U.S. Department of Transportation
Federal Transit Administration

FOUR-YEAR REPORT

on Battery-Electric Transit Vehicle Operation at The Santa Barbara Metropolitan Transit District

May 1995

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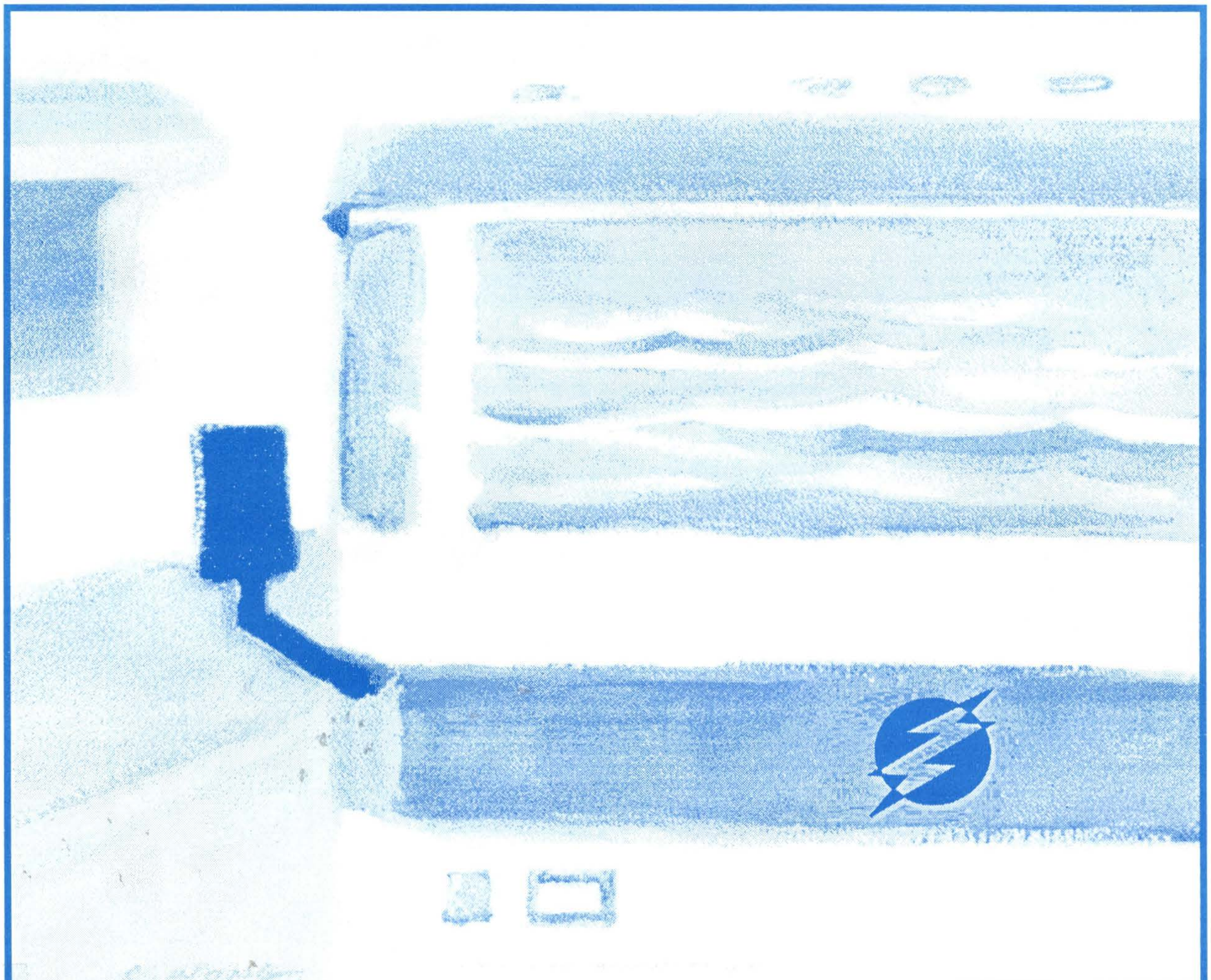

Office of Technical Assistance and Safety

FOUR-YEAR REPORT
on
Battery-Electric Transit Vehicle Operation
at
The Santa Barbara Metropolitan Transit District

May 1995

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General Manager: Gary Gleason

16. Abstract

The objectives of this four-year report are to provide an overview and discussion of the Santa Barbara Metropolitan Transit District's (MTD) experiences with electric-vehicle (EV) operation and maintenance, and to provide technical information relating to MTD's ongoing "real-world" evaluation of various products attendant to battery-electric transit vehicle operation. The material covered represents a compilation of the information most frequently requested by interested third parties.

The comparative costs of operation and maintenance between MTD's electric and diesel-powered transit vehicles are presented. Information relating to driver energy management, traction batteries, battery chargers, range extenders, powertrains, energy consumption, and emissions is also presented.

This report should prove useful to agencies that are contemplating the implementation of battery-electric vehicle operations, and will provide a solid foundation for other transit operators that have already made the decision to proceed with battery-electric transit programs. The information presented will also be of interest to manufacturers of electric vehicles and EV components. This report will promote an understanding of the unique requirements of battery-electric vehicle operation, and will thereby increase the opportunities for successful integration of the technology.

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METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0	1	2	3	4	5	6	7	8	9	10

CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 | 25.40

QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

NOTICE

SBMTD BATTERY-ELECTRIC TRANSIT VEHICLE PROGRAM
FOUR-YEAR EV REPORT

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EXECUTIVE SUMMARY

The Santa Barbara Metropolitan Transit District (MTD) introduced battery-electric transit vehicles into regular service in January of 1991. This novel application of electric propulsion ensured quiet, exhaust-free, odorless operation, and proved to be an immediate success with riders, as evidenced by a ten-fold increase in ridership during the first year of all-electric operation (from 100,000 passengers per year to 1,000,000 passengers per year). During the ensuing four years, MTD has logged more than 300,000 miles and 60,000 hours of service on its battery-electric fleet, and has carried more than 3 million passengers during the course of 8,000 driving cycles.

MTD's battery-electric fleet presently stands at twelve vehicles, with another six in fabrication. Vehicles range from the twenty-two foot open-air trolley-style shuttle vehicles, to a thirty-five-foot heavy-duty transit bus that incorporates several advanced material and drivetrain features. The electric shuttles regularly perform an eight-hour duty cycle without the assistance of opportunity charging or battery-swap schemes, and travel up to 80 miles per day.

The operation of electric vehicles in regular transit service (as opposed to short-term experimental demonstrations) has produced a wealth of useful data. MTD employs a comprehensive data acquisition and reduction system in order to accurately track operational parameters of interest. This effort enables the daily evaluation of issues such as driver energy management, vehicle performance, battery energy efficiency, charger efficiency, and range extension due to regenerative braking. Performance summaries are sorted by route, and sub-sorted by driver and vehicle. Some of the more significant findings are presented below.

Operational Factors

- The cost of recharging an electric vehicle per mile driven is a function of the cost of electricity and the AC energy consumption rate. At the present rate of 8.5¢ per kWh that MTD pays for off-peak electricity, the per-mile cost of "refueling" MTD's Electric Villager is 24% higher than that for its diesel-powered Villager counterpart. However, the electric rate structure for commercial EV recharge facilities is currently under review by the Public Utilities Commission; under the proposed rate of 4.3¢ per off-peak kWh, the refuel cost for the electric bus would be 37% less than that for the diesel bus.

- Battery energy efficiencies for the MTD fleet average 70%. Individual set efficiencies range from the low 60% range to the low 80% range, depending upon battery age, chemistry, and recharge profile.

- Passenger loads and most accessory power loads have less impact on vehicle range than do route characteristics and driver performance. MTD experience has shown that driver energy consumption can vary by up to 50%, depending upon route characteristics. Therefore, the implementation of appropriate driver training can be critical to the success of any given operation. The use of advanced battery chemistries to achieve substantial increases in performance costs tens of thousands of dollars per transit vehicle. *It is therefore clear that the economics of electric vehicle technology are such that performance increases derived from reductions in energy consumption are far more cost effective than those obtained by increases in available energy.*

- Regenerative (electrical) braking extends vehicle range by an average of 17% on MTD's routes. The use of regenerative braking has also extended the life of the mechanical braking system by approximately three-fold.

- Occasionally, during the course of normal route service, an electric bus does not possess sufficient remaining energy to complete its usual mission. The causes of such occurrences include deficient battery cell(s), an excessive energy consumption rate, incomplete battery recharge the previous night, and cold-temperature operation. MTD's electric vehicles exhibit a higher incidence of road calls than occur with the diesel fleet by a factor of approximately two. It is anticipated that future availability of advanced performance batteries will permit fleet operation with greater margins between required energy and available energy, thereby reducing the incidence of low-power events.

- The fluctuating "micro-cycle" energy-transfer environment attendant to electric vehicle (EV) operation results from varying power-transfer levels during vehicle acceleration, steady-state motoring, regenerative braking, and brief dwell periods. Such micro-cycle energy-transfer is quite different from that approximated by constant-current discharge tests, and, in some respects, appears less troublesome for multi-module strings.

- Energy-efficient accessories, particularly vehicle climate-control equipment, must become commercially available at reasonable cost in order for battery-electric transit to achieve greater applicability. Various promising technologies are currently in development, but are not yet competitively priced. Until such technologies mature, heating and cooling of passenger compartments are probably best handled by fossil-fuel-driven apparatuses, despite the potential loss of ZEV consideration.

- MTD has evaluated a 7-kW propane-powered range extender in conjunction with its twenty-two-foot electric transit bus. Continuous operation of the on-board generator yields a 50% increase in vehicle range, although the incorporation of such equipment effectively converts an EV to hybrid-electric status, thereby precluding Zero Emission Vehicle (ZEV) certification. The use of such equipment also compromises the noise reduction and odor-free benefits derived from pure battery-electric operation.

- The energy-storage potential of chemical batteries is low in comparison with that of fossil fuels. The relatively high efficiency with which the electric propulsion system converts stored energy to mechanical energy partially overcomes this limitation, however. The replacement of a diesel propulsion system with an electric one on a 30-foot transit bus reduced the vehicle's energy consumption by approximately 70%.

- Emissions associated with the converted bus were also greatly reduced, even after consideration of the emissions from the power plants that produce the electricity. It is estimated that the aggregate emissions of nitrogen oxides, reactive organic gases, particulate matter, and carbon monoxide are reduced by at least 95% after electric conversion.

Maintenance

- The cost of maintaining MTD's electric fleet is 40% lower than that for its small-diesel fleet on a cost-per-day basis. The battery-electric fleet has a reduced range capacity as compared with the diesel fleet, however, which results in application of the electric fleet to lower average speed, reduced mileage service. Because of the reduced daily mileage associated with the electric fleet, cost on a per-mile basis favors the diesel fleet by approximately 10%. Nearly one-third of the cost of EV maintenance involves the traction battery. The majority of battery maintenance cost is related to the diagnosis and rectification of vehicle low-power occurrences. Such events are invariably caused by premature cell degradation. If valve-regulated "maintenance free" battery products prove to be more susceptible to premature degradation than the more abuse-tolerant "flooded" batteries, as most parties suggest, then the net impact of such products on maintenance costs will be unfavorable.

- During the 8,000 driving cycles performed by MTD's electric fleet, only 212 battery cells out of 1,852 have required replacement. This relatively low overall cell failure is believed to be the direct result of careful and methodical battery maintenance. A marked increase in cell failure rate has been encountered during the last quarter of 1994, however, as some of the battery sets begin to approach "end of life". Projected cycle life for the flooded lead-acid battery is at least 1,000 cycles.

Infrastructure

- MTD utilizes several battery charger topologies: ferroresonant, three SCR / three diode, and twelve SCR. The chargers vary in terms of delivered charge profile, profile adjustability, AC input current harmonic distortion (8% to 60%), power factor (0.67 to 0.99), DC ripple current (8 amps to 60 amps peak-to-peak), and AC to DC energy efficiency (0.87 to 0.96).

MTD has recently formed the Santa Barbara Electric Transportation Institute (SBETI), a non-profit entity organized to facilitate the introduction of battery-electric transportation. The functions of the SBETI include participation in appropriate technology evaluations and developments, acquisition and reduction of data pertinent to promising technologies, and dissemination of related information to the industry at large. The SBETI also provides assistance to other fleet operators that require support towards the implementation of battery-electric transit programs, including assistance with vehicle procurement specifications, driver and mechanic training, and data collection.

When the promotion and controversy concerning battery-electric transportation subsides, and all the maintenance, fuel, and life-cycle cost analyses have run their course, and whichever way regulations and market forces steer the future of the transportation industry, several simple, unequivocal facts will remain from the Santa Barbara MTD electric transportation experience. One is that the present state of battery-electric propulsion technology can be successfully applied to certain transit applications. Another is that the public *does* respond very favorably to creative approaches to public transportation. And a third is that during the first four years of battery-electric transit operation in Santa Barbara, the emission of over ten tons of air pollutants was prevented as a result of the replacement of diesel buses with battery-electric shuttles. Most parties will agree that these are significant accomplishments.

SBMTD BATTERY-ELECTRIC TRANSIT VEHICLE PROGRAM FOUR-YEAR EV REPORT

1. INTRODUCTION

1.1 HISTORY

The genesis of the Santa Barbara Metropolitan Transit District (MTD) battery-electric transit vehicle program began in 1989 with the desire to introduce a novel and rider-friendly transit product to an existing City of Santa Barbara sponsored "Shopper Hopper" service route. The prospect for successful marketing of the new transit product was of paramount interest. Several factors contributed towards the consideration of battery-electric vehicles as a replacement for the four diesel-powered buses originally utilized on the Shopper Hopper route. Among the factors providing impetus were a locally established vehicle engineering and manufacturing industry, local engineering experience with electric propulsion systems, a supportive electric utility company (Southern California Edison), and the progressive visions of City, MTD, and Community leadership.

MTD sponsored and played a lead role in the design of an aesthetically appealing, open-air, trolley-style low-floor shuttle vehicle. Utilization of an electric propulsion system ensured quiet, exhaust-free, and odorless operation. The procurement of two battery-electric shuttles was subsequently initiated. The first vehicle was placed in service in January 1991, and the second vehicle in May 1991. It was soon discovered that many riders would forego a ride on a diesel bus in order to wait for the next available electric shuttle. These occurrences were manifested in ridership statistics, which indicated that 75% of route ridership was on the two electric shuttles, with the remaining two diesel buses accounting for only 25% of total ridership, despite equivalent service hours.

MTD subsequently acquired six additional battery-electric shuttle vehicles, and formally introduced the Downtown-Waterfront Electric Shuttle service. Ridership thereupon increased ten-fold during the first year of all-electric operation (from 100,000 passengers per year to 1,000,000 per year). MTD added two additional vehicles to its electric shuttle fleet in 1994, increasing the shuttle fleet size to ten vehicles.

In addition to its fleet of ten battery-electric shuttle buses, MTD ordered the conversion of a 30-foot heavy-duty bus (12 year minimum life) from diesel drive to an electric drive that incorporates three AC traction motors, and commissioned a transit version of the shuttle bus. These two buses, along with the shuttles, are assigned to regular daily transit service in Santa Barbara where they have served over 3 million passengers and logged over 300,000 miles. The fleet has undergone more than 8,000 charge/discharge driving cycles. A fourth model 35-foot electric bus, presently under construction and scheduled for delivery during the second quarter of 1995, will incorporate several advanced material and drivetrain features. Five 25-foot electric buses, employing a fiber composite body design and a high ratio of on-board energy to vehicle weight, are scheduled for delivery in January, 1996.

1.2 MTD ACCOMPLISHMENTS

The Santa Barbara MTD has emerged as a world leader in battery-electric bus operations, and has demonstrated the integrity of the underlying propulsion technology during the course of the past four years. The MTD program has *not* been structured as a short-term demonstration project, but rather is the result of a commitment to utilize the technology in appropriate applications.

The MTD was instrumental in the design and fabrication of the electric shuttle vehicle, and is credited with sponsoring and successfully employing several mechanical improvements to electric buses. Among these improvements have been a chain drive transmission, gear transmissions, a constant-velocity-joint front-wheel-drive axle, start-up modules, and passive suspension systems for electric buses. The MTD has routinely documented the performance improvement in battery-electric buses attainable through specific training of drivers in optimal driving procedures, and through the provision of special meters and gauges to assist the driver's understanding of the demands and limitations of an electric bus.

The MTD has received various federal funding awards to stimulate the development of the battery-electric transit bus industry, and was invited to participate in the CALSTART electric bus program. CALSTART is a non-profit consortium of California businesses and utilities organized to develop advanced transportation technologies.

The MTD has become a preferred site for technical testing, and is frequently contacted by parties seeking information and guidance concerning the implementation of battery-electric transit programs. The preparation of this report was performed in-house by MTD personnel.

1.3 SANTA BARBARA ELECTRIC TRANSPORTATION INSTITUTE

Santa Barbara MTD regularly fields a large volume of requests for information and assistance relating to its battery-electric transit vehicle fleet. While MTD is pleased that its pioneering efforts have captured the interests of other agencies, the increasing frequency of such requests has unfortunately placed a burden on MTD resources. In an effort to accommodate the requirements of all interested parties, MTD has recently formed the Santa Barbara Electric Transportation Institute (SBETI), a non-profit entity organized to facilitate the introduction of battery-electric transportation. The functions of the SBETI include the participation in appropriate technology evaluations and developments, the acquisition and reduction of data pertinent to promising technologies, and the dissemination of related information to the industry at large. The provision of assistance to other transit operators that require support concerning operations, maintenance, and safety is also a primary focus of the SBETI. The production of this report represents one of the initial efforts of the SBETI. Among the possibilities for future publications is a focused primer on how to plan, procure, and implement a battery-electric transportation system.

The assessment of potential applications, the preparation of vehicle procurement specifications, and the training of electric vehicle drivers and mechanics are among the services offered by the SBETI. The SBETI is also developing a user-friendly, automated data acquisition and reduction system for use with battery-electric transit operations in order to provide operators with information essential to successful system management.

SBETI is uniquely positioned, via its relationship with MTD, to provide definitive leadership relative to the integration of battery-electric vehicle technology with transit applications. The services of the SBETI are available to all interested parties.

1.4 Parties Providing Financial and Technical Assistance

Integral to the success of the MTD electric bus project have been the collective contributions of numerous individuals and organizations. The initial vehicle procurement was co-sponsored by MTD and the City of Santa Barbara. Southern California Edison provided a portion of the necessary capital for the acquisition of the initial prototype. Bus Manufacturing, U.S.A. provided the first two electric shuttles at cost. APS Systems converted a diesel-powered transit bus to electric propulsion free of charge. Trojan Battery Company has donated batteries to the MTD project.

The Federal Transit Administration (FTA) has provided substantial, ongoing assistance, as has the CALSTART consortium. A portion of the data presented in this report has been developed in conjunction with the CALSTART project. The Federal Transit Administration's Office of Technical Assistance and Safety has co-sponsored an advanced battery demonstration project, and the California Energy Commission has contributed via third-party arrangements.

The sponsoring agencies, together with the many firms and individuals providing expert technical assistance and participation, have provided the necessary synergy to realize the program successes enjoyed to date.

1.5 Report Objectives

The objectives of this four-year report are to provide an overview and discussion of MTD's experiences with electric-vehicle operation and maintenance, and to provide technical information relating to MTD's ongoing "real-world" evaluation of various products attendant to battery-electric transit vehicle operation. The material covered herein represents a compilation of the information most frequently requested by interested third parties.

