Electric Bus Operation and Evaluation in California

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This study evaluated the performance, energy consumption, range, and costs of electric buses recently deployed around the campus of the University of California at Berkeley. These electric buses have a relatively low curb weight and purchase price compared with electric buses in operation elsewhere. The series-wound direct current motors of the electric buses result in poor hill-climbing ability. This study presents results of vehicle tests under controlled conditions, statistical models for hill-climbing speed, energy consumption in revenue service, and estimated vehicle range. It also compares capital, energy, and battery-replacement costs of the electric buses and diesel buses.

Vehicle emissions are a serious problem in California. The California Air Resources Board established a mandate requiring 2 percent of all vehicles sold in California by 1998, and 10 percent by 2003, to be zero-emission vehicles. Transit fleets represent an initial market niche for electric vehicles in the absence of more advanced batteries. The daily range requirements of transit vehicles are generally predictable, and existing bus garages can readily accommodate battery-recharging and battery change-out facilities.

The University of California at Berkeley (UCB) started deploying four medium-sized electric buses in late 1993 in fixed-route service around the campus perimeter (the perimeter route). This 4.4-km route, previously served by diesel buses, is a relatively low-speed bus operation because the route goes through built-up areas and downtown Berkeley. The UCB electric buses were manufactured by Electricar Inc.

OBJECTIVE

The objective of this study was to evaluate the performance, as well as the advantages and disadvantages, of the UCB electric bus operation using empirical data from revenue service runs and road tests under controlled conditions.

UCB ELECTRIC BUSES

Each UCB electric bus is 6.3 m long, 2.2 m wide, and 2.6 m high, with a 0.45-m floor height. It has one door and a wheelchair lift. The seating capacity is 16, plus 6 standees. The curb weight is 4680 kg, 29 percent of which is the weight of traction batteries; the rated gross vehicle weight is 6520 kg. Regenerative braking is activated whenever the throttle is released and the brake pedal is depressed. The specified maximum speed is 40 km/hr.

Traction power is provided by two 23-cm series-wound direct current (dc) motors and solid-state controllers. The dc motors have a nominal voltage of 120, maximum revolutions per minute (RPM)

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of 6,000, and maximum current of 400 amps. The motors are powered by four trays of lead-acid batteries, each tray consisting of ten 6-V U.S. Battery Deep Cycle batteries. The battery pack has 370 amp-hr (based on a 3-hr rating) and a 120-V nominal rating.

The charge in the battery pack decreases as the electric bus is driven. Each bus has spare battery packs to allow battery recharging to be done only at night, when electricity cost and demand are the lowest. A depleted battery pack can be exchanged for a fully recharged one at any time during the day. This battery change-out is accomplished with a specially designed forklift and can be done in 10 min.

PERIMETER ROUTE

The perimeter route is roughly rectangular, encompassing the campus (Figure 1). Four streets make up the sides of this rectangular: Shuttuck Avenue, Hearst Avenue, Piedmont Street, and Bancroft Way. The buses run in a one-way clockwise loop, covering 4.4 km per round trip.

The four streets making up the perimeter loop differ considerably from one another in road and traffic characteristics, such as number of lanes, roadway grade, average block length, amount of roadside development, pedestrian and traffic volumes, and percent of heavy vehicles (Table 1).

- Shuttuck Avenue. This is a very busy main street in downtown Berkeley. It is a four-lane divided avenue that is straight and almost flat. Curb parking is allowed on both sides. The street consists of very short blocks (130 m long on average). There are seven intersections, six of which have traffic signals.
- Bancroft Way. This busy street is south of the campus. It is a straight three-lane one-way street with long downhill slopes throughout. Curb parking is allowed on both sides. It has six evenly spaced intersections, three of which have traffic signals.
- Hearst Avenue. This is a four-lane street, two lanes of which are for parking. This street is unique because it consists of several steep upgrades of up to 12 percent. It has six intersections, one of which has a traffic signal.
- Piedmont Street. This street is much less busy than the other three streets. It is a winding two-lane street with mild uphills and downhills (up to $\pm$ 5-percent grade). There are two small intersections and no traffic signals.

