, and pickup suspension system), and low-power vehicle steering system. Currently, only two prototype vehicles (i.e., the PATH bus, and the Playa Vista's G-van) have been built. Both are retrofits of the existing vehicles. Therefore, projections of the capital cost of the vehicle subsystem presented in this report should be viewed as rough estimates.

Table 6 shows the projected initial capital cost of the vehicle subsystem for three vehicle types (buses, full-sized vans, and compact-sized passenger cars) at large-scale production. These estimates represent <u>incremental</u> costs relative to the comparable internal-combustion-engine vehicles (ICEV's). Thus, this study implicitly assumes that the capital cost of the vehicle itself

Table 6 Projected Costs of Vehicle Subsystem (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 (communication sensors, computer)	200	200	200
Labor	100	150	200
Battery	1,500	3,000	10,000
Total	3,000	5,325	13,550

(i.e., the body plus the motor) for the RPEV (at large-scale production) is comparable with that for the ICEV. The initial capital cost of the vehicle subsystem is projected to be $13,550, $5,325, and $3,000 for buses, full-sized vans, and compact-sized cars, respectively. Details of the cost components follow:

The onboard power electronics consist of AC capacitor, inductors, AC switches, rectifier, filter capacitor, and other miscellaneous equipment. The combined cost of these units does not vary in direct proportion with the vehicle gross weight or the ICS output power. Projections of the capital cost of the onboard power electronics are $1400, $1050, and $700 for transit buses, full-sized vans, and compact-sized passenger cars, respectively.

The pickup cost includes the cores and conductor packs. The cost of the cores varies linearly with the length of the pickup and the power rating, while the cost of the conductors increases slightly with the size. Projections of the capital cost of the pickup are $1750, $925, and $500 for transit buses, large vans, and compact-sized passenger cars, respectively.

Projections of the capital cost of the onboard control equipment are $200 for all three vehicle types, regardless of the vehicle size.

The capital cost of the RPEV's battery accounts for a significant percentage (at least one-half) of the vehicle subsystem cost. The capital cost of the battery is expected to vary with the vehicle weight, and is estimated to be $10000, $3000, and $1500 for transit buses, full-sized vans, and compact-sized cars, respectively.

The onboard power electronics, pickup, and onboard controls are expected to have the same useful life as the vehicle itself. Evidence suggests that a projected average useful life of electric buses is' probably about 18 years. As a comparison, an average useful life of existing diesel buses is about 12 years. The battery of an RPEV is expected to last about 3-4 years before battery replacement is required.

Not shown in Table 6 is the capital cost of the low-power steering assistance system. This is projected to be $1000 for buses and $300 for vans and cars. The expected useful life of this device is the same as the vehicle life.

7.3.2 Operating and Maintenance Cost of Vehicle Subsystem

Maintenance costs for electric drivetrains are almost certain to be lower than those for comparable internal combustion engines, due to fewer moving parts and the higher inherent reliability of electric motors. One prior study estimated that maintenance costs of electric drivetrains could be about 80 percent of those for internal combustion engines (Long et al, 1974). However, such savings are likely to be offset by the cost of battery replacement. It is difficult to accurately estimate the cost of the battery replacement because battery life is not accurately known for the RPEV duty cycle. A rough estimate could be $0.05-$0.10 per vehicle-mile of travel.

7.3.3 Energy Cost for RPEV

Whereas ICEV's energy cost includes gasoline and oil, the energy cost for the RPEV is primarily the electricity cost. Electricity is needed for charging from the roadway, as well as from the' wall outlet for overnight battery recharging. It is estimated that the cost of electricity for the roadway charging is about 10 cents per kilowatt (KW), and about 6 cents per KW for overnight charging. Preliminary analysis results indicate that the energy consumption for transit buses, vans, and passenger cars is 2.50, 0.50, and 0.20 KW per mile, respectively. Examinations of typical travel profiles of transit buses, vans, and passenger cars in California suggest that transit buses could be expected to draw 80-85 percent of energy from powered roadways and 15-20 percent from overnight recharging. Vans and passenger cars are expected to draw 75 percent of energy from the wall outlet and 25 percent from the powered roadway. Based on these preliminary projections, the energy cost for the RPEV (cents per vehicle-mile of travel) by the vehicle type is calculated and presented below.