It is hoped that this information will prove useful to interested agencies that are contemplating the implementation of battery-electric vehicle operations, and that it may provide a solid foundation to other transit operators that have already made the decision to proceed with battery-electric transit programs. A thorough understanding of the parameters attendant to battery-electric vehicle operations will increase the opportunities for successful integration of the technology, and will ultimately extend the applicability of the technology to more rigorous applications.

Future reports on these subjects and others will be prepared periodically as circumstances dictate.

2. FLEET DESCRIPTION

2.1 ELECTRIC SHUTTLE VEHICLE

MTD currently operates ten twenty-two-foot electric shuttle vehicles. This vehicle, which presents an aesthetically appealing trolley-style appearance, is depicted in Figure 1.

Source: SBMTD/ETI

Figure 1. Electric Shuttle Vehicle

The normally open-air configuration is easily modified in inclement weather with temporary, "pop-in" windows. The low-floor design facilitates passenger boarding and egress, and a manually operated hinged ramp provides wheelchair accessibility. The use of "off-the-shelf" propulsion system components contributed to simplicity of engineering design. The vehicle was designed to operate in downtown service on routes that yield low average speeds. Key dimensions and other salient characteristics of the electric shuttle vehicle are presented in Table 1.

Table 1. Electric Shuttle Vehicle Characteristics

Seated Passengers	19	Curb Weight	~11,000 lbs.
Standing Passengers	8	Gross Vehicle Weight	15,000 lbs.
Length	22 ft.	Payload	~4,000 lbs.
Width	92 in.	Accessible Energy (C/6 rate)	60 (Pb-acid) 82 (Ni-Cd) kWh
Height	105 in.	Regenerative Braking	Yes
Floor Height	13 in.	Range on a Single Charge	80 miles (pb-acid)
Entrance Height from Ground	12 in.		105 miles (ni-cd)
Turning Radius	25 ft.	Top Speed	40 mph

Source: SBMTD/ETI

The shuttle fleet is equipped with flooded-cell lead-acid batteries (tubular and flat plate), valve-regulated gelled tubular-cell lead-acid batteries, and nickel-cadmium batteries. Detailed battery information is presented in Section 6 of this report.

The shuttle vehicles are equipped with a chopper-controlled, separately excited DC traction motor rated at 30 kW continuous and 45 kW intermittent (15 minute) output. It is planned to retrofit one of the shuttles with an AC powertrain in the near future.

2.2 22-FOOT ELECTRIC TRANSIT BUS

MTD operates a fully equipped transit bus version of the electric shuttle vehicle. Although this vehicle is constructed from the same structurally integral monocoque body/chassis design as that for the shuttle vehicles, it is equipped with permanent windows, a hydraulic/electric door, and an electronic farebox. This bus was built in order to apply the basic shuttle design to a more traditional transit configuration, and to evaluate its performance on service routes that entail modest increases in duty cycle and passenger comfort. This vehicle is depicted in Figure 2. The key dimensions and other salient characteristics of the 22-foot electric transit bus are presented in Table 2.

To date, this vehicle has been equipped with the same propulsion system as is utilized by the shuttle vehicles. It has also been provided with a propane-fueled range extender, as presented in Section 7. The bus is currently in the process of retrofit with a 120 kW AC induction motor powertrain. A comparative discussion on the DC vs. AC powertrains is presented in Section 9 of this report.

Source: SBMTD/ETI

Figure 2. 22-Foot Electric Transit Bus

Table 2. 22-Foot Electric Transit Bus Characteristics

Seated Passengers	18	Curb Weight	12,400 lbs.
Standing Passengers	8	Gross Vehicle Weight	15,400 lbs.
Length	22 ft.	Payload	4,000 lbs.
Width	92 in.	Accessible Energy (C/6 rate)	60 kWh
Height	102 in.	Regenerative Braking	Yes
Floor Height	14 in.	Range on a Single Charge	60 miles
Entrance Height from Ground	12 in.	Range with Range Extender	90 miles
Turning Radius	25 ft.	Top Speed	38 mph

Source: SBMTD/ETI

2.3 30-FOOT ELECTRIC VILLAGER

The Villager is a light-weight, relatively small diesel bus that employs monocoque construction and is fabricated for twelve-year, heavy-duty transit service. MTD operates a fleet of nineteen 1988/89 diesel-powered Villagers. A twentieth Villager was converted from diesel-power to electric-power in 1993. This conversion (Figure 3) employs three 23 kW AC induction motors (69 kW total) and a 320 volt battery system. Because this vehicle is not a "purpose-built" electric vehicle, its performance suffers somewhat due to unnecessarily high chassis and body weights. Nevertheless, this vehicle has proven useful in everyday service, and provides a suitable benchmark for comparative analyses with its diesel-powered counterparts. The key dimensions and other salient characteristics of the Villager are presented in Table 3.

Source: SBMTD/ETI

Figure 3. 30-Foot Electric Villager

Table 3. Electric Villager Bus Characteristics

Seated Passengers	26	Curb Weight	23,940 lbs.
Standing Passengers	15	Gross Vehicle Weight	30,240 lbs.
Length	30 ft.	Payload	6,300 lbs.
Width	90 in.	Accessible Energy (C/6 rate)	61 kWh
Height	120 in.	Regenerative Braking	Yes
Floor Height	35 in.	Range on a Single Charge	50 miles
Entrance Height from Ground	15 in.	Top Speed	41 mph
Turning Radius	35 ft.		

Source: SBMTD/ETI

2.4 35-FOOT ADVANCED DESIGN ELECTRIC POWERED TRANSIT BUS

The 35-foot Advanced Design Electric Powered Transit (ADEPT) Bus utilizes advanced material and design concepts in order to produce a lightweight bus design that exhibits the heavy-duty characteristics of a typical urban transit bus. The bus also meets the weight requirements of the Federal Interstate System. The upper-truss design permits a true monocoque construction in which the external skin, floor, internal stanchions, and roof become part of the load-bearing structure, thereby reducing the need for a heavy load-bearing frame and permitting the use of aluminum frame members. Foam-centered, fiberglas-faced composites are utilized for the outer bus skin and floor. This bus is scheduled for delivery to MTD during the summer of 1995. The frame structure is presented in Figure 4, and key dimensions and other salient characteristics are presented in Table 4.

Source: SBMTD/ETI

Figure 4. 35-Foot Advanced Design Electric Powered Transit Bus Frame

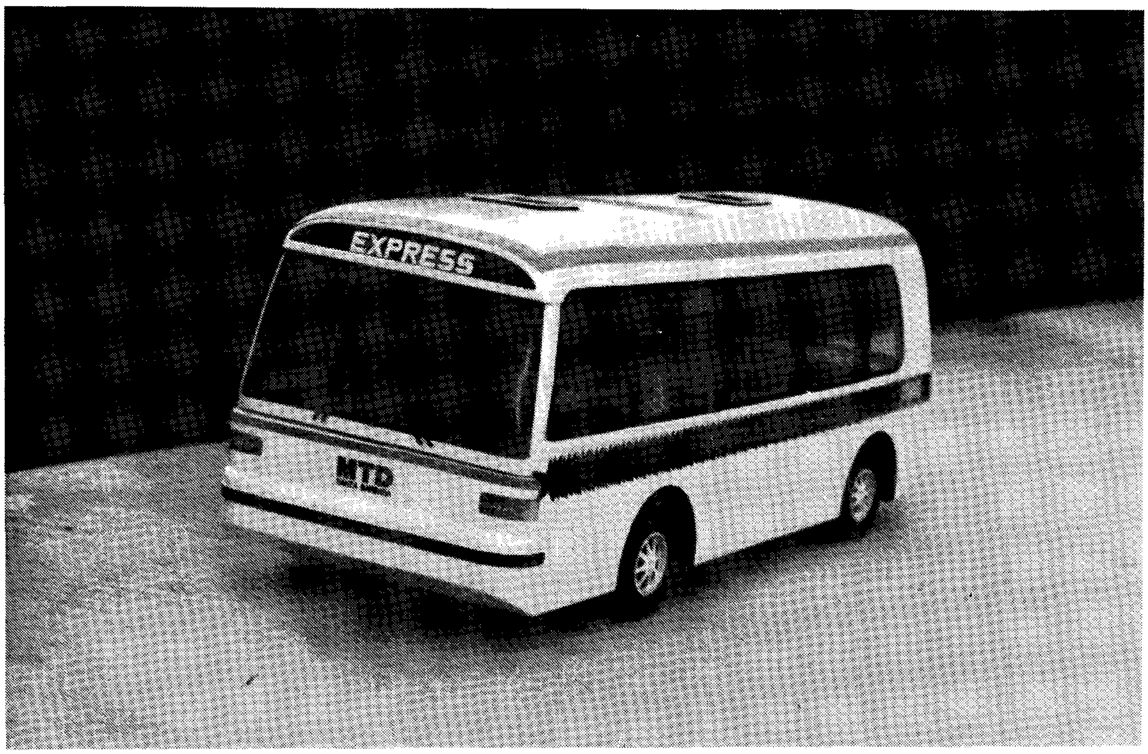
Table 4. 35-Foot Advanced Design Electric Powered Transit Bus Characteristics

Seated Passengers	35	Curb Weight	18,000 lbs.
Standing Passengers	9	Gross Vehicle Weight	25,000 lbs.
Length	35 ft.	Payload	7,000 lbs.
Width	98 in.	Accessible Energy (C/6 rate)	109 kWh
Height	112 in.	Regenerative Braking	Yes
Floor Height	14 in.	Range on a Single Charge	80 miles
Entrance Height from Ground	12 in.	Top Speed	60 mph
Turning Radius	40 ft.		

Source: SBMTD/ETI

2.5 25-Foot Advanced Design Electric Bus

Fabrication of five medium-duty 25-foot advanced design electric transit buses is currently in process for MTD. These buses will utilize a full monocoque unibody consisting of fiber composite shell sections for reduced weight. The buses will be equipped with an AC powertrain and nickel-cadmium battery technology, and will present a high ratio of energy to vehicle weight. It is anticipated that the vehicles will have an operational range of between 95 and 130 miles between recharges, depending upon route characteristics. The buses, a model of which is presented in Figure 5, are scheduled for delivery in February, 1996. The key dimensions and other salient characteristics of the 25-foot bus are presented in Table 5.



Source: SBMTD/ETI

Figure 5. 25-Foot Advanced Design Electric Bus Model

Table 5. 25-Foot Advanced Design Electric Bus Characteristics

Seated Passengers	25	Curb Weight	11,800 lbs.
Standing Passengers	12	Gross Vehicle Weight	16,700 lbs.
Length	25 ft. 8 in.	Payload	5,700 lbs.
Width	96 in.	Accessible Energy (C/6 rate)	123 kWh
Height	110 in.	Regenerative Braking	Yes
Floor Height	14 in.	Range on a Single Charge	~115 miles
Entrance Height from Ground	13 in.	Top Speed	45 mph
Turning Radius	27 ft.		

Source: SBMTD/ETI

2.6 VEHICLE COST

All five battery-electric vehicle configurations in use at (or under manufacture for) MTD were precipitated by MTD developed designs and/or technical specifications. Consequently, the cost of these vehicles have reflected the prototype nature of the vehicle fabrication processes and are not reflective of future production prices. Some battery-electric transit bus manufactures have begun to offer "standardized" product lines to take advantage of economies of scale, in some cases offering vehicles based on MTD initiated developments. To date, MTD has elected to continue in its leadership role of sponsoring the development of battery-electric bus designs that afford urban-bus operators an attractive alternative to diesel-powered vehicles. As the applicability and integrity of these designs continue to be proven, increases in vehicle production volume will result in reduced unit prices.

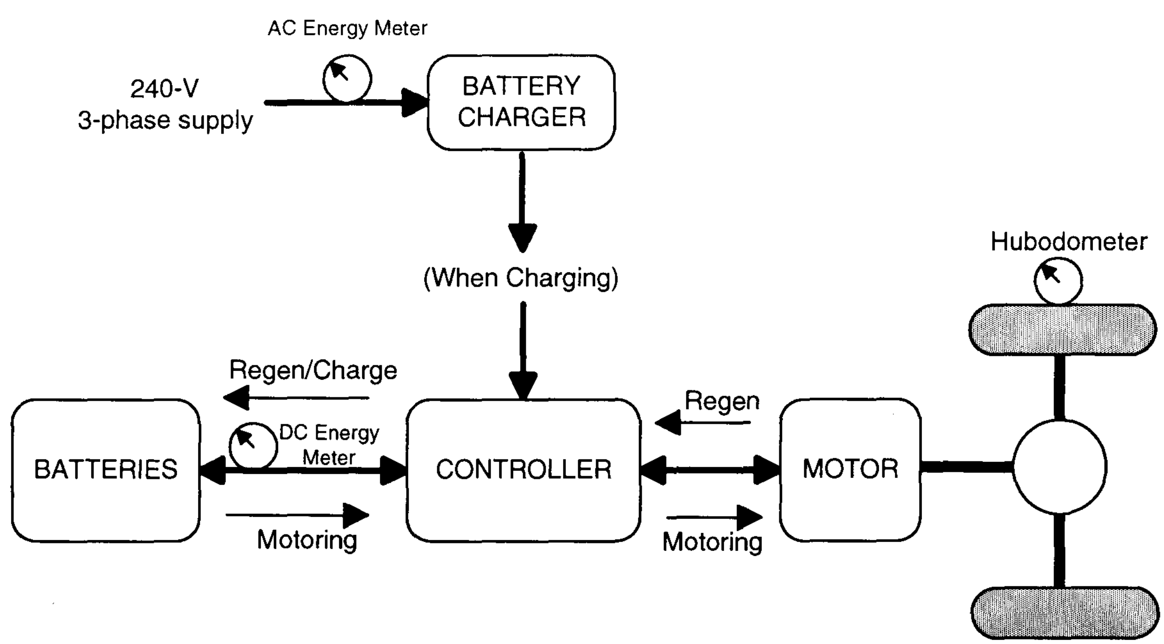
The interested party is encouraged to contact the appropriate manufacturers to obtain current market prices on existing battery-electric transit vehicles. The use of the bid process is also an effective way to establish market prices. The SBETI can assist in the structuring and preparation of vehicle procurement documentation.

3. DATA ACQUISITION METHODOLOGY

3.1 OVERVIEW

Santa Barbara MTD employs a comprehensive data-acquisition program to accurately track operational parameters of interest. This program forms the basis for most of the data presented in this report.

Data are collected on a daily basis for every vehicle in the fleet. Such data collection enables the daily evaluation of driver energy management, vehicle performance, battery energy efficiency, charger AC to DC energy conversion efficiency, net energy consumption, and effective range extension due to regenerative braking. The data generated are useful in the diagnosis of vehicle low-power events. A block diagram depicting various elements of the data collection effort is presented in Figure 6, and further discussion is provided below.



Source: SBMTD/ETI

Figure 6. SBMTD Data Acquisition Block Diagram

3.2 AC ENERGY

The AC energy consumed at each battery charging station is measured by means of a digital AC kilowatt-hour meter; values are recorded on a daily basis. The meter possesses ± 1% accuracy, and the output is displayed at 1-kWh resolution via a supplemental high definition module. High monitoring accuracy is achieved, even in the presence of input waveform distortion and phase displacement, by processing the input waveforms in analog format prior to digital conversion.

Conventional digital AC energy meters display output at 8-kWh intervals. Given that daily energy consumption figures are the difference between two such readings, the maximum potential daily reading error with such instrumentation is ± 8 kWh, which results in accuracy of only one significant figure for the daily energy usage totals typical of transit use. Because such an accuracy level is not satisfactory for day-to-day comparisons, MTD uses the more accurate 1-kWh meter for all of the AC energy monitoring.

3.3 DC Energy

The DC energy consumption, regeneration (from regenerative braking function), and recharge are measured by means of a custom DC power monitor that was designed and manufactured specifically for the MTD application. The meter measures the magnitude and direction of electrical current flow by monitoring a 500-ampere / 50-millivolt shunt installed in the traction-battery positive line. Battery discharge current (motoring mode) is recorded separately from battery charge current (regenerative braking and recharge modes) in order to enable direct evaluation of regenerative braking and battery energy efficiency. Battery system voltage is monitored through a voltage sense line. Amperes and volts are multiplied to yield power (kilowatts) for both charge and discharge channels. Energy (kilowatt-hours) is calculated by the integration of power over time. The unit also records ampere-hours, and stores peak values for amperes, volts, and kilowatts. An RC filter, positioned at the signal input, provides a 0.25-second time constant in order to mitigate signal noise transients. Data are sampled at a rate of 2.8 times per second. Instrument excitation power is provided by the vehicle's 12-volt battery system.

One of MTD's DC power monitors has been equipped with an RS-232 output to enable real-time data acquisition in conjunction with a notebook computer. Plots of battery-charger output profiles and propulsion system discharge and regeneration profiles, presented later in this report, have been developed with this instrumentation.

3.4 Other Instrumentation

A Metricom Universal Meter was used to develop the power factor data associated with various charger types, as presented in Section 8. A BMI Model 3030A power system analyzer and an HP-54501A digital storage oscilloscope were used to record the harmonic distortion and DC ripple current data also presented in Section 8.

3.5 Mileage

Daily vehicle mileage is determined by means of a hubodometer mounted on the left rear wheel. Mileage is recorded in one-tenth-mile increments to provide for accuracy to three significant figures.

3.6 PASSENGERS CARRIED

Passenger counts are tracked by the vehicle operator and are entered on the driver's daily record sheet.

3.7 BATTERY WATERING

Battery watering is performed by the maintenance department at regularly scheduled intervals. Volume of water added (and therefore consumed during the previous period) is recorded for each vehicle at each watering event.

3.8 BATTERY CYCLES

The number of charge/discharge cycles that each battery pack experiences is monitored. Two types of cycles are recorded: "driving cycles", i.e., those that result in substantial energy discharge and recharge (greater than 25% of total capacity), and "total cycles", i.e., any time the vehicle is coupled to the charger, even if the vehicle has not been operated that particular day (such events result in several kilowatt-hours of energy transfer due to "conditioning" of the electrolyte during the overcharge process). Because of the repetitive nature of the MTD mission requirement, virtually all driving cycles constitute depth-of-discharges greater than 60% of rated capacity.

3.9 MAINTENANCE COSTS

All maintenance work performed on the MTD fleet is recorded on work order forms. Such documentation specifies labor and materials utilized on each job. These data are then entered into fleet maintenance software for subsequent abstraction by specific vehicle, vehicle type, and/or maintenance category. The cost-of-maintenance information presented later in this report has been developed from this database.

4. OPERATIONS

4.1 SHUTTLE ROUTE - DUTY CYCLE REQUIREMENTS

MTD's electric shuttle vehicles operate primarily on two routes: a "Downtown" route that services a 1.5-mile stretch of State Street in the heart of Santa Barbara's commercial district, and a "Waterfront" route that provides service along a 2-mile stretch of Santa Barbara's beachfront boulevard. Service routes are occasionally modified. An example is the Summer-1994 extension to the Waterfront route that provided service continuation into Montecito's Coast Village Road shopping district. The vehicles are also occasionally utilized to provide commuter shuttle service between the business district and outlying parking areas. The shuttles perform the daily eight-hour duty cycles without the assistance of opportunity charging or battery-swap schemes.

Batteries are recharged at night between midnight and 6 a.m. when electricity rates are lowest. Shuttle route characteristics are presented in Table 6, and are discussed below.