SPEED CAPABILITY OF UCB ELECTRIC BUSES

Observed Speed Characteristics in Road Tests

Road tests under controlled conditions were conducted before the UCB electric buses were put into revenue service operation. These
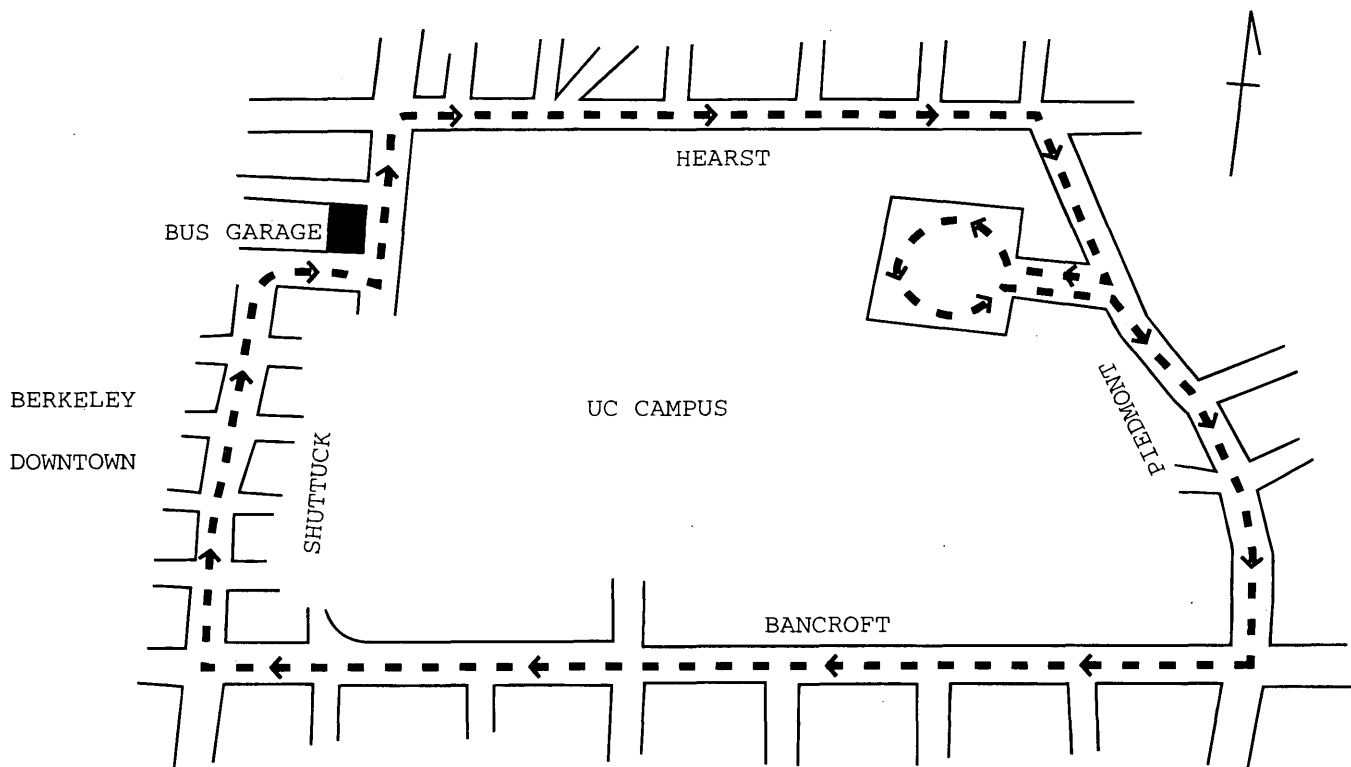
FIGURE 1   Diagram of perimeter route.

tests were conducted on a test track and on roads with little traffic. The bus was test-driven at a fixed driving cycle and carried no passengers (bus loading was accomplished with ballast of known weight). One test driver was employed for all of the road tests.

Results of the controlled road tests revealed an important power characteristic of the bus's series-wound dc motor (Figure 2). The motor developed peak power at about 15 km/hr, well below the manufacturer-specified top speed of 40 km/hr. As vehicle speed increased beyond 15 km/hr, the power decreased quickly. This characteristic has advantages and disadvantages. Because the power initially increased rapidly to the maximum value, the UCB electric bus will always have good initial acceleration from a stopped position. The limited power available at higher speeds also minimizes overall energy consumption and thus maximizes the driving range. On the other hand, the limited power at higher speeds results in poor acceleration at high speeds and at low speeds on steep upgrades.

TABLE 1   Characteristics of Streets Making Up Perimeter Route

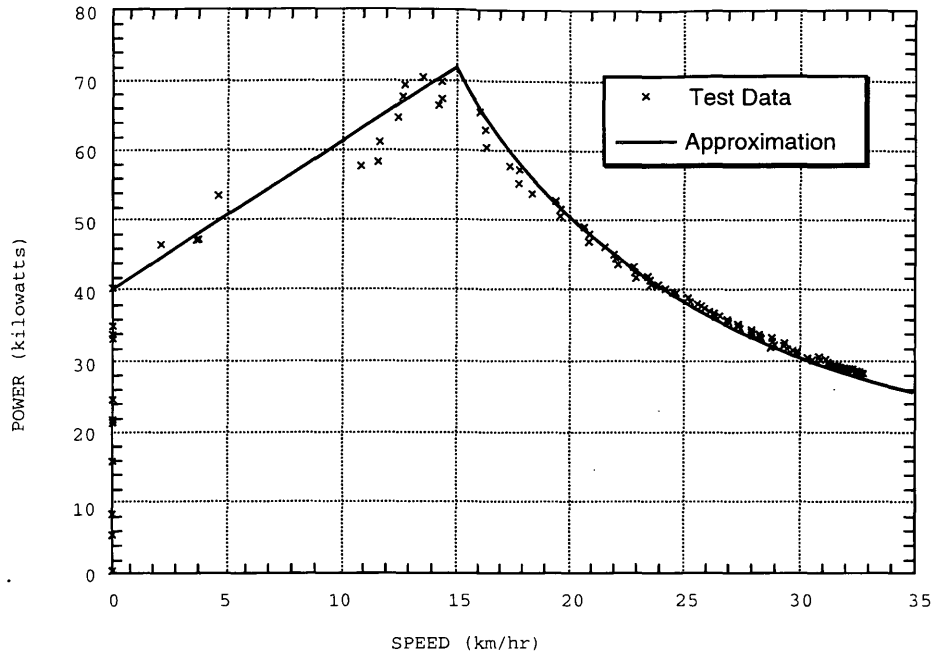| Street Characteristic		Shuttuck	Bancroft	Hearst	Piedmont
1.	Street length (km)	0.9	1.4	0.9	1.2
2.	Effective # of lanes	4	3	2	2
3.	Max grade (%)	+2	-5	> +11	± 6
4.	Aver block length (km)	130	230	150	600
5.	Intersections/km	7.8	4.3	6.7	1.7
6.	Signalized intersections/km	6.7	2.1	1.1	none
7.	Bus stops/km	2.5	3.0	3.5	0.8
8.	Shops and offices	very high	medium	low	none
9.	Pedestrians	very high	very high	medium	low
10.	Vehicle volume (vph)				
	- Afternoon peak	2500	2160	1420	1620
	- Off-peak	1880	1760	1040	1080
11.	% heavy vehicles				
	- Afternoon peak	2	4	3	2
	- Off-peak	5	10	9	6