Vehicle Type	Energy Cost (cents/mile)
Buses	23.5
Vans	3.5
Cars	1.4

As a comparison, energy costs for diesel buses are typically about 22 cents per mile.

7.4 Estimated Costs of Three Public Demonstration Phases

The costs of the RPEV hardware presented above are all based on large-scale production. In estimating costs of each of the three public-demonstration phases in El-Monte Busway, allowance has to be made in the hardware cost to reflect smaller-scale production associated with early deployment. In this regard, the hardware initially produced in limited quantity could cost as much as 100 percent more than that from large-scale production. As production quantities increase, the cost could drop by approximately 25 percent. Projected unit costs for static chargers, electrified roadway, and roadway powered electric buses for various production levels are given below; they represent the best available guestimates at this time.

Static Chargers:	$80,000 per charger for the first four
	$60,000 per charger for the remainder
Electrified Road:	$4 million per lane-mile for the first four
	$3 million per lane-mile for the remainder
Buses:	$600,000 for the first bus
	$450,000 per bus for the next ten
	$350,000 per bus for the remainder

Cost estimates for each of the three phases are shown in Table 7. Please note that the hardware cost shown includes both the hardware and installation, but not include the engineering cost (which could account for an additional 5 percent). Because the

Table 7 Projected Costs of Public Demonstration by the Phase

	Total Round Trip Time (minutes)	Buses Required	Layover Point Static Charges	Bus Stop Static Charges	Electrified Roadway (lane-miles)	Incremental Hardware Cost** ($M)
Phase I Downtown Shuttle (five-minute headways)	40	8	2	-	-	4.0
Phase 2 Downtown/El Monte Shuttle (five minute headways downtown)						
5-min. headways to El Monte	80	16	3	38	-	5.4
10-min. headways to El Monte	120	11	3	38	-	3.7
15-min. headways to El Monte	160	10	3	38	-	3.2
20-min. headways to El Monte	200	9	3	38	-	2.7
Phase 3 Operation of nine electrified routes	-	68***	≈12	38	22	92.8****

** Does not include spare buses, optional charging locations, or hardware purchased in previous phases

Cost		
	Static Charges	$80K per charger for first 4 $60K per charger for remainder
	Electrified Roadway	$4M per lane-mile for first 4 lane-miles $3M per lane-mile for remainder
	Buses	$600K per bus for first one $450K per bus for next ten $350K per bus for remainder

*** 30-minute service headway for all bus routes

**** An incremental amount over $5.4 million in Phase 2 three phases involve incremental installations relative to the preceding phase, the cost estimate shown for each phase is an <u>additional</u> amount required for that phase.

7.4.1 Projected Costs of Phase I

The projected hardware cost for implementing the Downtown Shuttle bus service using static chargers exclusively is about $4.0 million. The capital cost of the buses dominates in Phase I. A minimum of four static chargers and eight buses are recommended to provide the service headway of 5 minutes.

7.4.2 Projected Costs of Phase II

In Phase II, the Downtown Shuttle service of Phase I will be expanded to the Downtown/El-Monte Shuttle service. As a result, a total of 41 static chargers will be required. Additional buses will also be needed, the number of which varies with the service headway to be provided for the El-Monte loop. The smaller this service headway is, the more buses will be required. Additional hardware cost for Phase II is projected to be $2.7 million to $5.4 million, for 5-minute service headway in the downtown loop and 5-20 minute headway for the El-Monte loop.

7.4.3 Projected Costs of Phase III

The incremental hardware cost for Phase III is projected to be about $93 million. Of these, 75 percent is the cost of electrifying about 22 lane-miles of El-Monte Busway. Most of the remaining 25 percent of this hardware cost is for acquiring additional 50 roadway-powered electric buses (10 buses have already been acquired before Phase III starts).

The above hardware cost estimate of $93 million does not take into account the fact that the new roadway powered electric buses would make it possible for the transit agency not having to replace about 60 existing diesel buses when their service life expires. If this is taken into consideration, the hardware cost of Phase III will drop from $93 million to about $74 million.

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