Table 6. Shuttle Route Characteristics

Route	Daily Miles	Stops per Mile	Gradient (avg.)	Average Max. Speed	Energy Dschrg'd (DC kWh)	Energy Regen. (DC kWh)	Net Energy Dschrg'd (DC kWh)	Net DC kWh per mile
Waterfront	75 mi.	2.6	level	20 mph	57.4 kWh	8.4 kWh	49.0 kWh	0.66
Downtown	40 mi.	12.8	2%	9 mph	44.7 kWh	6.6 kWh	38.1 kWh	0.96

Source: SBMTD/ETI

Stops per mile include all stops resulting from passenger pickup and traffic conditions. *Average gradient* reflects the average of gradient absolute values (obviously, the net gradient for a circuitous route is zero). *Average maximum speed* represents the average of the maximum speeds attained during all stop-to-stop travel components. *DC energy* figures represent average daily performances of all drivers. *Energy discharged* reflects the total energy delivered to the motor during the course of the day's service. *Energy regenerated* represents the recoverable energy regenerated, i.e., the metered DC energy generated during regenerative braking, multiplied by an empirically derived battery energy efficiency factor for regenerative charge conditions. *Net energy discharged* reflects the energy discharged minus the recoverable energy regenerated, and is therefore indicative of the quantity of energy discharged that was originally stored in the battery. *Net DC kWh per mile* represents the net energy (discharged minus regenerated) drawn out of the battery expressed on a per-mile basis. In simple terms, the net energy consumption determines the quantity of energy that must be purchased from the utility, while energy regenerated represents that which is "manufactured" or "produced" on-board.

The energy data presented above have been collected for the presently configured MTD shuttle that is powered by a Nelco DC motor (30 kW continuous power, 45 kW intermittent power) and a Chloride Mk5A traction controller. It is planned to install and evaluate an AC propulsion system on-board one shuttle in the near future for comparative purposes.

4.2 22-FOOT ELECTRIC TRANSIT BUS ROUTE - DUTY CYCLE REQUIREMENTS

MTD's 22-foot Electric Transit Bus services conventional MTD transit routes. Representative of this utilization is service on Line 23 on Santa Barbara's Upper Eastside. The bus satisfactorily performs the five-hour duty cycle totaling 48 miles per day on this line. The bus has also satisfactorily operated on Line 21, a 3.5-hour, 49-mile route along the Waterfront that includes gradients of up to 7.2%. The 22-foot Electric Transit Bus also operates without the assistance of opportunity charging or battery-swap schemes. The use of an on-board 7-kW generator has been demonstrated to extend range by 50% (further information on the range extender evaluation is presented in Section 7). Although technical information is not fully developed for these routes, representative information is provided in Table 7.

Table 7. 22-Foot Electric Transit Bus Route Characteristics

Route	Daily Miles	Stops per Mile	Gradient (avg.)	Average Max. Speed	Energy Dschrg'd (DC kWh)	Energy Regen. (DC kWh)	Net Energy Dschrg'd (DC kWh)	Net DC kWh per mile
Line 23	48 mi.	8	3%	25 mph	56.9 kWh	10.5 kWh	49.6 kWh	1.03

Source: SBMTD/ETI

4.3 ELECTRIC VILLAGER ROUTE - DUTY CYCLE REQUIREMENTS

MTD's 30-foot Electric Villager conversion services conventional MTD transit routes. Representative of the utilization is service on MTD's Line 21 along the Waterfront. The bus satisfactorily performs the 3.5-hour, 49-mile route that includes gradients of up to 7.2%. This bus also operates without the assistance of opportunity charging or battery-swap schemes. The Electric Villager will soon be equipped with an on-board energy meter to permit the analysis of the energy parameters attendant to its operation.

4.4 VEHICLE AND ROUTE MOTORING/REGENERATING POWER PROFILE

The energy transfer attendant to electric transit vehicle operation is substantially different from that approximated by constant-current discharge representations. The daily driving cycle is actually comprised of a multitude of "micro-cycles". These micro-cycles are the result of varying power discharge levels during vehicle acceleration and steady-state motoring, bursts of battery charging current during periods of regenerative braking, and periodic rest intervals while the bus is stopped in traffic or at bus stops. The resulting micro-cycle profile defies accurate representation by constant-current discharge scenarios, and has therefore prompted the establishment of standardized "driving schedules" for purposes of battery performance evaluation, such as SFUDS (Simplified Federal Urban Driving Schedule).

The micro-cycle profile associated with the 2% up-gradient portion of MTD's Downtown Shuttle Route is depicted in Figure 7 (a complete circuit profile is contained in the Appendix). Discharge current and power are presented as positive values, whereas regenerative (charging) current and power are presented as negative values. Flooded tubular-cell, lead-acid batteries provided the traction power during this data collection event. It may be noted from the complete circuit profile provided in the Appendix that, as expected, regenerative-braking energy recovery is greater on the down-gradient portion of the route.

The micro-cycle profile associated with the same portion of the Downtown Shuttle Route under nickel-cadmium power is depicted in Figure 8. The data collection events for both the lead-acid and nickel-cadmium profiles were conducted at the mid-point of the Shuttle Route duty-cycle. Comparison with the power profile presented in Figure 7 (same route, lead-acid batteries) reveals a higher voltage and reduced sensitivity to varying current loads of the nickel-cadmium battery voltage as compared with that for lead-acid battery performance. These characteristics of the nickel-cadmium chemistry contribute to its ability to deliver the necessary power at reduced states-of-charge. The power available from a nickel-cadmium battery at 80% depth-of-discharge is not substantially different from that available at 20% depth-of-discharge,[1] thereby enabling vehicle operation without performance diminution.

4.5 ROUTE/VEHICLE/DRIVER ENERGY REQUIREMENTS AND PERFORMANCE

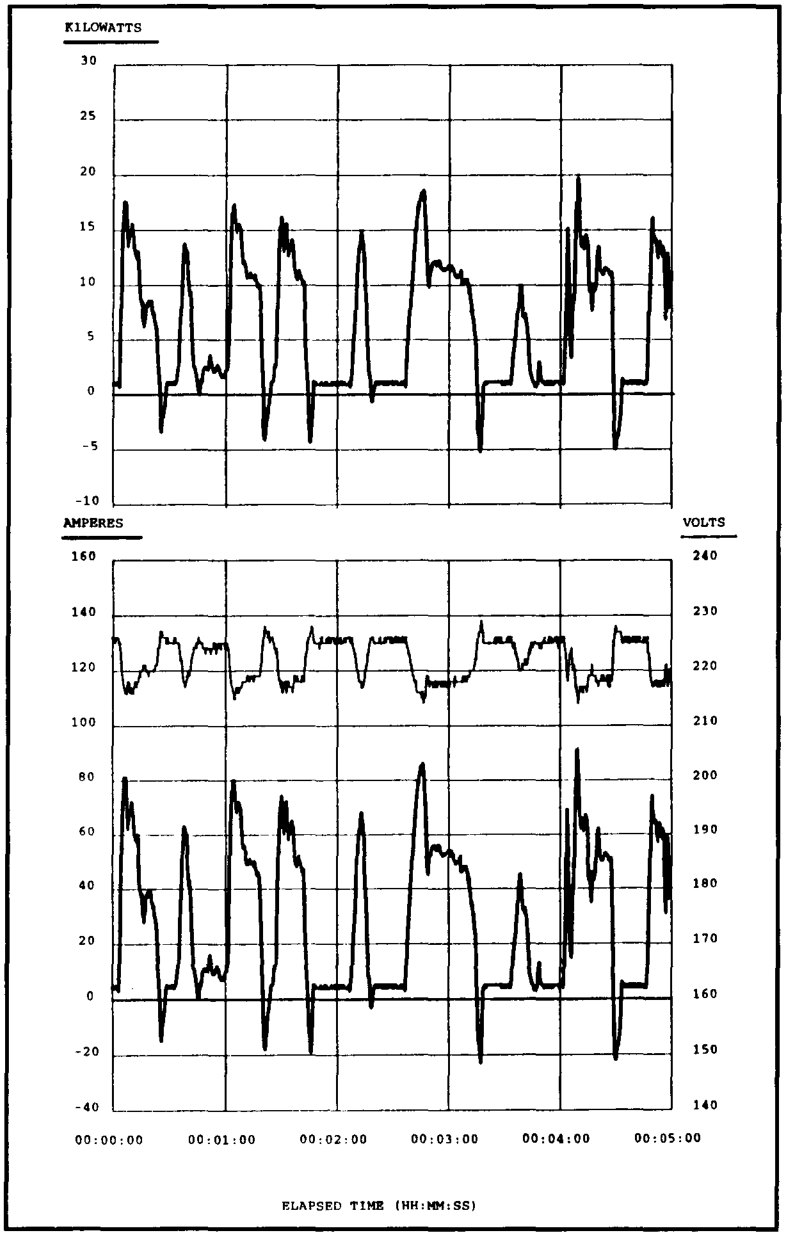
The data acquisition protocol described earlier in Section 3 is performed every day on the electric vehicle fleet. The generated data are subsequently reduced and developed in a computer database in order to yield appropriate and useful information concerning fleet operation. Performance summaries are sorted by route, and sub-sorted by driver and vehicle. Such information management enables the evaluation of issues such as driver energy management performance, the influence of route characteristics and passenger loads on energy consumption, regenerative braking efficiency, battery energy efficiency, and charger efficiency.

Summary sheets of driver energy management and vehicle energy performance are presented in Tables 8 and 9, respectively.[2] A discussion of the various parameters is

[1] Private communication: Jim Miller (Saft) to P. Griffith, February 1995

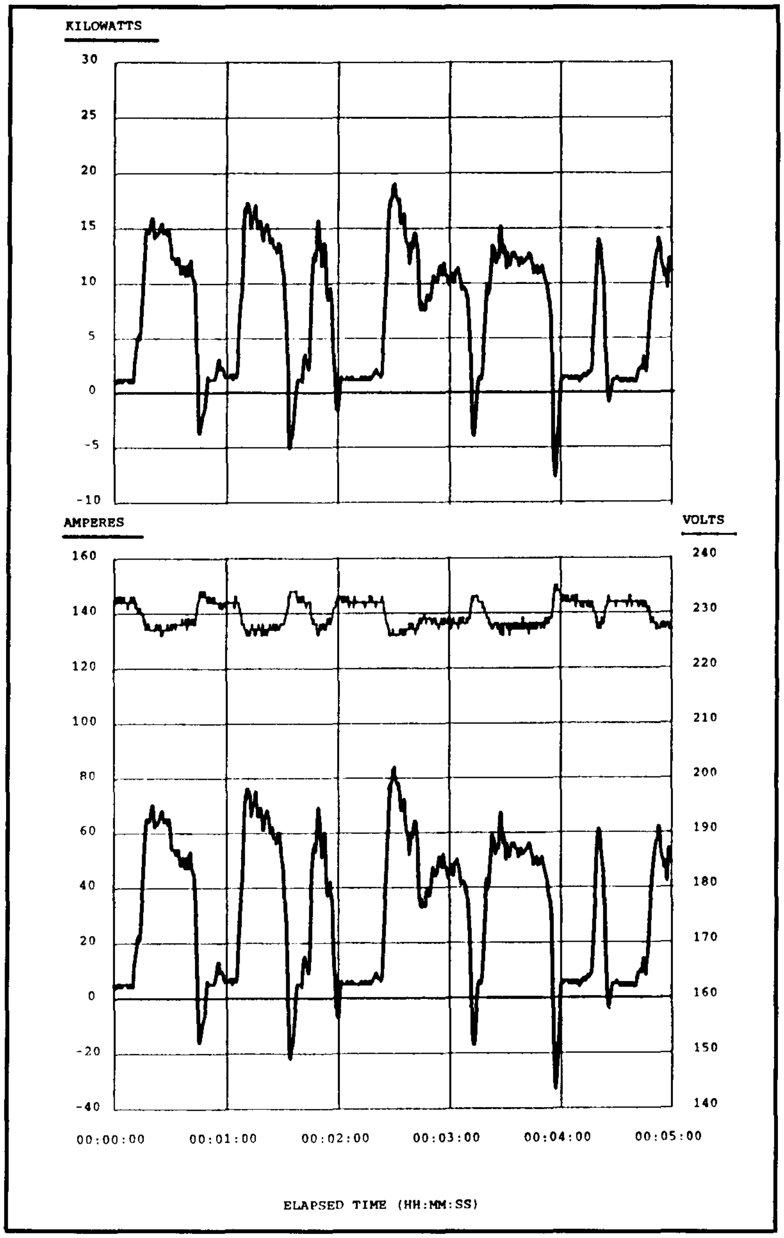
[2] Although the data presented in Table 8 represent actual driver performances, driver names are fictitious.

presented in the following pages. Data developed in these summary sheets are periodically referenced throughout this report.



Source: SBMTD/ETI

Figure 7. Downtown Shuttle Route Power Profile (lead-acid batteries)



Source: SBMTD/ETI

Figure 8. Downtown Shuttle Route Power Profile (Ni-Cd batteries)

Table 8. Driver Energy Management Performance

Route	Driver	Number of Runs	Passengers Carried (per day)	Miles Driven (mi)	Energy Discharged (DC kWh)	(DC kWh/mi)	Energy Regenerated (metered) (DC kWh)	(DC kWh/mi)	Effective Regen Range Extension (%)	Net Energy Used (DC kWh)	Driver Energy Management (DC kWh/mi)	(std. dev.)
Waterfront												
	Belgrade	1	195	50.5	47.0	0.93	16.3	0.32	31%	36.0	0.71	0.00
	Helsinki	20	254	73.3	61.2	0.84	14.2	0.20	21%	50.7	0.70	0.06
	Osaka	40	159	76.0	55.3	0.73	9.4	0.12	15%	48.2	0.63	0.03
	Perth	1	179	78.5	67.3	0.86	13.6	0.17	20%	56.1	0.71	0.00
	Prague	1	161	78.1	64.1	0.82	11.1	0.14	14%	56.2	0.72	0.00
	All Drivers	**63**	**190**	**74.8**	**57.4**	**0.77**	**11.1**	**0.15**	**17%**	**49.0**	**0.66**	**0.05**
Waterfront / CVR extension												
	Athens	10	233	67.8	54.4	0.80	8.8	0.13	13%	48.2	0.71	0.03
	Babylon	32	203	66.4	49.0	0.74	7.5	0.11	12%	43.9	0.66	0.04
	Bangkok	7	286	65.0	50.6	0.78	9.7	0.15	15%	44.1	0.68	0.05
	Hamburg	1	234	66.9	50.6	0.76	9.2	0.14	18%	43.0	0.64	0.00
	Helsinki	11	171	69.3	50.0	0.72	8.7	0.13	13%	44.4	0.64	0.03
	Jerusalem	1	155	66.5	50.2	0.76	9.3	0.14	18%	42.5	0.64	0.00
	Montreal	10	201	64.6	51.9	0.80	10.8	0.17	18%	44.1	0.68	0.05
	Naples	7	294	65.1	52.3	0.81	10.9	0.17	16%	45.2	0.70	0.03
	Osaka	26	161	67.1	49.7	0.74	9.0	0.13	14%	43.5	0.65	0.03
	Reykjavik	2	232	71.4	53.3	0.75	8.2	0.11	11%	48.1	0.67	0.02
	Stuttgart	13	279	67.0	52.2	0.78	10.1	0.15	14%	45.6	0.68	0.03
	Venice	2	137	70.0	50.4	0.72	7.9	0.11	12%	44.8	0.64	0.00
	All Drivers	**122**	**211**	**66.8**	**50.7**	**0.76**	**8.9**	**0.13**	**14%**	**44.6**	**0.67**	**0.04**
Downtown												
	Athens	20	356	42.2	46.5	1.10	9.7	0.23	18%	39.6	0.94	0.06
	Auckland	11	316	40.6	42.5	1.05	8.9	0.22	19%	35.8	0.88	0.04
	Babylon	7	268	44.0	45.7	1.04	8.5	0.19	14%	40.1	0.91	0.03
	Bangkok	20	627	38.8	43.8	1.13	9.2	0.24	18%	37.2	0.96	0.04
	Belgrade	2	116	44.7	48.3	1.08	8.4	0.19	15%	42.0	0.94	0.02
	Bombay	1	187	33.5	37.9	1.13	7.1	0.21	18%	32.0	0.96	0.00
	Cairo	88	474	39.7	41.3	1.04	7.1	0.18	14%	36.3	0.92	0.07
	Calcutta	3	283	45.8	46.9	1.02	10.7	0.23	20%	39.0	0.85	0.03
	Florence	2	196	35.2	36.3	1.03	6.9	0.20	14%	31.9	0.91	0.00
	Frankfurt	5	265	36.9	39.1	1.06	8.2	0.22	17%	33.5	0.91	0.02
	Geneva	74	422	39.1	44.1	1.13	10.1	0.26	19%	37.0	0.95	0.06
	Genoa	1	475	27.9	36.6	1.31	7.3	0.26	13%	32.4	1.16	0.00
	Havana	2	272	42.3	38.4	0.91	7.2	0.17	17%	32.8	0.78	0.02
	Helsinki	53	408	41.1	46.4	1.13	9.8	0.24	17%	39.6	0.96	0.07
	Jericho	32	380	38.9	45.5	1.17	9.8	0.25	18%	38.6	0.99	0.08
	Johannesburg	1	42	36.1	37.4	1.04	7.9	0.22	16%	32.4	0.90	0.00
	Moscow	8	482	35.9	45.3	1.26	9.1	0.25	16%	39.1	1.09	0.07
	Naples	21	580	38.8	47.3	1.22	10.9	0.28	19%	39.7	1.02	0.05
	Osaka	1	331	41.6	46.2	1.11	7.5	0.18	13%	41.0	0.99	0.00
	Paris	1	270	33.2	33.5	1.01	6.1	0.18	13%	29.6	0.89	0.00
	Rome	3	178	39.3	38.4	0.98	6.4	0.16	14%	33.8	0.86	0.01
	Rotterdam	3	339	41.4	45.6	1.10	7.6	0.18	14%	40.0	0.97	0.03
	Seoul	1	84	31.0	36.5	1.18	9.2	0.30	22%	29.9	0.96	0.00
	Stuttgart	61	464	41.2	46.8	1.14	10.4	0.25	18%	39.6	0.97	0.10
	Sydney	23	482	41.3	50.7	1.23	12.4	0.30	22%	41.7	1.01	0.05
	Waikiki	2	362	42.6	53.0	1.24	13.4	0.31	20%	44.3	1.04	0.01
	Waterloo	2	435	39.0	39.9	1.02	7.3	0.19	12%	35.5	0.91	0.02
	All Drivers	**448**	**435**	**40.0**	**44.7**	**1.12**	**9.4**	**0.24**	**17%**	**38.1**	**0.96**	**0.08**
Overall Summary:		**633**	**368**	**48.7**	**47.1**	**1.02**	**9.5**	**0.21**	**17%**	**40.4**	**0.87**	