FIGURE 2   Power characteristics of motors of UCB electric buses.

Figure 3 shows the observed available power (with 680-kg loading) from the road tests and required power versus speed for upgrades of 0, 5, 10, and 15 percent. The required power for a 0 percent grade was observed in the road tests, whereas those for 5, 10, and 15 percent grades were derived from the following formula (assuming drivetrain efficiency of 100 percent).

$$P_G = P_0 + W \times g \ (G/100) \times V \qquad (1)$$

where

P_G = required power for G percent grade (watt),
P_0 = required power for 0 percent grade (watt),
W = total vehicle weight (kg),
g = the gravity force (9.81 m/sec²),
G = the percent grade, and
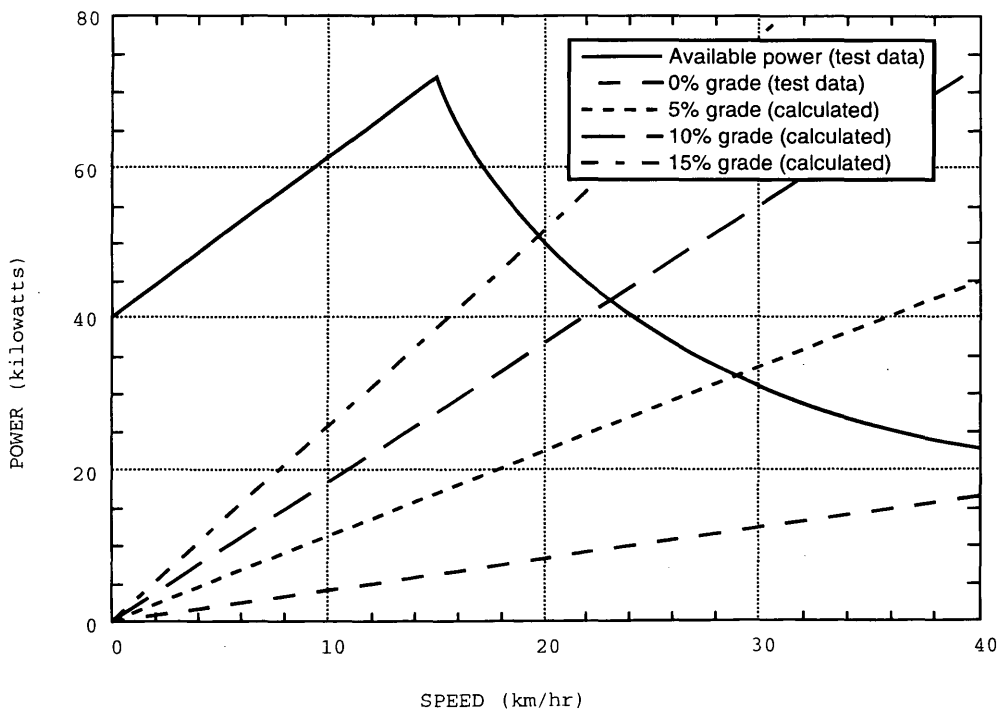V = vehicle speed (m/sec).

FIGURE 3   Available and required power for various speeds and upgrades.

The intersection between available and required power for a particular roadway grade indicates the upper limit of speed capability for that grade.

Results from the road tests also indicated that as the battery became more and more discharged, the available power decreased by as much as 10 to 15 percent.

Observed Effect of Battery Depth-of-Discharge (DOD) on Speed

DOD is defined as the percent of charge removed from the battery as the bus is driven. A higher DOD value indicates that less charge is available. Results of the controlled road tests indicated a nonlinear effect of the battery DOD on vehicle speed. That is, observed speed profiles for full and half-full batteries were similar. However, observed speed for a deeply discharged battery (with 80 percent DOD) was up to 10 percent lower than speeds for full and half-full batteries. This may be caused by the battery's ability to maintain output current well until it is deeply discharged.