Source: SBMTD/ETI

Table 9. Vehicle Energy Performance

Route Vehicle	Number of Runs	Miles Driven (mi)	Psngrs Carried (per day)	Energy Discharged (DC kWh)	Energy Discharged (DC kWh/mi)	Energy Regenerated (metered) (DC kWh)	Energy Regenerated (metered) (DC kWh/mi)	Energy Recharged (DC kWh)	Energy Recharged (AC kWh)	Charger AC to DC Efficiency	Battery Energy Efficiency	Effective Regen Range Extension (%)	Net Energy Used (DC kWh)	Energy Consumption (DC kWh/mi)	Energy Consumption (AC kWh/mi)
Waterfront															
EV01 (3SCR/3D)	17	73.0	209	55.6	0.77	11.1	0.16	61.1	63.2	97%	77%	18%	47.1	0.65	0.87
EV02 (ferro)	14	77.1	241	60.8	0.79	13.9	0.18	69.9			73%	20%	50.7	0.66	
EV03 (ferro/ new batt)	10	74.6	183	55.0	0.74	10.4	0.14	63.0			75%	16%	47.2	0.63	
EV04 (ferro)	1	75.0	169	54.2	0.72	9.3	0.12	71.8			67%	13%	48.0	0.64	
EV05 (ferro)	8	71.8	148	52.1	0.73	8.1	0.12	68.3	73.3	93%	68%	12%	46.6	0.65	1.03
EV06 (3SCR/3D/ gel)	4	78.5	122	60.4	0.77	10.4	0.13	63.2	68.7	90%	82%	16%	51.8	0.66	0.88
EV07 (ferro)	1	71.9	175	55.2	0.77	12.5	0.17	58.4	61.0	96%	78%	21%	45.4	0.63	0.85
EV09 (12SCR/ 60A)	3	77.3	171	59.3	0.77	9.2	0.12	65.2	72.5	89%	80%	14%	51.9	0.67	0.94
EV10 (12SCR)	5	76.0	138	64.3	0.85	11.8	0.15	74.3	81.8	91%	75%	16%	55.6	0.73	1.07
All Vehicles	**63**	**74.8**	**190**	**57.4**	**0.77**	**11.1**	**0.15**	**65.8**	**68.6**	**94%**	**75%**	**17%**	**49.0**	**0.66**	**0.93**
Waterfront / CVR extension															
EV01 (3SCR/3D)	10	65.9	183	50.5	0.77	10.4	0.16	55.9	61.2	94%	76%	19%	42.6	0.65	0.93
EV01 (Spgl ferro)	1	64.0	197	47.5	0.74	8.1	0.13	59.7			70%	14%	41.8	0.65	
EV02 (ferro)	2	68.0	167	47.9	0.70	9.9	0.15	57.1			72%	17%	40.8	0.60	
EV03 (ferro)	10	65.0	196	46.2	0.71	8.1	0.12	66.4			62%	12%	41.2	0.63	
EV03 (ferro/ new batt)	6	68.2	297	49.1	0.72	8.8	0.13	59.6			72%	15%	42.8	0.63	
EV04 (ferro)	6	67.0	271	51.2	0.76	9.6	0.14	69.6			65%	14%	44.9	0.67	
EV05 (ferro)	19	68.3	214	50.7	0.74	9.2	0.13	71.5	74.6	96%	63%	13%	44.9	0.66	1.09
EV06 (3SCR/3D/ gel)	9	67.1	204	53.9	0.80	10.5	0.16	55.1	62.4	89%	82%	19%	45.2	0.67	0.93
EV07 (ferro)	19	68.0	186	49.6	0.73	9.3	0.14	62.2	63.3	98%	70%	15%	43.1	0.63	0.94
EV08 (ferro)	34	65.6	206	51.6	0.79	7.9	0.12	72.5			64%	11%	46.5	0.71	
EV09 (12SCR/ 50A)	6	68.3	265	54.1	0.79	8.7	0.13	66.7	73.5	91%	72%	13%	47.9	0.70	1.04
All Vehicles	**122**	**66.8**	**211**	**50.7**	**0.76**	**8.9**	**0.13**	**66.2**	**67.6**	**96%**	**68%**	**14%**	**44.6**	**0.67**	**1.00**
Downtown															
EV01 (3SCR/3D)	7	41.1	564	51.0	1.24	13.6	0.33	52.8	54.7	94%	77%	26%	40.6	0.99	1.35
EV01 (Spgl ferro)	7	37.5	556	46.1	1.24	12.0	0.32	54.2			69%	22%	37.7	1.01	
EV02 (ferro)	42	39.5	509	44.5	1.14	11.9	0.30	49.5			72%	24%	35.9	0.92	
EV03 (ferro)	4	35.5	536	40.1	1.14	8.7	0.25	58.4			60%	15%	34.9	1.00	
EV03 (ferro/ new batt)	29	38.5	475	42.9	1.13	8.9	0.23	49.1			74%	18%	36.3	0.96	
EV04 (ferro)	51	40.4	454	43.5	1.08	9.3	0.23	62.1			61%	15%	37.8	0.94	
EV05 (ferro)	102	40.6	395	44.6	1.10	8.8	0.22	61.7	65.1	94%	63%	14%	39.0	0.97	1.61
EV05 (Spgl ferro)	1	47.6	347	51.5	1.08	10.7	0.22	64.2			69%	17%	44.2	0.93	
EV06 (3SCR/3D/ gel)	53	40.9	479	48.3	1.18	10.3	0.25	47.8	53.8	89%	83%	21%	39.8	0.97	1.32
EV07 (ferro)	59	40.0	426	43.4	1.09	9.6	0.24	54.3	55.8	97%	68%	18%	36.9	0.92	1.40
EV08 (ferro)	30	39.1	420	44.2	1.13	8.6	0.22	61.1	52.0	94%	64%	14%	38.7	0.99	1.31
EV09 (12SCR/ 50A)	2	40.8	506	49.9	1.23	9.7	0.24	56.8			75%	17%	42.6	1.05	
EV09 (12SCR/ 60A)	40	40.0	375	44.9	1.13	7.5	0.19	48.8	55.7	88%	80%	15%	39.0	0.98	1.42
EV10 (12SCR)	21	39.8	334	43.5	1.09	8.7	0.22	48.8	54.1	90%	76%	18%	36.9	0.93	1.35
All Vehicles	**448**	**40.0**	**435**	**44.7**	**1.12**	**9.4**	**0.24**	**55.1**	**59.1**	**93%**	**70%**	**17%**	**38.1**	**0.96**	**1.47**
Overall Summary:	**633**	**48.7**	**368**	**47.1**	**1.02**	**9.5**	**0.21**	**58.3**	**61.4**	**94%**	**70%**	**17%**	**40.4**	**0.87**	**1.34**

Source: SBMTD/ETI

"*Number of runs*" represents the number of daily driving runs that comprise the line-item averages. In Table 8, for example, a "20" count in the "Number of Runs" column means that the line-item average is comprised of 20 runs that the subject driver performed on the subject route. Due care should be exercised when drawing conclusions from data records with low number of runs. In these cases, each daily record must be evaluated in order to ascertain that the variance levels associated with the parameters of interest are such that statistical significance is present.

"*Passengers carried*" represents the average daily passenger load associated with the line-item data.

"*Miles driven*" represents the average daily mileage associated with the line-item data.

"*Energy discharged*" represents the DC kWh flow from the traction battery to the motor during vehicle motoring. This data, expressed as an average per run, is presented on both absolute and per mile bases.

"*Energy regenerated*" represents the metered DC kWh flow from the motor to the traction battery during periods in which the motor acts as a generator to retard vehicle motion (regenerative braking). This data, expressed as an average per run, is presented on both absolute and per mile bases. It is important to bear in mind that metered regenerative energy does not represent usable energy because the electrical energy must be converted to chemical energy and back again to electrical energy (round trip path through the battery) prior to re-utilization. Such an energy path is subject to the inefficiencies attendant to the conversion processes, thereby reducing the magnitude of energy recovered.

"*Battery energy efficiency*" is the ratio of the energy delivered by a battery during discharge to the total energy required to restore it to a full state-of-charge condition, and can be derived from a simplified energy balance equation. If a discharge/charge cycle begins and ends at the same battery state-of-charge, then

$$Energy_{out} = Energy_{in}$$

$$DC\ kWh_{discharge} = (DC\ kWh_{regen}) \times (\eta_{regen}) + (DC\ kWh_{recharge}) \times (\eta_{recharge})$$

where:

η_{regen} = round trip energy efficiency under regenerative braking energy input

$\eta_{recharge}$ = round trip energy efficiency under recharge energy input

"*Charger AC to DC efficiency*" is the ratio of the DC energy output from a charger to the AC energy consumed by the charger. The rectification of the alternating-current signal (as is supplied by the electric power grid) to one of direct-current (as is required to accomplish battery recharge) is accompanied by energy conversion into heat, thereby yielding an efficiency ratio of less than unity.

"*Effective regen range extension*" is a measure of the elongation in vehicle range attributable to regenerative braking. Range extension is expressed as the ratio of recovered regenerative braking energy to battery energy discharged:

$$\text{Range Extension}_{\text{regen}} = \frac{DC\ kWh_{\text{regen}} \times \eta_{\text{regen}}}{DC\ kWh_{\text{discharge}} - (DC\ kWh_{\text{regen}} \times \eta_{\text{regen}})}$$

Metered regen energy must always be multiplied by battery energy efficiency prior to analysis in order to calculate in terms of recovered energy. The denominator is reduced by recovered regen energy in order to express energy discharged in terms of that energy originally stored in the battery after recharge; such compensation accommodates the recurring marginal recovery of previously recovered regenerative energy.

"*Net energy used*" is a measure of the net energy discharged from the batteries, and is calculated by subtracting recovered regen energy from energy discharged.

"*Driver energy management*" is derived by dividing the net energy consumption by the miles driven, and is a measure of the energy efficiency with which the vehicle was driven (the lower the value, the more efficient the performance). Standard deviation is a statistical measure of the variance of the data records that comprise the set, and is expressed as one sigma (a variance of plus or minus one sigma will capture 65% of a normal Gaussian distribution, and plus or minus two sigma will capture 95% of the data set).

"*Energy consumption*" is only provided on the vehicle energy performance summary sheet, and is expressed in terms of both DC and AC energy consumption per mile driven. The AC kWh consumption represents the AC energy required by the vehicle system (including charger and battery inefficiencies), and together with the electric rate determines "refueling" cost.

As can be seen from the summary sheets, MTD's Waterfront and Downtown routes result in average daily vehicle mileage of 75 and 40 miles, respectively. Energy consumption on the Downtown route is almost 45% higher than that on the Waterfront route on a per-mile basis, however, because of the increased stop/start frequency and the presence of a modest gradient. The result is an average net discharge of 49.0 DC kWh per day on the Waterfront route, and 38.1 DC kWh per day on the Downtown route.

4.6 IMPORTANCE OF DRIVER TRAINING

The high energy content of fossil fuels affords the diesel bus operator an abundance of on-board energy. Consequently, relatively little attention is given to issues such as driver energy management of diesel powered buses. In comparison, the present development status of energy storage devices available to battery-electric vehicles renders on-board energy a precious commodity that must be carefully managed. MTD experience has shown that driver energy management performance can vary by up to 50%, depending upon route characteristics. Therefore, the implementation of appropriate driver training can be critical to the success of any given operation.

Referring to Table 8, it is evident that driver-to-driver variances are relatively small among most MTD drivers. Occasionally, however, operational circumstances necessitate that an electric bus be operated by a driver who is regularly assigned to diesel bus operation. Although all such occurrences are filled by drivers who have received training in electric bus operation, infrequent assignment to electric bus operation can result in the deterioration of EV driving skills.

A case in point is the performance of Driver "Genoa" on the Downtown route. "Genoa", who predominantly drives a diesel bus, delivered a 1.16 DC kWh/mi energy management performance as a substitute driver. This consumption level exceeds the highest single-day consumption performance of all but one other driver. It represents a 21% increase over the average route performance for all drivers, and a 49% increase over the most efficient average performance. "Moscow" is another driver who has exhibited a statistically significant elevation in energy consumption rate on the Downtown route (14% higher than the average for all drivers). MTD regularly tracks the energy consumption performance of all drivers, and provides focused refresher training as circumstances dictate. It should be stressed that the relatively low variances in driver-to-driver performance and driver day-to-day performance are a direct result of the excellent driver training program in place at MTD.

Electric-bus energy consumption can be beneficially influenced by the driver's management of vehicle acceleration and deceleration rates. It is important that the driver refrain from initiating unnecessarily high acceleration rates and corresponding high motor current. Deceleration should be effected at moderate rates in order to minimize the burst nature of the regenerative energy, thereby delivering energy to the battery over the longest possible time period.

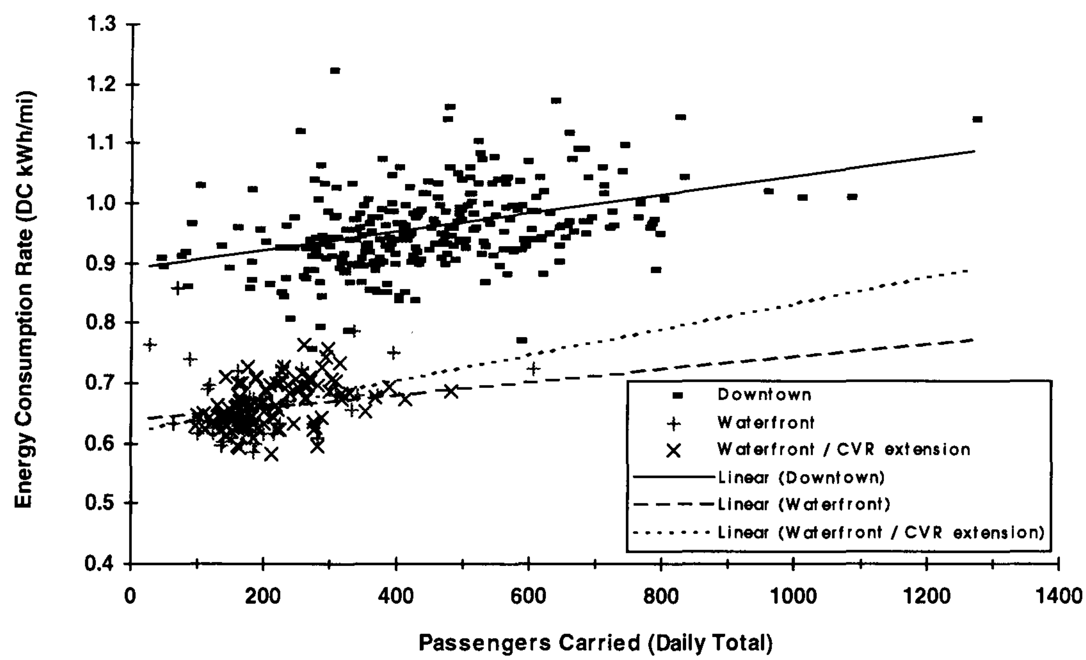
Depression of the accelerator pedal in a diesel bus is frequently followed by a brief delay in acceleration response. The natural tendency of the driver is to compensate for the inherently sluggish response by effecting greater pedal displacement than is otherwise necessary in order to achieve faster acceleration response. The electric propulsion systems of the MTD battery-electric fleet exhibit quicker acceleration response than the diesel counterparts, however, and the driver must therefore become accustomed to making correspondingly smaller pedal modulations to avoid unnecessarily high discharge currents.

In order to further maximize the benefits derived from driver training, MTD initiated an addendum to the driver union contract which stipulates that drivers who wish to drive EVs have the opportunity to do so for a period of at least one year. The contract also provides MTD with the authority to reassign drivers to the diesel fleet if they demonstrate driving patterns that are incompatible with good energy management, however. The objective of this policy is to ensure that the investment in EV driver training is applied to the greatest extent possible, and to establish continuity of EV driving habits.

The procurement costs associated with the use of advanced battery chemistries to achieve the foregoing referenced performance increases amount to tens of thousands of dollars. It is therefore clear that the economics of electric vehicle technology are such that performance increases derived from reductions in the rate of energy consumption are far more cost effective than those obtained by increases in available energy.

4.7 INFLUENCE OF PASSENGER LOAD ON ENERGY REQUIREMENTS

One of the initial uncertainties of the electric vehicle operation concerned the sensitivity of energy consumption to variations in passenger load. A graphical representation of the resulting dependency is illustrated in Figure 9, which plots daily energy consumption rates versus daily passenger load carried. Linear-regression trendlines (least squares method) have been superimposed over the data sets. The data scatter shows that vehicle energy consumption is less sensitive to the passenger load range experienced with MTD's electric shuttle service than it is to other influences, such as route characteristics and driver energy-management skill levels.



Source: SBMTD/ETI

Figure 9. Energy Consumption Rate vs. Passenger Load

4.8 INFLUENCE OF VEHICLE ACCESSORIES ON ENERGY REQUIREMENTS

The use of energy consuming accessories on MTD's battery-electric fleet is minimized to the greatest extent possible. For example, leaf spring suspension is employed rather that compressor driven, active suspension systems on the majority of the electric fleet. Energy consuming accessories present on MTD battery-electric shuttle vehicles consist primarily of windshield wipers, lights, and a hydraulic pump that serves the power brake and power steering systems; two of the shuttles also incorporate driver compartment heaters. In addition, the two other MTD electric buses are equipped with hydraulic-electric doors, and the electrified Villager bus utilizes an air compressor in conjunction with an air suspension system. The door, hydraulic pump and air compressor all operate on a regular, intermittent schedule; associated energy consumption is an inevitable, ongoing consequence of the daily operation. Operation of windshield wipers and exterior/interior lighting is seasonally influenced, however, and the associated energy usage is therefore sporadically incurred; the related energy consumption therefore becomes a matter of interest in order to determine the potential for periods of heavy usage to unfavorably influence vehicle range.

Virtually all vehicle accessories, including wipers and lighting, operate on the low voltage system (typically either 12V or 24V). Data collected during power monitoring of accessory loads in the electric shuttle vehicle are presented in Table 10. Given that the shuttles demonstrate an average power load of 5.0 kW (system average of 40 kWh consumed in 8 hours of service), the increase in energy consumption due to continuous windshield-wiper operation is approximately 1%, and that of continuous lighting operation is approximately 7%. Because wiper and light operation periods are usually restricted to only a portion of the service period, their operation has a relatively inconsequential impact on overall energy consumption, and hence range.

Table 10. Accessory Power Loads

Accessory	Current Load	Voltage	Power	Percentage Increase in Average Motoring Power Load[3]
Headlamps, marker lights	17 A	13 V	0.221 kW	4.4%
Interior Lights	10 A	13 V	0.130 kW	2.6%
Windshield Wipers - low speed	4 A	13 V	0.052 kW	1.0%
- high speed	6 A	13 V	0.078 kW	1.6%
Driver Compartment Heater	10 A	229 V	2.290 kW	45.8%
Heater Fan - low speed	5 A	13 V	0.065 kW	1.3%
Heater Fan - high speed	17 A	13 V	0.221 kW	4.4%

Source: SBMTD/ETI

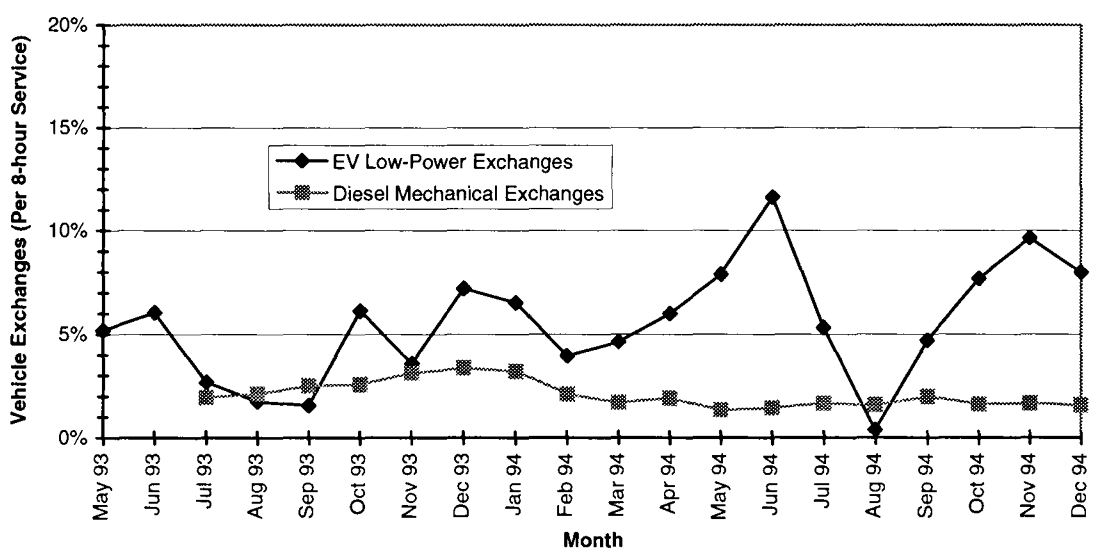
[3] Based on average motoring power load of 5.0 kW (40 kWh / 8 hours of service)

Santa Barbara's temperate climate renders bus air-conditioning systems non-essential; no vehicles in MTD's bus fleet, electric or diesel, are equipped with air-conditioning. Vehicle heating systems are present on MTD's diesel-powered vehicles, but not on the battery-electric vehicles. The relatively small driver-compartment heater and fan on the shuttle vehicle increase vehicle energy consumption by approximately 50%. Further discussion concerning heating and air conditioning systems is presented in Section 10.

4.9 Frequency of Vehicle Low-Power Events

Occasionally, during the course of normal route service, a bus does not possess sufficient remaining energy to complete its usual mission. The causes of such occurrences include deficient battery cell(s), an excessive energy consumption rate, incomplete battery recharge the previous night, and cold-temperature operation. These occurrences usually manifest as low-power events which necessitate an exchange of vehicles. Such events have an obviously undesirable impact on passenger convenience and cost of operation, and so the successful battery-electric transit operation will structure battery capacity, mission requirements, driver training, and maintenance operations such that low-power occurrences are minimized.

A plot of the frequency of electric vehicle exchanges due to low-power conditions is presented in Figure 10. This information is expressed as the ratio of vehicle exchanges per number of eight-hour service periods. As a reference, the frequency of road calls due to mechanical failures of MTD's diesel fleet per eight-hour service period is also included for comparison (mechanical failures exclude those involving fare box, radio, lift, tires, fuel, or accidents).



Source: SBMTD/ETI

Figure 10. Frequency of Vehicle Exchanges

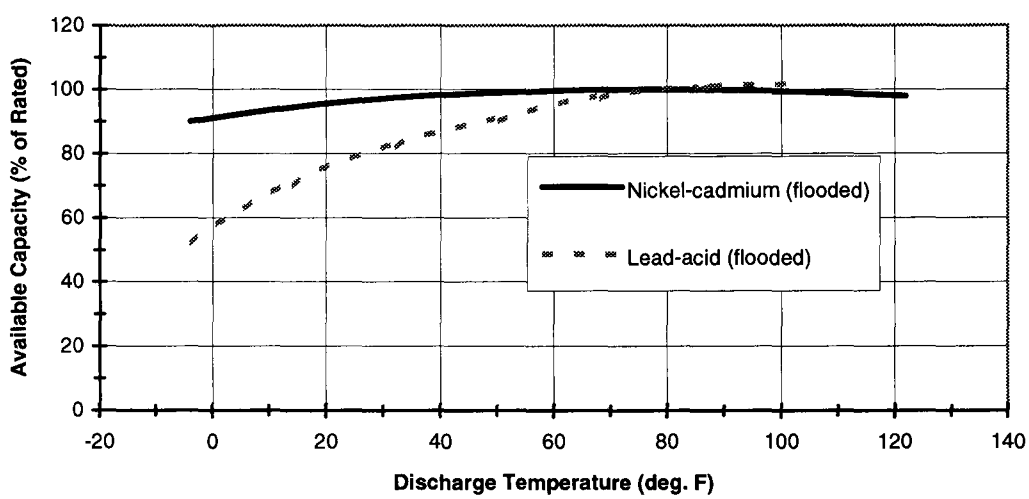
It is evident from these data that there is a higher overall incidence of electric vehicle exchanges than is experienced with the diesel fleet. It is interesting to note, however, that virtually all exchanges associated with the electric fleet are low-power oriented; the rest of the propulsion system has proven to be extremely reliable. The gradual upward trend in the frequency of low-power events is believed to be a natural progression of an increasing number of cycles on fleet batteries.

It is anticipated that future availability of advanced performance batteries will permit fleet operation with greater margins between required energy and available energy, thereby reducing the incidence of low-power events.

4.10 INFLUENCE OF COLD WEATHER ON VEHICLE LOW-POWER EVENTS

The ability of a chemical battery both to store and discharge energy is dependent upon the temperature at which the recharge and discharge events are undertaken. This dependency of the chemical reactions on electrolyte and electrode temperature manifests as a diminution of available energy as battery temperature deviates from standard conditions.

For example, the relationship between deliverable energy and battery discharge temperature for two of the battery products in use at MTD is presented in Figure 11. This data assumes that batteries have been fully charged under standard temperature conditions, and that energy is discharged at the C/5 rate.[4] It is evident from these data that the Ni-Cd chemistry retains its ability to deliver energy at low temperatures better than does the lead-acid chemistry.



Source: Chloride Motive Power, Saft, SBMTD/ETI

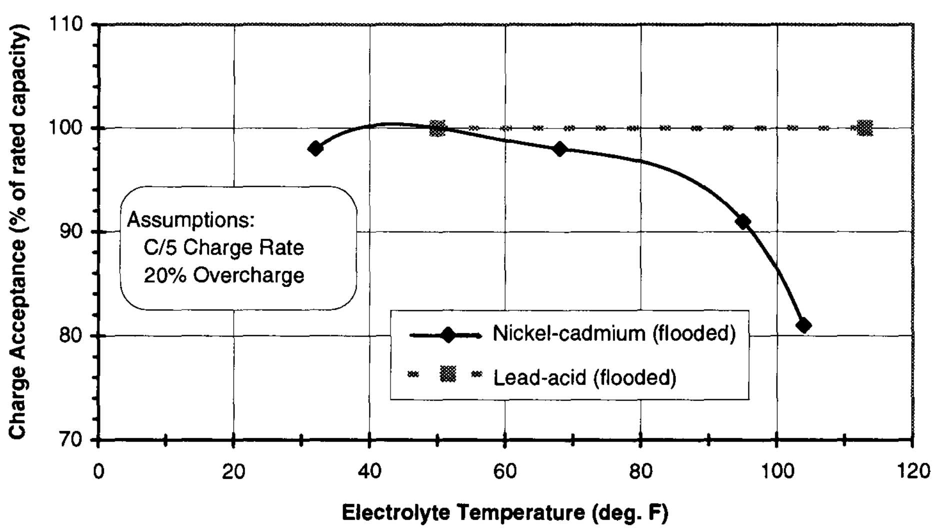
Figure 11. Available Energy Capacity vs. Discharge Temperature

[4] See Section 6.2 for definition of C-rate

Santa Barbara's temperate climate does not produce extreme temperature swings. As a result, the incidence of vehicle low-power events is largely independent of seasonal temperature variations, as is evident from Figure 10. However, operations in geographic regions for which colder temperatures are inevitable will more than likely experience measurable reductions in vehicle energy at the lower temperatures; successful integration of battery-electric transit in these regions will require the acknowledgment and accommodation of such influences.

4.11 CHARGE ACCEPTANCE AS A FUNCTION OF TEMPERATURE

Because both the discharge and recharge processes for batteries are exothermic (produce heat), battery temperature increases during usage. The ability of a battery to accept recharge is a function of the battery's internal temperature. Among the batteries in service at MTD, the nickel-cadmium chemistry produces the most heat during operation, and the chargeability of the nickel-cadmium product exhibits the highest sensitivity to battery temperature (Figure 12). Battery health can also be adversely affected by charging the Ni-Cd product at high temperatures. For this reason, the temperature of the Ni-Cd battery is monitored during recharge by the charger in order to adjust the charge profile to accommodate temperature concerns. In addition, thermal management is required for the Ni-Cd battery in order to maintain battery temperature within prescribed levels. There is no measurable increase in the temperature of a flooded lead-acid battery at discharge rates of C/5 or slower, and only slight temperature increase at faster discharge rates.[5]



Source: Chloride Motive Power, Saft, SBMTD/ETI

Figure 12. Battery Charge Acceptance vs. Electrolyte Temperature

[5] Private communication: K.D. Merz (Chloride Motive Power) to P. Griffith, April 1995

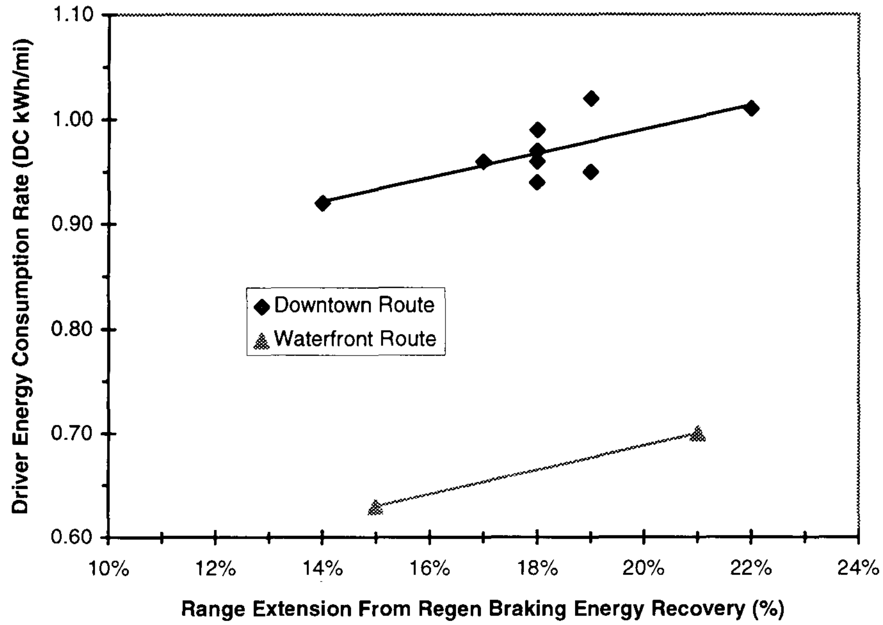
4.12 Range Extension Due to Regenerative Braking

Vehicle range is extended during coasting and braking by means of automatic operation of the motor as a generator, thereby producing electrical power while providing retardation of motion. The implementation of regenerative braking during coasting creates a sensation similar to the "compression braking" experienced with internal combustion engines during coasting operation. The utilization of electromagnetic force to impede vehicle motion also provides the added benefit of extending the life of the mechanical braking system (further discussion of this effect is provided in Section 5.9). The greatest benefit of regenerative braking, given the relatively limited on-board energy storage capacity, is the extension of vehicle operating range achieved through periodic battery recharge.

In order to determine the recoverable component of metered regenerative braking energy, it is necessary to establish the round-trip efficiency with which the battery accepts the regenerative charge. This was accomplished by operation of a vehicle for several days with regenerative braking disabled, and comparing the resulting battery energy efficiency under battery charger recharge only against that under a mix of both regen recharge and charger recharge. The results indicated that battery energy efficiency is within 1 or 2% for both cases. Therefore, the algorithms used in this report for the determination of range extension due to regenerative braking assume a round-trip efficiency equal to that under conventional recharge conditions. Although such an assumption introduces some sources of error, it is believed that the adopted method presents a reasonable first-order approximation.

It is interesting to note by reference to Table 8 that the drivers who experience the greatest benefit from regenerative braking do not necessarily perform at the most favorable energy management level. A case in point is the comparison of the performances of Driver "Naples" and Driver "Cairo" on the Downtown route. Although "Naples" recovers more regenerative energy than does "Cairo" (19% vs. 14%), his corresponding energy consumption is less favorable (1.02 DC kWh/ mile vs. 0.92 DC kWh/mile). Such a phenomenon can occur because a less efficient driver converts more chemical potential energy into kinetic energy than necessary, which must then be dissipated by braking, thereby increasing the potential regenerative yield. Unnecessary conversion of energy from chemical to electrical to kinetic formats, and the subsequent reconversion along the reverse path during regenerative braking are inherently inefficient processes and thereby reduce overall efficiency.

The relationship between driver energy consumption rate and regenerative energy recovery rate is presented in Figure 13 for all drivers with twenty or more runs on a given route. Linear regression trendlines (least squares method) have been superimposed over the data. The data is suggestive of an inverse correlation between driver energy management efficiency and regen energy recovery (i.e., drivers with the highest percentage recovery of regenerative braking energy exhibit the poorest overall energy management). The similarity in the slopes of the trendlines for the two routes may be noted.

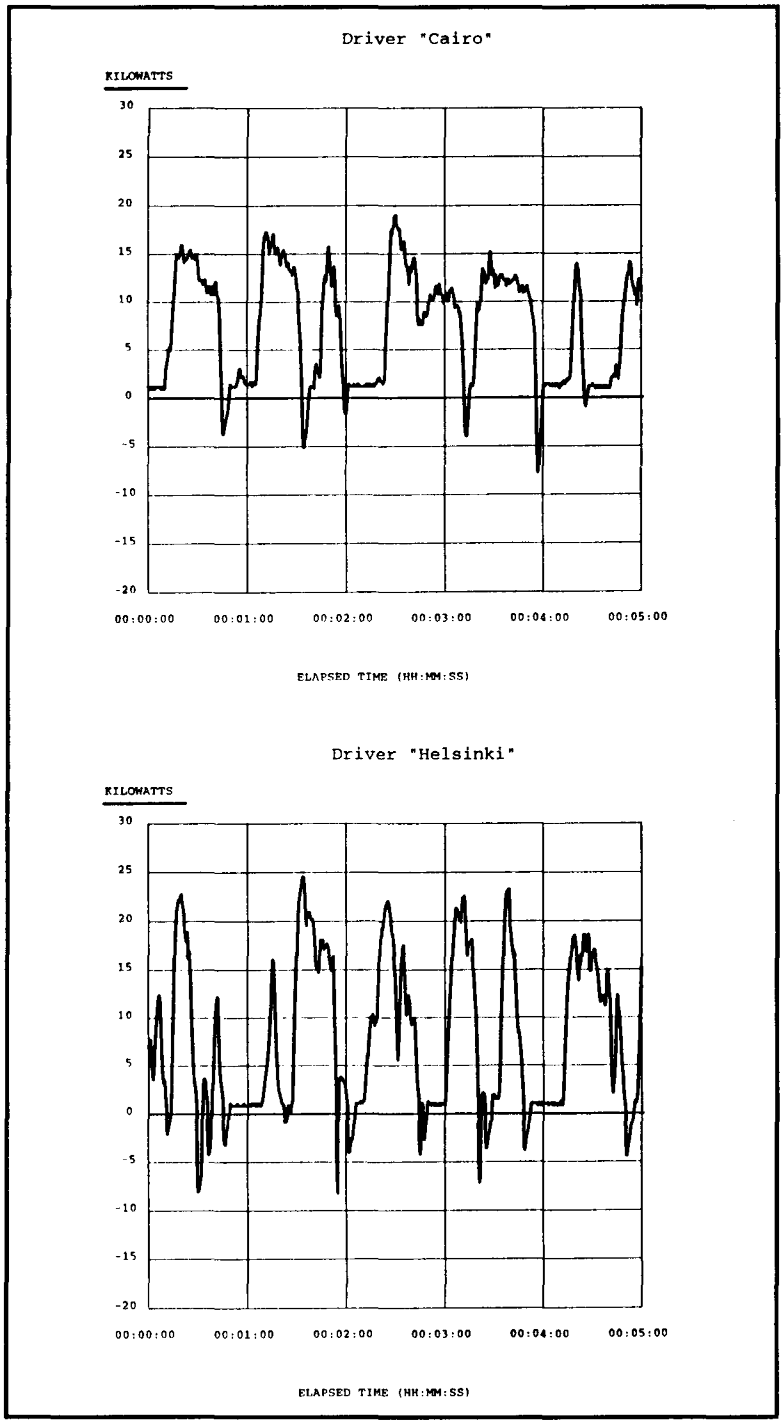


Source: SBMTD/ETI

Figure 13. Driver Energy Consumption Rate vs. Regen Energy Recovery

The relationship between energy consumption rate and regenerative energy recovery can be further illustrated by an examination of driver power profiles on the same route component (Figure 14). Driver "Cairo" exhibits a more favorable net energy consumption rate than Driver "Helsinki" (0.92 vs 0.96 DC kWh/mile), but a lower regen recovery (14% vs. 17%). "Helsinki" draws more energy from the battery during vehicle acceleration than does "Cairo", and consequently develops excess vehicle energy that must be dissipated by braking, as is evidenced by a two-fold increase in braking frequency.

Prior to leaving the subject of regenerative braking, a word concerning its compatibility with maintenance-free, valve-regulated (VRLA) batteries is in order. VRLA batteries are less abuse-tolerant than their flooded counterparts, and can be damaged by overcharge conditions. Consequently, many battery experts believe that the high recharge currents associated with regenerative braking can damage a fully charged VRLA battery. For applications that employ VRLA technology, it may therefore be necessary to disable regenerative braking at high battery states-of-charge to prevent premature battery degradation. MTD is presently evaluating this issue.



Source: SBMTD/ETI

Figure 14. Driver Power Profiles

4.13 Battery Recharge Protocol

MTD's fleet of battery-electric buses are recharged at night in order to take advantage of the most favorable utility rates. Each vehicle has its own dedicated charger and charge station. All vehicles, regardless of whether they have provided service on any given day, are coupled to their chargers by a utility worker or mechanic in the late evening. Battery charging is automatically initiated by timer at midnight. Once the integrity of the charge initiation process is confirmed (i.e., no blown fuses or tripped breaker switches), the process continues unsupervised. All chargers in use at MTD are of the self-terminating variety, and automatically power-down when the battery has achieved full state-of-charge. Naturally, if a vehicle has not been used in service on any particular day, charge termination occurs after relatively little recharge energy is delivered.

An equalization charge consists of a regular charge that is extended until all the cells in a battery system reach a common charge condition. Such an effort is undertaken approximately once per month, or whenever the open-circuit battery voltage subsequent to charge termination averages less than 2.13 volts per cell.

The MTD charging facility consists of a canopy-covered, "open-shed" structure. Such an arrangement assures ample ventilation to achieve adequate dispersal of the gases evolved during the battery-recharge process. Hydrogen gas is explosive, and an atmosphere of enriched oxygen greatly enhances any combustion process. The gases released during recharge are also accompanied by a sulfuric acid mist that can be injurious to human health if allowed to accumulate. Prolonged exposure to pure oxygen is also known to produce deleterious health effects, although it is unlikely that problematic concentrations would be present even if charging were conducted within an enclosed space.

4.14 Existing Electric Rate Schedule

Electricity consumed at the MTD charging facility is subject to rate-schedule payment known as "Time-Of-Use, General Service, Super Off-Peak demand metered " (TOU-GS-SOP).[6] Presently, this rate schedule results in the most favorable off-peak electricity cost available from Southern California Edison. The rate schedule includes a fixed "customer charge" of $72.05 per month, and variable cost components based upon time-of-day, time-of-season usage, as presented in Table 11.

Table 11. Charging Facility Electric Rate Schedule - Variable Cost Components

Energy Charge			Demand Charge			
On-Peak	Mid-Peak	Super Off-Peak	Non-Time Related	On-Peak	Mid-Peak	Super Off-Peak
$0.10072/kWh	$0.06281/kWh smr $0.06347/kWh wntr	$0.02864/kWh	$6.30/kW	$41.10/kW	$1.10/kW smr $0.50/kW wntr	$0.00/kW

Notes: Super Off-Peak: Midnight to 6:00 am all year, everyday
On-Peak: 1:00 pm to 5:00 pm, summer weekdays except holidays
Mid-Peak: All other hours - all year, everyday

Source: SCE, SBMTD/ETI

The cost of electric vehicle recharging under this rate schedule is dependent upon the number of kWh's consumed during each time-of-use period ("energy charge"), and the

[6]Revised California PUC Sheets No. 17507-E, 16787-E, 17508-E, 16789-E, 16790-E, 16791-E, Southern California Edison.

maximum rate at which energy is drawn (power or "demand charge"), both overall and during each time-of-use period.