Observed Effect of Payload on Speed

Controlled road tests were conducted to assess the effect of payload on vehicle speed. The results indicated that vehicle speed decreased slightly as loading increased.

Observed Acceleration Capability in Road Tests

Controlled road tests were conducted in which the UCB electric bus was driven up a 7 percent upgrade with a battery DOD of about 80 percent. The driver stopped the test bus approximately midway on the upgrade and then restarted the bus. The bus had no problem starting and accelerating from a stopped position on the 7 percent upgrade, even when the battery was deeply discharged.

Model for Hill-Climbing Speed in Revenue Service

The revenue service operation around the perimeter route is characterized by real-world driving cycles, frequent vehicle stopping and starting, variable passenger loading, different drivers (with different driving styles), variable roadway grades, variable traffic conditions, and other factors. The limited top speed of the UCB electric bus does not present a problem in revenue service runs on level roads. However, on steep upgrades along the perimeter route, speed could drastically decrease. Therefore, hill-climbing speed of the UCB electric bus is an important performance characteristic because it can affect adherence to the schedule, as well as users' perceptions of the electric buses.

A statistical model was developed to express hill-climbing speed in the revenue service operation as a function of various influencing independent variables. The dependent variable was the maximum attainable hill-climbing speed, defined as the maximum speed at which the bus could cruise while traveling on an upgrade. Road sections with grades greater than 0 percent were included in the modeling.

A computerized data-acquisition system was installed on the electric bus to record second-by-second vehicle speed, output current, and output voltage in revenue service runs.

Candidate independent variables included the percent grade, the length of grade, passenger loading, battery DOD, and time of day. Passenger loading was represented by the "load ratio," defined as the ratio of actual passenger loading to the manufacturer's allowable maximum payload. Passenger loading was derived from passenger counts multiplied by an assumed average passenger weight of 72 kg. The allowable maximum payload was the difference between the rated maximum gross vehicle weight and the curb weight. Battery DOD was computed for the beginning of each upgrade section. Time of day was represented by peak and off-peak hours, and was an indicator of the vehicular and pedestrian volumes. It was incorporated in the regression analysis as a dummy (0,1) variable.

The best-fit model for hill-climbing speed capability was found to be:

$$Y = 38.78 - 7.961\,X_1^{0.33} - 3.137\,X_2 \qquad (2)$$

where

Y = maximum hill-climbing speed,
X_1 = percent upgrade, and
X_2 = load ratio.

The t-statistics for the coefficients of X_1 and X_2 were -15.73 and -3.68, respectively, indicating that both independent variables were statistically significant at most reasonable levels of the probability of Type I error (α). R^2 is 0.77, indicating that 77 percent of total variation in the dependent variable was explained by the estimated model. The estimated standard error was 2.08 and the sample size was 86.

This estimated model implied that maximum hill-climbing speed was lower for steeper upgrades and higher payload, as expected. Length of upgrade, battery DOD, and time of day were found to be statistically nonsignificant in revenue service. Figure 4 shows estimated hill-climbing speeds in revenue service operation plotted against the percent upgrade for three load ratios.

ENERGY CONSUMPTION

Observed Energy Consumption in Controlled Road Tests

Vehicle energy consumption is the dc energy drawn from the battery to drive the electric bus. It can be calculated from observed current and voltage as follows:

$$W = \int V i \cdot dt \qquad (3)$$

where

W = vehicle dc energy consumption (watt-sec),
V = voltage (volt),
i = current (amp), and
t = time (sec).