Electric vehicle charging at MTD is generally conducted between midnight and 6:00 a.m., although charger operation occasionally occurs outside this period because of equipment testing and check-out. Recharge during the "super off-peak" period results in the most favorable energy rates. The typical electric bill is comprised of the elements and monthly charges depicted in Table 12. It may be noted from Table 12 that the demand charge is a substantial component of the cost of electricity under the present rate schedule.

Table 12. Nighttime Fleet Recharge Cost Under TOU-GS-SOP Rate Schedule

Customer Charge			
per month			$72
Energy Charge			
typical number of vehicles charged per day	9		
typical AC energy consumed per recharge	63 AC kWh		
typical days per billing period	30		
Total Energy Consumed	17,010 AC kWh	@ $0.02864/kWh	$487
Demand Charge			
chargers subject to simultaneous, full start-up	10		
average initial demand, each charger	14 kW		
Maximum Demand	140 kW	@ $6.30/kW	$882
Total Bill			
total kWh	17,010 AC kWh		$1,441
Cost per kWh			8.5¢

Source: SBMTD/ETI

This rate schedule also carries with it a power-factor adjustment rate if maximum demand exceeds 200 kW for three consecutive months. The rate adjustment under such circumstances consists of a billing increase of 25 cents “per kilovar of maximum reactive demand”, as determined by multiplying the kilowatts of measured maximum demand by the ratio of kilovar-hours to kilowatt-hours. MTD usage has not yet required the imposition of such an adjustment.

4.15 PROPOSED ELECTRIC RATE SCHEDULE

Southern California Edison has filed an application with the California Public Utilities Commission (PUC) for the introduction of rate schedules specific to electric vehicle recharging. It is anticipated that the PUC will make a determination concerning this request by the summer of 1995. Proposed schedule TOU-EV-3 [7] would apply to general

[7] Private communication: Deepak Nanda (Southern California Edison) to P. Griffith, January 1995

service time-of-use charging; a separate schedule would apply to residential EV charging. Schedule TOU-EV-3, which would eliminate demand billing and the "mid-peak" period, is presented in Table 13.

Table 13. Proposed Rate Schedule TOU-EV-3

	Summer	Winter
Customer Charge (per meter per day)	$0.43000	$0.43000
TOU Meter Charge (per meter per day)	$0.16700	$0.16700
Energy Charge		
All On-Peak kWh (per kWh)	$0.28512	$0.07631
All Off-Peak kWh (per kWh)	$0.04000	$0.04340

Notes: On-Peak: Noon to 9:00 pm all year, every day
Off-Peak: All other hours - all year, every day
Summer: 12:00 am, June 1 through 12:00 am, October 1
Winter: All other months

Source: SCE, SBMTD/ETI

It may be noted that under the proposed schedule the period of most favorable rates ("off-peak") has been expanded as compared to the present rate schedule, thereby allowing for charge initiation at 9:00 pm as opposed to midnight. Also, a power-factor adjustment rate apparently is not contemplated. The projected costs associated with MTD electric vehicle recharging under the proposed schedule is presented in Table 14, and results in an average cost of 4.3¢ per kWh, as compared with 8.5¢ under the current schedule (a 50% cost reduction).

Table 14. Nighttime Fleet Recharge Cost Under Proposed TOU-EV-3 Rate Schedule

Customer Charge			
per month			$13
TOU Meter Charge			
per month			$5
Energy Charge			
typical number of vehicles charged per day	9		
typical AC energy consumed per recharge	63 AC kWh		
typical days per billing period	30		
Total Energy Consumed	17,010 AC kWh	@ $0.04227/kWh (1)	$719
Total Bill			
total kWh	17,010 AC kWh		$737
Cost per kWh			4.3¢

(1). Weighted Seasonal Average

Source: SBMTD/ETI

4.16 "FUEL" COSTS

The cost of recharging an electric vehicle per mile driven is dependent upon the cost of electricity and the AC energy consumption rate. The energy consumption rate is in turn a function of such factors as vehicle weight, road/load characteristics, energy conversion efficiencies, and driver energy-management skill. For the MTD electric shuttle application, electric "fuel" is consumed at an average rate of 1.35 AC kWh per mile. At the present cost of 8.5¢ per AC kWh, the cost of "refueling" the electric shuttle fleet is 11.5¢ per mile. This cost is, of course, subject to reduction in proportion to changes in the cost of electricity. For example, at the 4.3¢ per AC kWh of the proposed rate before the PUC, the "refueling" cost for the electric shuttle fleet would be 5.8¢ per mile instead of the present 11.5¢ level.

By comparison, the diesel-powered Villager buses, which the electric shuttles replaced on the Downtown-Waterfront route, travel an average of 5.8 miles per gallon of diesel fuel consumed. Diesel #2 fuel currently costs the MTD $0.76 per gallon, inclusive of all applicable taxes, yielding a fuel cost of 13.1¢ per mile. The Villager is a larger bus than the shuttle, however, with more passenger carrying capacity, thereby biasing the fuel cost comparison in favor of the electric shuttle. However, the 5.8 miles per gallon figure is developed on routes that entail less frequent stop/start events, thereby introducing a reverse bias in favor of the diesel vehicle.

Another fuel cost comparative analysis can be developed by comparison of the diesel Villager (13.1¢ per mile) with its electrified counterpart. Recharging of the electric Villager takes place at a rate of 1.90 AC kWh per mile. At the present rate that MTD pays for off-peak charging (8.5¢ per AC kWh) the "fuel" cost of electric-Villager operation is 16.2¢ per mile. At the proposed rate of 4.3¢ per AC kWh, the fuel cost would be 8.2¢ per mile. While this comparison evaluates fuel costs over similar road/load conditions, the electrified Villager is subject to considerable parasitic weight loads that a purpose-built electric vehicle would not carry.

A summary of the fuel cost analysis is presented in Table 15.

Table 15. Fuel Cost Comparison

30' Villager (Diesel)	13.1¢ per mile diesel fuel cost	
	Present Electric Rate Schedule (8.5¢ per kWh)	**Proposed Electric Rate Schedule (4.3¢ per kWh)**
30' Villager (Electric)	16.2¢ per mile electricity cost	8.2¢ per mile electricity cost
22' Electric Shuttle	11.5¢ per mile electricity cost	5.8¢ per mile electricity cost

Source: SBMTD/ETI

4.17 Other Operating Costs

In addition to fuel cost, the other principal non-maintenance cost associated with transit vehicle operation is the cost for the vehicle operator. The wage-plus-benefits cost of MTD driver labor totals $19 per hour. Factoring in an eight and one-half hour day (eight hours of service plus thirty minutes vehicle check-out / debriefing) and an average daily shuttle service of 50 miles, the driver labor cost amounts to $3.23 per mile. This cost far outweighs the costs associated with fuel and maintenance. The reader is therefore encouraged to employ appropriate perspective during evaluation of the differentials in fuel cost (and cost of maintenance presented in the following section) between diesel and electric transit operations.

5. MAINTENANCE

5.1 INTRODUCTION

Maintenance is the prevention and monitoring of potential and realized failures. The objective of the Maintenance Department is to provide safe and reliable vehicles at a quantity sufficient to accomplish the objectives of the Operations Department.

5.2 ROUTINE EV INSPECTIONS

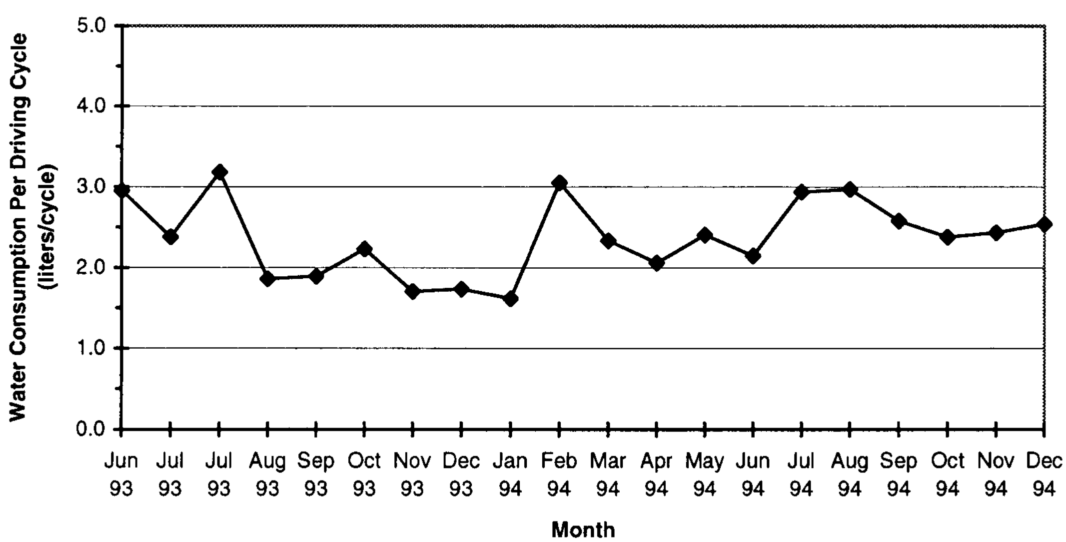
Routine inspections on the battery-electric fleet that are EV specific are related primarily to the DC motors and battery system. The three motors that are inspected are the traction motor, cooling-fan motor for forced convective cooling of the traction motor, and the hydraulic motor for power steering and braking systems. Motor brushes are inspected monthly or quarterly depending on motor age. Traction motor brushes and springs are replaced on an annual basis (~15,000 miles). The cooling-fan motor and the hydraulic motor are replaced on an annual basis.

Electrolyte-acid gravity in flooded cells is inspected and adjusted on a quarterly basis, as well as after vehicle low-power events.

5.3 BATTERY WATERING

Flooded lead-acid batteries are watered approximately twice per week by means of a vacuum watering system. The nickel-cadmium battery is watered approximately three times per month via a gravity feed system.

Water consumption per driving cycle is presented on a monthly basis in Figure 15.



Source: SBMTD/ETI

Figure 15. Battery Water Consumption Per Driving Cycle

5.4 Equalization Charge

An equalization charge consists of a regular charge that is extended until all the cells in a battery system reach a common charge condition. Such an effort is undertaken approximately once per month, or whenever the open-circuit battery voltage subsequent to charge termination averages less than 2.13 volts per cell.

5.5 Diagnosis/Rectification of Vehicle Low-Power Events

Electric vehicles occasionally experience low battery power prior to the completion of regular mission service, thereby necessitating diagnosis and rectification of the contributing condition(s). Information concerning the frequency of such events was presented in Section 4.9. Vehicle low-power events at MTD are addressed in accordance with the following protocol sequence.

Upon return to the MTD terminal of a low-power vehicle, battery cell voltages are measured. Cells exhibiting low voltage are further evaluated for electrolyte volume and specific gravity, and corrective action is taken as necessary. The battery is then recharged and monitored during constant-current discharge testing to assure proper cell function. Trickle charging of problematic cells may also be performed. If electrolyte adjustment and trickle charging do not rectify anomalous cell behavior, cell replacement is necessary.

The energy-management performance of the driver is also analyzed after vehicle low-power events in order to determine whether a high energy consumption rate may have been a contributing factor.

Expired cells are collected and recycled by third-parties (see Section 6.3). Electrolytic by-products from watering and recharge operations are neutralized (sulfuric acid with baking soda, potassium hydroxide with citric acid) and are collected by third-parties.

5.6 Corrosion Control On Cases and Bus Frame

Battery cases and vehicle frame structural elements are subject to corrosion from electrolyte exposure if not properly maintained. MTD corrosion control protocol includes scrape and protective-coat application twice per month. MTD is currently evaluating a thermoplast powder-spray coating in order to assess its potential to reduce corrosion mitigation efforts.

Maintenance-free battery products (such as gel or absorbent glass matte) do not produce gas under normal operational and recharge environments, and therefore do not release the sulfuric acid mist that precipitates corrosive action. MTD's experience to date with maintenance-free batteries suggests that they do not promote corrosive activity.

The potassium hydroxide electrolyte used in nickel-cadmium batteries has no corrosive effect on carbon steel.[8] Both sulfuric acid and potassium hydroxide produce severe corrosive effects on aluminum, however.

5.7 Charger Preventive Maintenance Inspections

Charger cable plug-ends are inspected on a monthly basis. Plug connectors are disassembled and tightened as necessary.

5.8 Charger Repair

Battery-charger failures have been infrequent in MTD's experience. When they do occur, they are generally restricted to blown fuses and failures of either the circuit board or diode rectifiers.

5.9 Impact On Brake System Overhaul

The presence of electrical regenerative braking results in a significant beneficial affect on mechanical brake longevity. To date, no vehicle in the MTD electric vehicle fleet has required any rear brake repair (up to 50,000 miles); front brake rotors have been turned more as a precautionary measure than out of absolute necessity. It is estimated that without the contributing influence of regenerative braking, some vehicles in the MTD electric fleet would have required two or three complete brake jobs (front and rear) at this juncture.

5.10 Propulsion System Contamination From Road Debris

Propulsion system contamination from road debris represents a relatively minor concern in the MTD operation as the powertrain components are well sealed against incursion of water and dust. Road dust does tend to accumulate on the battery packs, however, and is periodically removed by steam cleaning (approximately every two months) in order to prevent the possibility of electrical shorting between terminals.

5.11 Maintenance Costs: EV vs. Diesel

5.11.1 EV Fleet Maintenance

SBMTD routinely tracks all costs associated with fleet maintenance. From the introduction of the battery-electric vehicles to the MTD fleet in January 1991 through December 1994, a total of $172,192 has been spent on EV maintenance. A breakdown of maintenance costs is provided in Table 16, and is discussed on the following pages.

[8] Chemical Resistance Data, Tecumseh Products Company, Oklahoma City, OK

Table 16. SBMTD Electric-Fleet Maintenance Costs, 1/91 - 12/94 (316,013 miles)

Category	Parts	Labor	Total	% of Total
Preventive Maint. Inspections	$0	$41,594	$41,594	24%
Tires	$8,353	$344	$8,697	5%
Battery Maintenance				
Battery Watering	$4,189	$9,454	$13,643	8%
Other Battery Maintenance	$25,515	$13,820	$39,335	23%
Charger Repairs	$1,720	$969	$2,689	2%
Other Routine Maintenance/Repairs	$36,069	$30,165	$66,234	38%
Total	**$75,846**	**$96,346**	**$172,192**	**100%**

Source: SBMTD/ETI

Because the first utilization of maintenance-free battery technology in the MTD fleet did not begin until June 1994 (and then only on one bus), the above statistics apply principally to vehicles equipped with flooded-cell battery technology. It may be noted that battery maintenance accounts for 31% of the total cost of vehicle maintenance, but that only one-fourth of the battery maintenance cost is cost of watering. The majority of battery maintenance is related to diagnosis and rectification of vehicle low-power events (the associated effort was discussed above in Section 5.5).

The ultimate effect of the so-called maintenance-free products on cost of maintenance is of considerable interest to MTD. It is not entirely clear at this juncture whether the maintenance-free products will yield a net decrease or increase in the overall cost of maintenance. This uncertainty is the result of the general belief that valve-regulated maintenance-free cells are less tolerant to over-charge/over-discharge abuse than their flooded-cell counterparts, and may be more subject to premature cell failure. Therefore, the maintenance cost savings gained by elimination of watering and the avoidance of low-power events caused by watering system failure may be partially or fully offset by the costs associated with an overall increase in the frequency of premature cell failures. This important issue will be evaluated as MTD's electric bus project continues.

5.11.2 Maintenance Cost Comparison: EV vs. Diesel

The maintenance costs associated with MTD's diesel-powered Villager fleet provides a basis for comparison against those associated with MTD's electric fleet. Comparative figures are presented in Table 17, and are discussed on the following page.

Table 17. Maintenance Cost Comparison (Parts & Labor) 1/91 - 12/94

	Villager Fleet (diesel) (19 buses)	Electric Fleet (12 buses)
Cost per day per vehicle	$29.71	$18.05
Miles per day per vehicle	61.0	33.1
Cost per mile	$0.47	$0.54

Source: SBMTD/ETI

It is evident from the data presented above that MTD's battery-electric vehicles are approximately 40% less costly to maintain on a cost-per-day basis. The battery-electric fleet has a reduced range capacity as compared with the diesel-powered fleet, however, which results in application of the electric fleet to lower average speed / reduced mileage service; *miles per day per vehicle* represents total fleet mileage amortized over total vehicle-days, and therefore includes the influence of spare vehicles that do not see service on a particular day. Because of the reduced daily mileage associated with the electric fleet, cost accounting on a per-mile basis favors the diesel fleet by approximately 10%.

6. BATTERIES

6.1 OVERVIEW

Batteries are the only available energy storage devices presently suitable for on-board motive power applications. Although there are a multitude of battery chemistries currently under development, the field of presently available chemistries available for traction applications is limited to lead-acid, nickel-iron, and nickel-cadmium (Ni-Cd). Near-term chemistries include nickel-metal hydride and zinc-air. Development efforts that may ultimately yield useful traction batteries include lithium-aluminum/iron sulfide, zinc-bromine, zinc-nickel oxide, aluminum-air, sodium-metal chloride, and lithium-polymer. Unfortunately, the development period of batteries is inherently protracted, and such chemistries will probably not be commercially available for many years.

Few battery chemistries have matured to a level satisfactory for application to electric vehicles, even under controlled test conditions. MTD has heretofore utilized flooded lead-acid batteries (both tubular cell and flat plate designs), valve-regulated tubular cell gelled lead-acid batteries, and nickel-cadmium batteries in conjunction with its electric bus fleet. Flooded, tubular-cell lead-acid batteries power the majority of the vehicles in MTD's battery-electric fleet. The Ni-Cd powered bus is the first application of this battery technology to a battery-powered transit vehicle in the United States. The Ni-Cd technology possesses favorable specific energy characteristics and a long life span. MTD also plans to evaluate valve-regulated absorbent glass matte (starved electrolyte) lead-acid batteries. The valve-regulated designs do not produce gassing of hydrogen and oxygen during charge, and therefore do not require periodic watering. Such battery designs also virtually eliminate the potential for electrolytic acid leakage under crash conditions.

Mechanical energy storage devices, namely flywheel "batteries", are also the subject of considerable attention and funding. This approach utilizes energy storage in kinetic form, rather than as chemical potential energy as is employed with conventional batteries. Such an approach promises increased specific energy and energy densities, lower capital costs, and longer cycle life than that available with chemical batteries. Several technical impediments require resolution prior to successful implementation of this technology, however. MTD is poised to evaluate such systems if and when they become available for controlled testing.

Fuel cells are also being utilized in transit bus demonstration projects, although the cost of the technology is quite high at this point.

Ultra-capacitor technology also promises to eventually contribute to electric vehicle performance as a result of its inherently high specific power level, although the specific energy of this technology is presently low.

MTD's battery evaluation program includes studies of battery energy capacity as a function of the number of discharge/charge cycles, the influence of operating conditions on battery performance, and maintenance issues. Battery energy efficiency, or the efficiency with which a battery converts electrical energy to chemical energy and back again to electrical energy, is also addressed.

Certain battery-specific information has previously been presented in Section 4 "Operations", and will not be repeated in this section. The interested reader is encouraged to refer to Section 4 as necessary.

6.2 BATTERY PRODUCTS UNDER EVALUATION AT MTD

To date, MTD has utilized two types of flooded-cell lead-acid batteries (tubular cell and flat plate variants), a gelled lead-acid battery, and a nickel-cadmium battery in its electric bus fleet. Manufacturer-provided specifications for battery products presently in use are listed in Table 18, and are discussed on the following pages.

Many of the parameters presented in Table 18 relate to battery energy. Battery energy capacity is a function of several conditions, most notably the rate at which the energy is discharged, the condition of the battery, and the temperature at discharge (temperature influences were discussed in Sections 4.10 and 4.11). Battery cells exhibit a lower effective internal resistance at slower discharge rates, a condition that results in higher efficiency discharge and increased energy availability. In order to facilitate meaningful comparisons among products, an effort has been made to present the data under normalized conditions. Of particular note is the expression of energy under C/3 and C/6 discharge rates. C/"n" designation represents the total energy capacity under constant-current discharge conditions such that all stored energy is delivered during an "n" hour period. The C/3 rate is often used to express battery performance because it is considered representative of electric vehicle applications. While this may be true for automobile applications, MTD experience suggests that the C/3 rate reflects a discharge condition that is more extreme than actually encountered. A C/6 rate is probably more reflective of MTD electric-shuttle application given the eight-hour operation period (to 80% maximum depth-of-discharge [DOD]) with no significant dwell periods. The reader is advised to bear in mind, however, that appropriate C-rate representation of actual mission requirements varies from application to application and is a function of the ratio of the vehicle battery energy capacity to the vehicle energy consumption rate.

The current discharge profile produced by actual driving conditions varies considerably from a constant-current scenario, however. The discharge level typically peaks during maximum vehicle acceleration and then declines until steady-state road speed is achieved. The battery is subsequently exposed to brief periods of recharge current produced by regenerative braking and coasting functions. Furthermore, virtually no energy discharge occurs while the bus is stopped in traffic or at passenger-pickup points. Thus, the correlation of constant-current discharge ratings with actual driving cycles is somewhat tenuous. Nevertheless, the constant-current discharge rating remains a convenient method of expressing energy capacity. Further discussion of this subject is presented in Section 6.4.

Table 18. Manufacturer Specifications for Battery Products Under Evaluation at MTD

Manufacturer	Chloride	Trojan	Trojan	Oldham	Saft Nife
Description	tubular cell flooded lead acid	flat plate flooded lead acid	flat plate flooded lead acid	tubular gel valve-regulated lead acid	Nickel-Cadmium
Designation	S32Y-11 (216 Volt system) 3 pack	160-TEB-240 (320 V system - Villager) 6 pack	174-CEB-195 (348 Volt system) 3 pack	GTV5 (216 Volt system) 4 pack	STM5-180 (216 Volt system) 3 pack - 2 // strings
Vehicle	ESV 1,2,3,4,5,7,8,10	Villager	22' Bus	ESV 6	ESV 9
Total Rated Capacity	62 kWh C/3 75 kWh C/6	68 kWh C/3 76 kWh C/6	60 kWh C/3 68 kWh C/6	60 kWh C/3 78 kWh C/6	84 kWh C/3 87 kWh C/6
Max. Recommended DOD	80%	80%	80%	70%	95%
Accessible Energy	50 kWh C/3 60 kWh C/6	54 kWh C/3 61 kWh C/6	48 kWh C/3 54 kWh C/6	42 kWh C/3 55 kWh C/6	79 kWh C/3 82 kWh C/6
Aggregate Cell Weight	4212 lbs	6325 lbs	4125 lbs	5638 lbs	3675 lbs
Rated Specific Energy	33.0 Wh/kg C/3 @ 86F 39.6 Wh/kg C/6 @ 86F	23.5 Wh/kg C/3 @ 77F 26.6 Wh/kg C/6 @ 77F	32.0 Wh/kg C/3 @ 77F 36 Wh/kg C/6 @ 77F	23.6 Wh/kg C/3 @ 77F 30.5 Wh/kg C/6 @ 77F	50 Wh/kg C/3 @ 68F 52 Wh/kg C/6 @ 68F
Rated Energy Density	79 Wh/L C/3 @ 86F 95 Wh/L C/6 @ 86F	79 Wh/L C/3 @ 77F 89 Wh/L C/6 @ 77F	113 Wh/L C/3 @ 77F 128 Wh/L C/6 @ 77F	64 Wh/L C/3 @ 77F 83 Wh/L C/6 @ 77F	110 Wh/L C/3 @ 68F 114 Wh/L C/6 @ 68F
Accessible Specific Energy	26.4 Wh/kg C/3 @ 86F 31.7 Wh/kg C/6 @ 86F	18.8 Wh/kg C/3 @ 77F 21.3 Wh/kg C/6 @ 77F	25.6 Wh/kg C/3 @ 77F 28.8 Wh/kg C/6 @ 77F	16.5 Wh/kg C/3 @ 77F 21.4 Wh/kg C/6 @ 77F	48 Wh/kg C/3 @ 68F 49 Wh/kg C/6 @ 68F
Accessible Energy Density	63 Wh/L C/3 @ 86F 76 Wh/L C/6 @ 86F	63 Wh/L C/3 @ 77F 71 Wh/L C/6 @ 77F	90 Wh/L C/3 @ 77F 102 Wh/L C/6 @ 77F	45 Wh/L C/3 @ 77F 58 Wh/L C/6 @ 77F	105 Wh/L C/3 @ 68F 108 Wh/L C/6 @ 68F
Spec. Power (20% SOC)	160 W/kg	(not available)	(not available)	(not available)	175 W/kg
Manufacturer Projected Cycle Life (to max. DOD)	~1000	~1000	~1000	~750	~2000
Rapid Charge	No	No	No	Yes	Yes (80% capacity in 2 hrs.)
Maintenance Schedule	weekly	weekly	weekly	none (maintenance free)	tri-weekly
Capital Cost ($ per accessible capacity)	$ 233 / kWh (C/3) $ 194 / kWh (C/6)	(obsolete)	$ 226 / kWh (C/3) $ 201 / kWh (C/6)	$ 466 / kWh (C/3) $ 356 / kWh (C/6)	$ 638 / kWh (C/3) $ 615 / kWh (C/6)
Life Cycle Cost ($ per accessible kWh, total cycles)	$ 0.23 / kWh (C/3) $ 0.19 / kWh (C/6)	(obsolete)	$ 0.23 / kWh (C/3) $ 0.20 / kWh (C/6)	$ 0.62 / kWh (C/3) $ 0.47 / kWh (C/6)	$ 0.32 / kWh (C/3) $ 0.31 / kWh (C/6)

Source: Chloride, Trojan, Oldham, Saft, SBMTD/ETI

Specific energy is the gravimetric measure of a battery's capacity to store energy, and is therefore expressed in terms of energy per unit mass. *Energy density* is the volumetric measure of a battery's capacity to store energy, and is therefore expressed in terms of energy per unit volume. In essence, energy density dictates how much energy will "fit" in an available volume, and specific energy determines how much that energy will "weigh". Unfortunately, these two units are frequently and erroneously used interchangeably in the literature, and the reader is therefore strongly encouraged to be aware of the difference between these parameters and their respective impacts on energy storage issues. Ideally, an advanced performance battery should offer increases in both categories, because most transportation applications are subject to both volume and mass constraints.

By referring to Table 18, it is apparent from comparison of specific energy values that performance relationships between battery products differ depending upon the C-rate evaluated. For example, the Saft nickel-cadmium product exhibits a 52% advantage in rated specific energy over the Chloride lead-acid product when compared at the C/3 rate, but that performance advantage declines to 31% when compared at the C/6 rate. The reader should bear in mind, however, that rated specific energy values are based upon total battery energy, and that the actual realized performance advantage of the nickel-cadmium product is greater than indicated by a cursory comparison of rated specific energy values because of the greater allowable depth of discharge associated with the Ni-Cd product.

Capital cost refers to the ratio of battery cost to the quantity of accessible energy during each cycle. Battery cost includes intercell connectors, terminal shrouds, cabling, watering system tubing (if required), but does not include battery trays or off-board watering system equipment. *Accessible energy*, rather than total rated energy, is believed to be a more appropriate means of comparison because of the variations in allowable depths of discharge (which range from 70% to 95% for battery products under evaluation at MTD). *Life cycle cost* refers to the ratio of battery cost to the total quantity of accessible energy over the life expectancy of the battery; such analysis incorporates variations in expected cycle life (which range from 750 cycles to 2000 cycles for battery products under evaluation at MTD).

6.3 OTHER BATTERY ISSUES OF INTEREST

Occasionally, concern is expressed about the potential for a nickel-cadmium traction battery to exhibit the so-called "memory effect" demonstrated by consumer electronics products. The memory effect occurs when a nickel-cadmium battery is repeatedly discharged to and recharged from a level less than a fully discharged state. Under such circumstances, the battery may temporarily lose its capacity to store and deliver beyond the partially discharged position. In this event, the battery is usually recovered via a reconditioning discharge/recharge protocol.

MTD is advised that the memory effect sometimes associated with nickel-cadmium chemistry is a function of the construction of the cadmium electrode, and that only cadmium electrodes that have been fabricated by sintering are susceptible to the memory effect.[9] The nickel-cadmium traction batteries in use at MTD do not employ sintered cadmium electrodes, and the manufacturer claims that the memory effect associated with this product is negligible. Other sources also downplay the so-called memory effect.[10] MTD has not observed such an effect to date.

The battery energy data presented in Table 18 represents average performance ratings. The maximum potential performance variance from module to module (primarily among

[9] Private communication: Jim Miller (Saft) to P. Griffith, February 1995

[10] Ronald Khol, Basics of Design Engineering, 1991 Reference Volume, Penton Publishing

different production runs), is a function of battery chemistry and quality control procedures. Among the battery products in service at MTD, the Ni-Cd chemistry is subject to the greatest inter-module performance variance. For instance, although the average C/6 rate specific energy of the STM5-180 module is 52 Wh/kg, while the AQL1.0 performance (99% of units perform better, 1% worse) is 47 Wh/kg, a reduction of approximately 10%. For comparison, the capacity variance of the tubular-cell flooded lead-acid battery is plus or minus 5%.[11] As always, the reader should employ caution when applying battery rating figures, and should include the consideration of minimum performance values when the potential for high performance variance is suspected.

The various battery chemistries also require differing management considerations. Ni-Cd batteries require thermal management because of heat generation during both the discharge and recharge processes. Valve-regulated, sealed technologies require control management in order to minimize the potential for over-discharge and over-charge (sealed battery technology is less tolerant to such abuse than the flooded products).

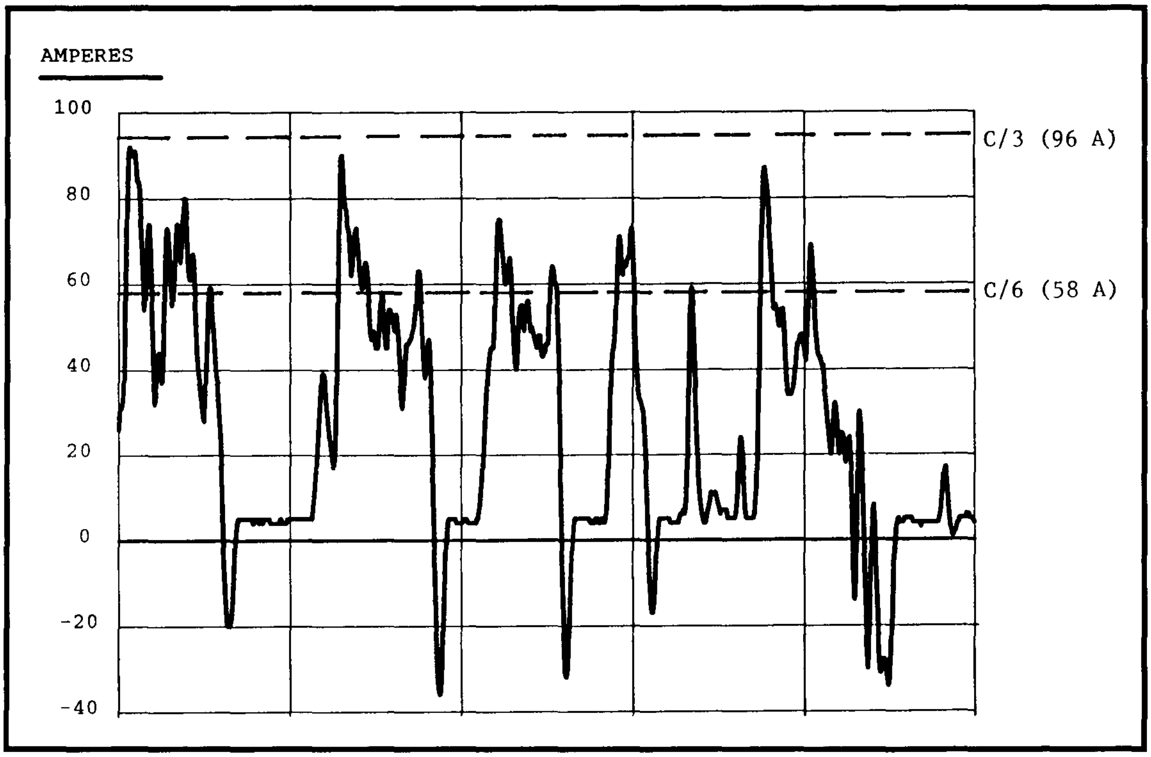
Battery recycling infrastructure is well developed for lead-acid products. Such processing results in the beneficial utilization of 97% of the weight of each battery (and nearly 100% of the lead).[12] The manufacturer of MTD's nickel-cadmium battery also accepts the return of expired modules for recycling, at no cost to the customer.

6.4 CONSTANT-CURRENT DISCHARGE VS. ACTUAL DRIVING CYCLE

As discussed above, the correlation between constant-current discharge and an actual driving cycle environment is imprecise. The current discharge profiles associated with lead-acid and nickel-cadmium powered electric shuttle vehicle operation on MTD's Downtown Route are presented in Figures 16 and 17, respectively. Superimposed upon each profile are the C/3 and C/6 constant current rates attendant to each battery system.

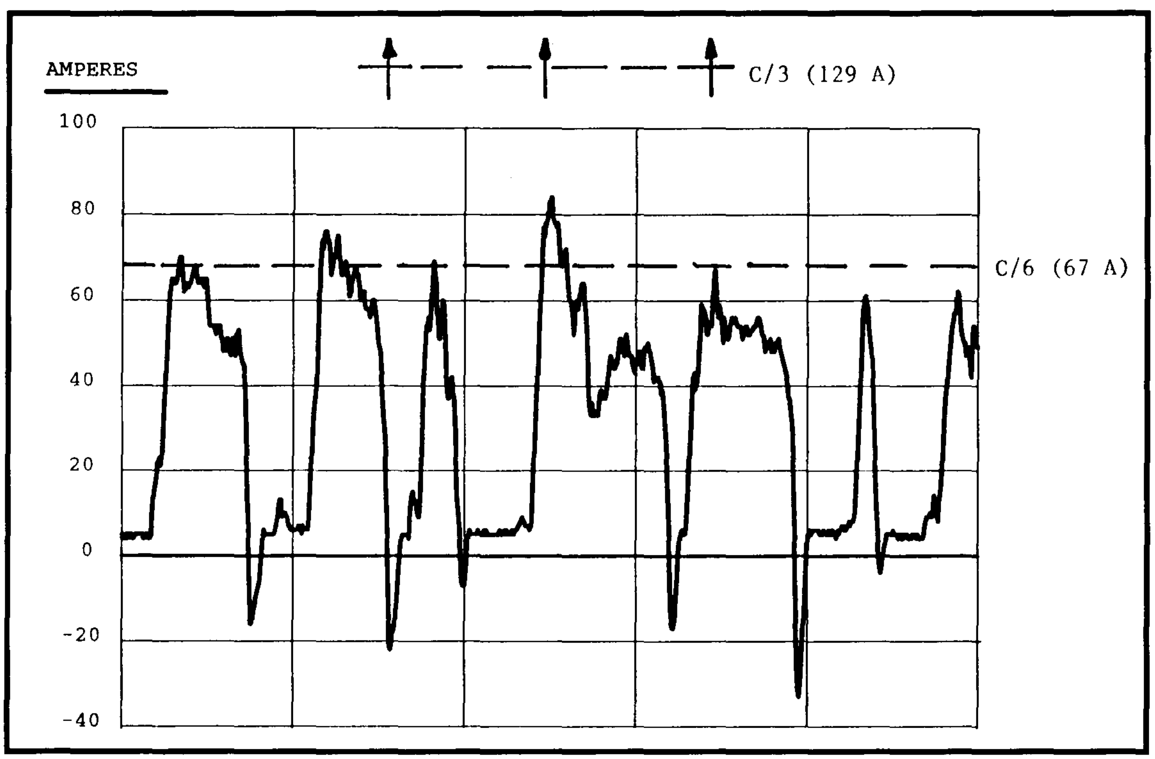
It is evident from evaluation of these relationships that discharge at the C/3 rate is too aggressive to be representative, and that the C/6 rate is probably more reflective of the actual environment.

[11] Private communication: K.D. Merz (Chloride Motive Power) to P. Griffith, April 1995
[12] Scrap Battery Processing, GNB Technologies



Source: SBMTD/ETI

Figure 16. Downtown Shuttle Route Current Profile (lead-acid batteries)

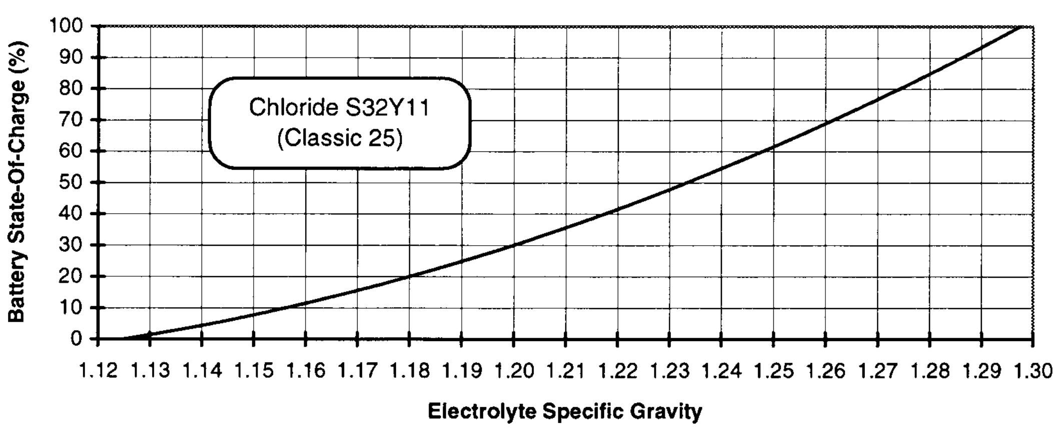


Source: SBMTD/ETI

Figure 17. Downtown Shuttle Route Current Profile (nickel-cadmium batteries)

The question of correlation between constant-current discharge and the micro-cycle environment could be more accurately addressed if precise battery state-of-charge instrumentation were available. The change in battery state-of-charge from the beginning to the end of a service period could then be coupled with data concerning net energy discharged, thereby permitting extrapolation of total battery energy capacity under the operational conditions. This information could then be correlated with a constant-current discharge rating. Unfortunately, instrumentation that precisely measures battery states-of-charge would have to account for and reflect the deleterious effects of sulfation, shedding of active plate material, insufficient electrolyte volume, improper acid concentration, temperature extremes, and other conditions that adversely influence available energy. Such instrumentation is not presently available.