The controlled road tests indicated that observed vehicle dc energy consumption rates (per vehicle kilometer) were different between travel on level roads and travel on uphills; the rates were 0.78 and 0.82 kW $\cdot$ hr/km for level roads and 7 percent upgrades, respectively.
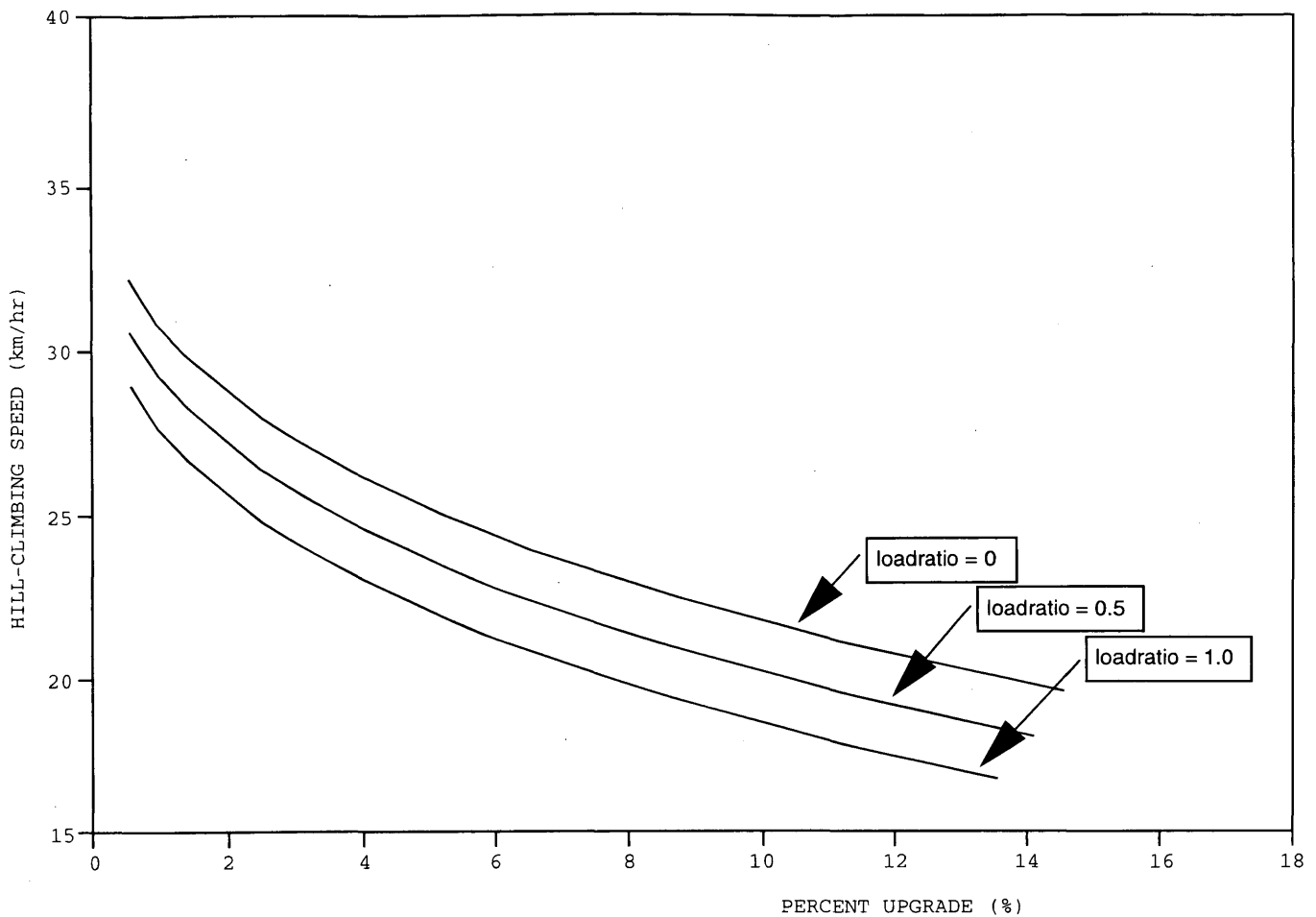
FIGURE 4 Estimates hill-climbing speed versus upgrade.

Models for Energy Consumption in Revenue Service

First Energy-Consumption Model

The primary purposes of the first energy consumption model were to provide input for reliable estimations of vehicle range and energy cost, and to determine systematically factors affecting the energy consumption. This model explored how bus route and operation characteristics affected the vehicle's dc energy consumption. Bus route characteristics included various street and traffic variables such as the street's longitudinal profile, number of lanes, average block length, vehicular and pedestrian volumes, number of intersections, number of stops per kilometer, density of businesses and shops, and other factors. Bus operation variables included average bus travel speed and passenger loading.

The dependent variable for the first energy-consumption model was vehicle dc energy consumption per vehicle-kilometer.

Candidates for independent variables were as follows. The four streets making up the perimeter route are very different from one another in terms of bus route and operation variables (see Table 1). Longitudinal profiles of these four streets are shown in Figure 5. The four streets collectively formed a composite independent variable. That is, this independent variable consisted of four levels, each representing one street. The variable was incorporated in the regression analysis as a set of dummy variables. Other candidate independent variables examined were load ratio, battery DOD, average vehicle travel speed, number of vehicle stops per kilometer of street, and peak and off-peak hours.
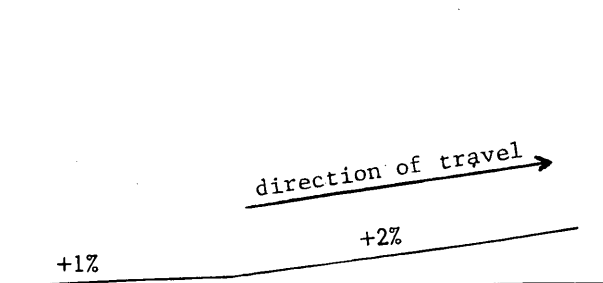
The best-fit model was:

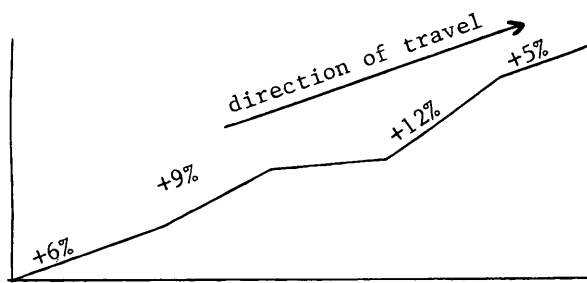$$Y = 0.753 + 0.169\,X_1 - 0.002\,X_2 + 1.028\,X_3 - 0.129\,X_4 - 0.618\,X_5 \tag{4}$$

where

Y = energy consumption per kilometer of travel (kW · hr/km),
X_1 = load ratio,
X_2 = battery DOD (percent), and
X_3, X_4, X_5, and X_6 were a set of dummy variables representing Hearst Avenue, Piedmont Street, Bancroft Way, and Shuttuck Avenue, respectively; a regression analysis requires one of them to be excluded, in this case, X_6.
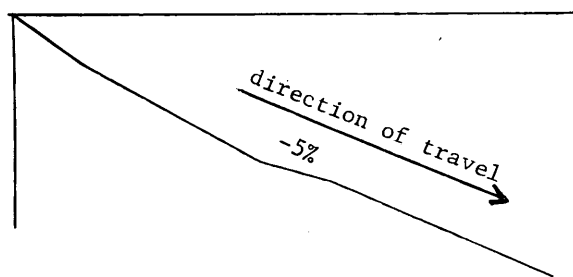
The t-statistics for all coefficient estimates in Equation 4 were significant at any reasonable value of α. The estimated standard error was 0.94 and the sample size was 80. R^2 was 0.98, indicating that 98
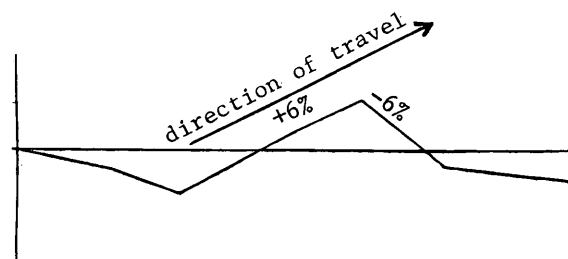
(a) Longitudinal Profile of
Shuttuck Ave (not to scale)

(c) Longitudinal Profile of Hearst
Ave (not to scale)

(b) Longitudinal Profile of
Bancroft Way (not to scale)

(d) Longitudinal Profile of Piedmon
Street (not to scale)

FIGURE 5   Longitudinal profile of perimeter route.

percent of total variation in the observed energy consumption per vehicle kilometer was explained by the estimated model. The other candidate independent variables were found to be nonsignificant.

Figure 6 shows estimated energy consumption per vehicle kilometer plotted against the load ratio for each of the four streets. The effects of street characteristics on the energy-consumption rate are evident in this figure. Specifically, the figure implied the following:

• Among the various street and traffic characteristics, the most dominant feature affecting the energy-consumption rate was the street's longitudinal profile (primarily the percent upgrade). This is evident in the energy-consumption rate on Hearst Avenue, which was approximately 2.4 to 2.5 times those on Shuttuck Avenue (almost flat) and Piedmont Avenue (with mild grades). Furthermore, Bancroft Way (a downhill street throughout) shows an extremely low energy-consumption rate (only 10 percent of the rate on Shuttuck).

• Other street and traffic characteristics affecting the energy-consumption rate were those collectively characterized as the degree of urbanization. Figure 6 reveals that higher degrees of urbanization slightly increased the energy-consumption rate. This is evident in the energy rate on Shuttuck (a busy main downtown

street that is almost flat), which was approximately 1.2 times that on Piedmont (a small nonbusy street with mild grades).

• Passenger loading also affected the energy-consumption rate, although to a lesser extent than the street's longitudinal profile did. As expected, the energy-consumption rate increased as passenger loading increases.

The estimated energy-consumption model (Equation 4) also indicated that the battery DOD affected the energy-consumption rate. As the battery DOD increased, slightly less energy could be drawn from the battery because there was less power available. This was consistent with the earlier finding from the controlled road tests.

Second Energy-Consumption Model

Results of the first energy-consumption model strongly suggested that the street's longitudinal profile was a dominant factor influencing the energy-consumption rate. Therefore, a second energy-consumption model was developed, aimed at quantifying the effect of the longitudinal profile (namely the percent upgrade and length of upgrade) on the energy-consumption rate of the UCB electric bus in revenue service operation.
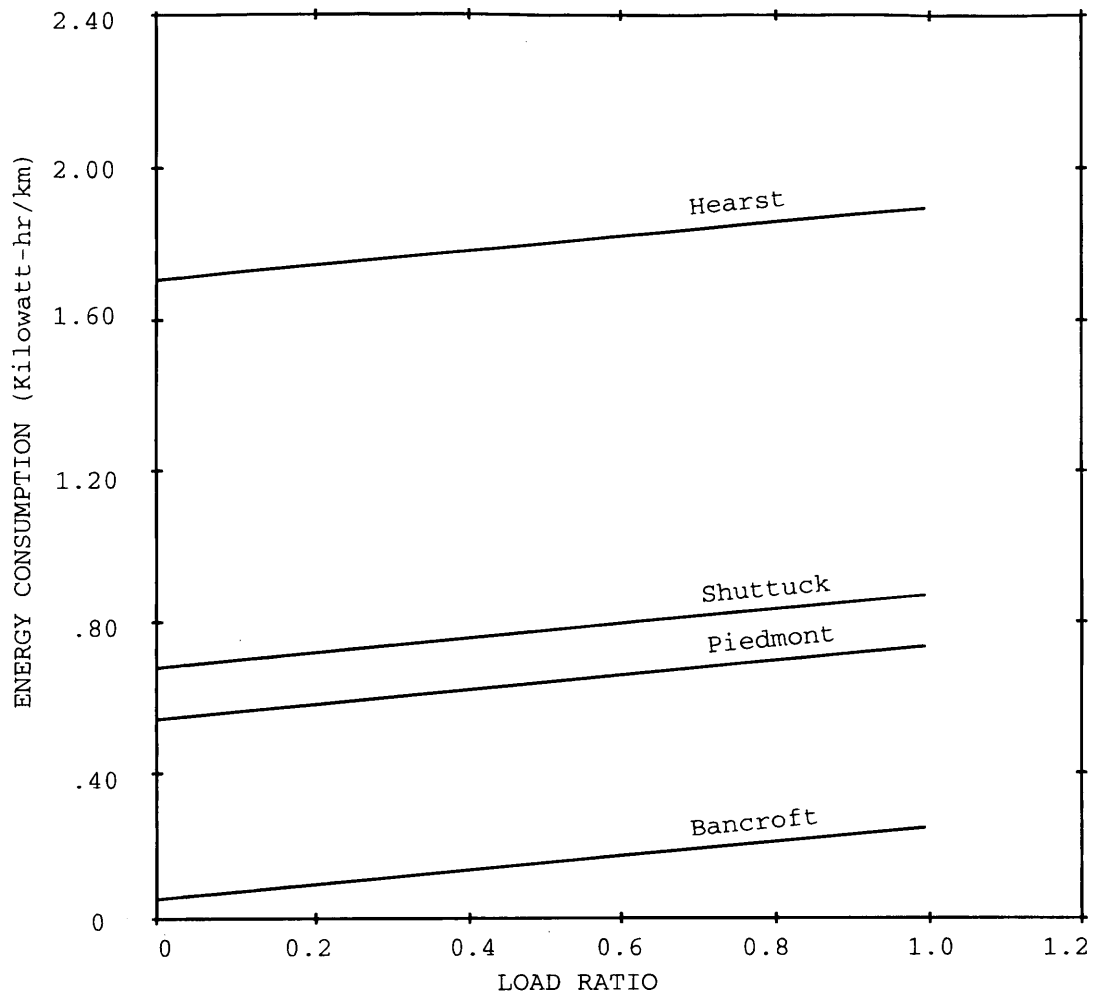
FIGURE 6   Estimated energy consumption versus load ratio for four streets.

The dependent variable in the second energy-consumption model was vehicle dc energy consumption per vehicle kilometer.

Candidate independent variables examined in the second energy-consumption model were percent roadway grade, grade length, passenger loading, and battery DOD.

The best-fit model was

$$Y = 0.139 + 0.137 \text{ (percent upgrade)} + 0.780 \text{ (load ratio)} \qquad (5)$$

where Y is vehicle dc energy consumption per vehicle kilometer (kW · h/km).

R^2 was 0.62, indicating that 62 percent of total variation in the observed energy-consumption rates was explained by Equation 5. The t-statistics for the percent upgrade and load ratio were statistically significant at any reasonable value of α. The sample size was 155.

The estimated model of Equation 5 indicated that the energy consumption increased as the upgrade became steeper and the passenger loading increased, as expected. On the other hand, the grade length and battery DOD were found to be statistically non-significant.

Regenerative Energy

With regenerative braking, a portion of the kinetic energy in braking is returned to the battery. From the data collected in revenue service, average regenerative energy was found to be about 15 percent of vehicle dc energy consumption. This was a relatively high percentage, probably caused by the following two factors. Bus operation on Bancroft Way (a downhill street throughout) required drivers to frequently slow down and apply the brakes so that the RPM would not exceed the critical 6000. In addition, three out of the four streets were busy city streets with high vehicular and pedestrian volumes, a configuration that resulted in frequent vehicle stops and starts.

RANGE OF UCB ELECTRIC BUSES

Estimates of the range of the UCB electric buses in revenue service operation were derived from two sources: vehicle range derived from the estimated first energy-consumption model (Equation 4), and vehicle kilometers between battery change-outs, recorded daily by the drivers.

Vehicle Range Estimated from Energy-Consumption Model

The first energy-consumption model (Equation 4) was used to estimate the distance the UCB electric bus traveled before the battery reached 80 percent DOD. The estimated range values were 48 km for a load ratio of 0.5 (a half-full bus) and 44 km for a load ratio of 1.0 (a full bus).

Reported Vehicle Kilometers Between Battery Change-Outs

Drivers were asked to record vehicle kilometers between battery change-outs on a daily basis. Based on such records during the first 2 months, the distances between battery change-outs were found to be mostly between 30 and 40 km, with an average of 34 km and a standard deviation of 4 km. This average range was lower than the estimate based on the energy-consumption model. This implies that the battery packs were usually changed out before the battery DOD reached 80 percent. Most drivers were probably being conservative because they did not want to come close to running out of energy while on the road.

COMPARISON OF COSTS OF UCB ELECTRIC AND DIESEL BUSES

Capital and energy costs of the UCB electric buses and the replaced diesel buses were compared. The UCB has operated two kinds of medium-sized diesel buses. One was essentially a modified school bus and will be referred to as the UCB diesel school bus. The other was a conventional diesel bus and will be referred to as the UCB diesel transit bus. Costs for both of these UCB diesel buses are presented in comparison with costs of the UCB electric bus.

At this time, the UCB electric buses have not had sufficient mileage to allow for an estimate of their routine maintenance and repair costs.

Capital Costs

The 1993 purchase price for each UCB electric bus was $100,000. This price included the bus, three lead-acid battery packs (i.e., two spare sets per bus), and the battery change-out hardware. (The price of the three battery sets alone was $10,000.) In addition, each battery charger (one per bus) cost another $2,000. The cost of converting and wiring the bus garage to accommodate battery recharging was about $2,000 (or $500 per bus). Therefore, the total capital cost for each UCB electric bus was about $102,500.

Because both types of the UCB diesel buses were purchased many years ago, their actual purchase prices had to be adjusted to the 1993 value. This is done by using the producers price index published in the February 1993 issue of *International Financial Statistics* by the International Monetary Fund.

Total capital costs for the UCB diesel school bus, diesel transit bus, and electric bus are summarized in Table 2. The table indicates that the total capital cost of the UCB electric bus was 1.23 times that of the UCB diesel transit bus and 2.42 times that of the UCB diesel school bus. Capital costs per passenger capacity are also given in Table 2. On a per-passenger-capacity basis, the electric bus's capital cost is about 2.35 times that of the diesel transit bus and about 5.06 times that of the diesel school bus.

Energy Costs

The energy source for the UCB diesel school and transit buses is diesel fuel, and for the electric bus is the alternating current (ac) output from the wall outlet, used to recharge the lead-acid battery packs.

The electricity cost for the UBC electric bus was based on an operating policy that limits battery recharging to nighttime only. The amount of electricity (ac output) from the wall outlet was derived from the average dc energy consumption rate for the revenue service of 0.82 kW · hr/vehicle-km. The combined efficiency of the batteries and battery charger was 77 percent. Therefore, electricity from the wall outlet needed per vehicle kilometer was 1.06 kilowatt-hour. Electricity cost at night is 6 cents/kW · hr, which yielded an energy cost for the UCB electric bus of 6.4 cents/vehicle-km.

For the two types of UCB diesel buses, fuel costs were obtained from 1992–1993 fuel records.

Energy costs per vehicle kilometer and per rider for the UCB electric bus, as well as for the two types UCB diesel buses, are summarized in Table 3. The table indicates that the energy cost for the UCB electric bus was substantially lower than the costs for the two types of diesel buses. On the per-vehicle-kilometer basis, the energy cost of the UCB electric bus was about 0.49 times that of the diesel school bus, and 0.30 times that of the diesel transit bus. On a per-rider basis, the energy cost of the UCB electric bus was about 0.31 times that of the diesel school bus and 0.11 times that of the diesel transit bus.

Battery-Replacement Cost for UCB Electric Buses

For the UCB electric bus, the battery replacement cost is likely to be a significant recurring cost during the vehicle's service life. At this time, the UCB electric bus has had relatively low revenue service mileage. This makes it impossible to determine accurately

TABLE 2   Total Capital Costs for UCB Diesel and Electric Buses

	Diesel School Bus	Diesel Transit Bus	Electric Bus
1993 price	$42,340	$91,200	$102,500
Passenger capacity	46	46	22
Cost/pass. capacity	$920	$1,982	$4,659

TABLE 3 Energy Costs for UCB Diesel and Electric Buses

	Diesel School Bus	Diesel Transit Bus	Electric Bus
Cost/km (cents)	13.1	21.3	6.4
Cost/rider (cents)	3.2	9.6	1.0

the battery's service life and thus battery replacement cost. Evidence in related literature indicates that lead-acid batteries may last about 32,000 vehicle km. If so, the battery-replacement cost for the UCB electric bus will be about 31 cents/vehicle-km, or 2.5 times the combined routine maintenance and repair costs for the UCB diesel bus.

CONCLUSION

Unlike the diesel buses they replaced, the UCB electric buses are very quiet. Vehicle acceleration and braking motion is fairly smooth, comparable with the motion of the replaced diesel buses. Drivers indicate that they did not have any problem making a transition from driving diesel buses to driving the UCB electric buses. Most said that they felt comfortable driving the electric buses after the first training run.

Low speed and acceleration capabilities of the UCB electric buses on steep uphills are caused by the properties of the series-wound dc motors used. Advanced motors such as ac motors or separately excited dc motors could substantially improve these capabilities of the UCB electric buses. The capital costs and battery-replacement costs of the UCB electric bus are high. However, energy cost of the UCB electric bus is considerably lower than that of the diesel bus it replaces.