MTD has conducted a test, however, in which an approximate approach to state-of-charge measurement was utilized in order to ascertain total battery capacity under operational conditions. The methodology made use of the fact that in a new flooded-cell battery (prior to the onset of sulfation, shedding of active material, or electrolyte imbalance), there exists a direct correlation between electrolyte specific gravity and battery state-of-charge, as depicted in Figure 18.



Source: Chloride, SBMTD/ETI

Figure 18. Battery State-Of-Charge vs. Electrolyte Specific Gravity

MTD's test was conducted on a Chloride battery set that had been exposed to only 21 discharge/recharge cycles. The average specific gravity for all cells at the beginning of the service run was 1.269 (after correction to standard temperature conditions), thereby indicating a starting state-of-charge of approximately 77%. The average, temperature-normalized specific gravity at the conclusion of the service run was 1.180, indicating a finishing state-of-charge of 20%. A net total of 43 kWh was consumed during this period in which the battery state-of-charge declined 57%. Therefore, 43 kWh represents 57% of the total energy capacity, yielding a total capacity under operational conditions of approximately 75 kWh. By referring to the data for the Chloride product as presented in

Table 18, it is apparent that such a capacity is consistent with a C/6 constant-current discharge rate.

6.5 AVAILABLE VEHICLE RANGE

As discussed in Section 4.1, the electric shuttles provide average daily service of 75 miles on the Waterfront Route and 40 miles on the Downtown Route. Idealized range projections for the shuttle vehicle are presented in Table 19 for MTD's lead-acid and nickel-cadmium batteries, assuming the C/6 rate capacity. The design of a transit route around such range projections would be impractical, of course, because of normal variations in energy consumption rates above the route average values listed in Table 19, and the lack of any allowance for diminution of available energy due to incomplete recharge events, temperature influences, or the naturally decreasing progression of a battery's capacity to store energy.

Table 19. Idealized Range Projections For Electric Shuttle (C/6 Capacity)

Battery Product	108 Chloride S32Y-11 Cells		72 Saft STM5-180 Modules	
Rated Capacity (C/6)	348 Ah; 75 kWh		400 Ah; 87 kWh	
Maximum D.O.D.	80%		95%	
Accessible Energy	60 kWh		82 kWh	
Route	Waterfront	Downtown	Waterfront	Downtown
Energy Consumption	0.66 DC kWh/mi.	0.96 DC kWh/mi.	0.66 DC kWh/mi.	0.96 DC kWh/mi.
Available Range	91 miles	63 miles	124 miles	85 miles

Source: SBMTD/ETI

6.6 MTD BATTERY USAGE HISTORY

Santa Barbara MTD tracks the usage history for all traction batteries placed in service on the electric buses. The rigors of MTD's "real-world" electric vehicle program occasionally result in the application of operational constraints to the demonstration program, however. For instance, it is periodically necessary to exchange battery sets between vehicles undergoing maintenance in order to maximize the number of vehicles available for transit service. As a result, several of the battery sets are presently on-board vehicles other than those in which they were originally installed. For this reason, battery usage data is presented in terms of battery sets rather than for individual vehicles. Battery usage data through December 31, 1994 is presented in Table 20.

Table 20. MTD Battery Usage History Through December 31, 1994

Battery Set Number	Battery Type	Date Placed in Service	Miles Driven	Driving Cycles	Number of Cells Replaced
T-1	Trojan 216V EB-400	12/10/91	9,289	436	12
T-2	Trojan 320V TEB-240	3/14/93	18,247	454	0
T-3	Trojan 216V EB-340	5/2/93	8,798	159	3
Subtotals			**36,334**	**1049**	**15**
C-1	Chloride 216V S32Y-11	12/19/90	27,668	639	14
C-2	Chloride 216V S32Y-11	4/10/91	25,083	531	31
C-3	Chloride 216V S32Y-11	1/21/92	27,961	766	41 (1)
C-4	Chloride 216V S32Y-11	1/31/92	36,151	884	22
C-5	Chloride 216V S32Y-11	2/15/92	32,992	921	17
C-6	Chloride 216V S32Y-11	2/27/92	20,797	607	29
C-7	Chloride 216V S32Y-11	5/15/92	26,738	708	3
C-8	Chloride 216V S32Y-11	5/15/92	27,839	572	5
C-9	Chloride 216V S32Y-11	4/9/93	13,749	358	29
C-10	Chloride 216V S32Y-11	5/20/93	20,597	528	4
C-11	Chloride 216V S32Y-11	8/5/94	4,918	102	2
C-12	Chloride 216V S32Y-11	8/5/94	4,045	104	0
Subtotals			**268,538**	**6720**	**197**
O-1	Oldham 216V GTV5 gel	6/8/94	5,860	137	0
S-1	SAFT STM 5-180 Ni-Cd	7/26/94	5,281	100	0
Totals	(1,852 cells total)		**316,013**	**8,006**	**212**

(1) 19 of these cells were replaced during third-party contractor evaluation. *Source: SBMTD/ETI*

Battery sets T-1 and T-3 were returned to Trojan Battery Company for cell disassembly and analysis. Twelve of the remaining fifteen battery sets provide daily service (the three extra sets are periodically rotated into the fleet).

It should be noted that 19 of the 41 cells replaced on Chloride battery set C-3 were replaced by a third-party contractor early in the set's history during the course of an off-site discharge-test battery checkout. It is probable that some of the cells that were identified as deficient during this evaluation were of sufficient quality to enable satisfactory performance in the operational environment (further discussion of this issue is presented in Section 6.7). MTD no longer utilizes the services of third-party contractors for the purposes of battery assessment.

The relatively low overall cell failure to cycle ratio experienced to date at MTD is believed to be the direct result of careful and methodical battery maintenance. A marked increase in cell failure rate has been encountered during the last quarter of 1994, however, as some of the battery sets begin to approach "end of life".

One of the intended objectives of the MTD electric bus evaluation project is to ascertain the life cycle cost per mile of battery-electric bus operation. An important component of such an evaluation includes the amortization of the battery capital cost over the actual battery life. MTD's ongoing battery evaluation project will provide the "real-world" data necessary to undertake a credible analysis of this subject.

6.7 Remaining Battery Energy Capacities, Battery Life Expectancy

At this date, all battery sets retain sufficient energy capacity to fulfill MTD operational requirements. An exact determination of remaining energy capacity has proven difficult to establish, however. Typically, energy capacity ratings are determined for single cells (or for individual modules comprised of several cells) by means of constant-current discharge testing. Such testing involves the measurement of ampere-hours discharged during progression from a fully charged condition to the manufacturer's recommended termination voltage (representative of a 100% discharged condition). While this is feasible for a limited number of cells, the performance of such a test on a series string of 108 or 160 used cells has proven to be difficult because of the inevitable presence of several marginally deficient cells. These cells typically reach the "knee" in the voltage vs. depth-of-discharge curve at approximately 75% DOD under constant-current discharge conditions, and thereafter begin a rapid decline in voltage (sometimes achieving a reverse voltage condition) prior to the balance of the cells reaching the termination voltage level. These cells can be recovered and reused if the discharge test is aborted relatively quickly after they have experienced voltage drop-off. However, premature termination of the discharge test precludes the determination of total battery capacity. Replacement of these marginally deficient cells is generally not warranted because they are known to perform in a satisfactory manner under the actual micro-cycle operational environment. MTD is presently exploring alternate methods of assessing battery capacity as a function of number of cycles.

Battery cycle life is customarily defined as the number of discharge/recharge cycles that the battery will endure before losing 20% of its initial rated storage capacity. Laboratory tests are generally conducted on single cells or modules, and are carried out to maximum allowable depth of discharge and under constant-current discharge conditions, although shallower discharge depths and driving cycle approximations are sometimes employed. The correlation between the results of such tests and the life expectancy of multiple-cell strings under actual operational conditions remains to be demonstrated, however.

The life expectancy of a battery set in actual service operation will not be determined by the "80% remaining storage capacity" specification of laboratory testing, but rather will be a function of the initial margin between available on-board energy and the energy requirements of the duty cycle. The greater the margin of "surplus" energy, the larger the reduction in battery capacity that can be tolerated, and consequently, the greater the number of useable battery cycles. In multiple-route applications, such as are employed by MTD, the assignment of aging batteries to progressively lighter duty cycles is one strategy that can be implemented in order to extend battery life.

The optimal strategy for battery cell replacement management has not yet been determined. By referring to Table 20, it is evident that some of the 108-cell battery systems in use at MTD have had as many as 25% of their original cells replaced. Given that these battery sets continue to deliver the required energy, it is clearly cost effective to have made the necessary cell exchanges rather than retiring the set. However, it is also clear that under a policy of unlimited cell replacement, a battery set would gradually transform into a collection of replacement cells with varying cycle counts. Therefore, the issue of battery-set retirement is more complex than simply an assessment of remaining capacity. The determination of battery "end of life" must also incorporate the cell-replacement ratio, or perhaps the rate of replacement. MTD continues to study this important issue as various battery sets approach expiration.

6.8 Battery Energy Efficiencies

Battery energy efficiency is defined as the ratio of the energy delivered by a battery during discharge to the total energy required to restore it to a full state-of-charge. As indicated in Table 9, the average battery energy efficiency for the MTD fleet is 70%. Individual battery-set efficiencies range from the low 60% range to the low 80% range. Battery energy efficiency is a function of both the condition of the battery and the recharge profile delivered by the battery charger.

The influence of battery condition and charge profile on battery energy efficiency can be determined by reference to the data presented in Table 9, portions of which are reproduced below in Tables 21 and 22 for easy reference. Table 9 data is sorted by route, and subsorted by vehicle and/or charger. Because route sortings are inconsequential for this particular parameter, the reader may consult inter-route comparative data. The information presented in Tables 21 and 22 represent system averages.

Table 21 demonstrates the influence that the charge profile has on battery energy efficiency. These data were developed by monitoring of electric shuttle vehicle EV1 during recharge by both a 3 SCR / 3 diode charger and a ferroresonant charger.

Table 21. Influence of Charger on Battery Energy Efficiency

Vehicle / Battery Set	Charger Type	Battery Energy Efficiency
EV1 / C-6 (flooded lead-acid tubular cell)	3 SCR / 3 diode	77%
	Ferroresonant	69%

Source: SBMTD/ETI

Table 22 demonstrates the influence of battery condition on energy efficiency. These data were developed by the monitoring of Electric Shuttle Vehicle EV3 and its ferroresonant charger both before and after replacement of an older battery set with a new set.

Table 22. Influence of Battery Condition on Battery Energy Efficiency

Charger Type	Battery	Battery Energy Efficiency
Ferroresonant	Flooded Lead-Acid Tubular Cell (~50 cycles)	74%
	Flooded Lead-Acid Tubular Cell (~700 cycles)	61%

Source: SBMTD/ETI

6.9 Advanced Battery Products

Several advanced performance batteries are presently moving closer to commercialization. Among those chemistries with near-term potential are nickel-metal hydride (GM Ovonic and Saft) and zinc-air (Electric Fuel, Lawrence Livermore National Laboratory (LLNL), and Zinc Air Power).

One of the differences among the zinc-air products are the methods to accomplish recharge. Both the Electric Fuel and LLNL developments utilize "mechanical recharge" techniques in which the battery components that undergo chemical transformation during discharge are physically removed from the battery housing and are chemically regenerated outside the vehicle. The advantage of "reconstructable" or "refuelable" batteries is that "mechanical recharge", (i.e. replacement of the discharged components with recharged components) can be accomplished quickly, thereby permitting rapid "refueling" turnaround time. The primary disadvantages of such recharge schemes would appear to be the requirement for unconventional supporting infrastructure, and the inability of the products to accept electrical regenerative braking energy.

Presently available published data[13, 14, 15, 16 17, 18] concerning these products is presented in Table 23. The reader should bear in mind, however, that this comparative information is for illustrative purposes only, as the various batteries are in different stages of development and the performance data has been developed under differing test conditions and configurations. Furthermore, performance figures associated with battery developments are transitory in nature, and subject to considerable fluctuation as the technologies approach commercial availability.

[13] Corrigan, D. A., et. al., Ovonic Nickel-Metal Hydride Electric Vehicle Batteries: From the First 10,000 Miles to the First 10,000 Vehicles, Proceedings of The 12th International Electric Vehicle Symposium (EVS-12)

[14] Cornu, Jean-Pierre, From Nickel-Cadmium to Nickel-Metal Hydride Battery: A Coherent Strategy For An Achieved Electric Vehicle, Proceedings of The 12th International Electric Vehicle Symposium (EVS-12)

[15] Harats, Yehuda, et. al., Electric Fuel and the Deutsche Bundespost Postdienst, A Joint EV Demonstration Program, Electric Fuel Ltd., Proceedings of The 12th International Electric Vehicle Symposium (EVS-12)

[16] Cooper, John F., Demonstration of a Refuelable Zinc/Air Battery to Enhance Range and Mission of Fleet Electric Vehicles, Presentation at CALSTART Participants' Meeting, April 1995

[17] Private communications: John F. Cooper (LLNL) to P. Griffith, February and April 1995

[18] Battery specification sheet, Zinc Air Power Corporation

Table 23. Projected Performance of Advanced Battery Products

Developer	Electric Fuel	LLNL	Zinc Air Power	GM Ovonic	Saft
Description	zinc-air	zinc-air	zinc-air	Ni-MH	Ni-MH
Specific Energy	215 Wh/kg	~142 Wh/kg	130 Wh/kg	71 Wh/kg (C/3)	65 Wh/kg
Energy Density	252 Wh/L	~210 Wh/L	250 Wh/L	172 Wh/L (C/3)	120 Wh/L
Max. Allow. DOD	100%	100%	100%	80%+	80%+
Spec. Power (20% SOC)	98 W/kg	90 W/kg	60 W/kg	226 W/kg	>150 W/kg
Manufacturer Projected Cycle Life (to max. DOD)	~350	~1500 (8 hour cycles)	~200 (to 80% DOD)	~750	~1500
Regen Braking Charge Accept.	no	no	yes	yes	yes
Rapid Charge	reconstructable	refuelable (10 minutes)	partial	yes	yes
Maintenance Schedule	none	none	monthly	none	none

Source: Electric Fuel, LLNL, Zinc Air Power, GM Ovonic, Saft, SBMTD/ETI

6.10 Anticipated Vehicle Range Using Advanced Batteries

The anticipated electric shuttle vehicle ranges (between recharges) achievable with two advanced battery products are provided in Table 24. These two products are examined in this simplified analysis because they are believed to be closer to commercialization than the others. Although it would probably not be appropriate to utilize an advanced battery product in a duty cycle for which conventional technology is adequate, the shuttle application has been selected for the purposes of this exercise in order to allow for benchmark comparison. This simplified assessment has not taken into consideration the volumetric and gravimetric influences of any battery management systems that may be required, and no adjustments have been made to energy consumption rates due to varying battery system weights or the inability to accept regenerative braking energy. Also, no adjustment has been made for the relatively low specific power associated with the zinc-air product, a condition that might necessitate zinc-air system augmentation with higher specific power components (such as lead-acid batteries) thereby diminishing range performance somewhat. Nevertheless, the commercial availability of either of these battery products at an affordable price level will result in substantial benefit to the applicability of battery-electric transit.

Table 24. Simplified Shuttle Range Analysis with Advanced Battery Products

Battery	Baseline Lead-Acid (Chloride)		Baseline Ni-Cd (Saft)		Zinc-Air (Electric Fuel)		Ni-MH (GM Ovonic)	
Available Battery Compartment Volume	790 liters		790 liters		790 liters		790 liters	
Total On-Board Energy	~75 kWh		~90 kWh		~199 kWh		~136 kWh	
Battery Weight	~4200 lbs.		~3800 lbs.		~2040 lbs.		~4200 lbs.	
Available Energy to Max. DOD	~60 kWh @ 80% DOD		~86 kWh @ 95% DOD		~199 kWh @ 100% DOD		~110 kWh @ 80% DOD	
Route	Waterfront	Downtown	Waterfront	Downtown	Waterfront	Downtown	Waterfront	Downtown
Energy Consumption	0.66 DC kWh/mi.	0.96 DC kWh/mi.	0.66 DC kWh/mi.	0.96 DC kWh/mi.	0.66 DC kWh/mi.	0.96 DC kWh/mi.	0.66 DC kWh/mi.	0.96 DC kWh/mi.
Available Range	~90 miles	~60 miles	~130 miles	~90 miles	~300 miles	~200 miles	~170 miles	~115 miles

Source: SBMTD/ETI

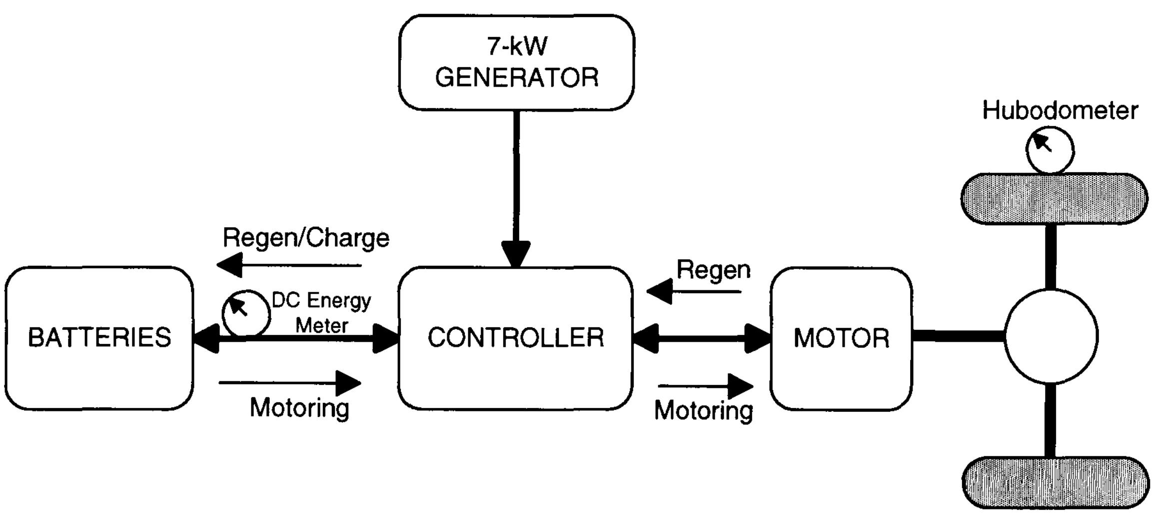
7. RANGE EXTENDERS

7.1 ONAN 7-KW RANGE EXTENDER EVALUATION

The on-board provision of internal-combustion engine powered generators, or "range extenders", are often contemplated as a means of extending the operational range of electric vehicles. The incorporation of such equipment effectively converts an EV to hybrid-electric status, however, and precludes ZEV (zero emission vehicle) certification. In addition, the operation of the internal-combustion engine compromises the noise reduction and odor-free benefits derived from pure battery-electric operation. Nevertheless, for applications where an increase in range (beyond that achievable on battery energy alone) is essential in order to successfully meet mission requirements, or where the operation of accessory devices such as heaters or air conditioners is necessary, a range extender can be an appropriate solution.

MTD recently evaluated a propane-fueled 7-kW range extender manufactured by Onan Corporation. The Onan system was configured to provide variable output power according to the instantaneous voltage of the nominal 216-volt battery system. System design called for the full 7 kW to be delivered at battery voltages of 224 V or lower, tapering off to zero power output at battery voltages of 256 V or higher. Testing was conducted on-board MTD's 22-foot electric transit bus in regular service on MTD's Line 4; the same two drivers were utilized on each day's service during this test period.

The test configuration is depicted in Figure 19.



Source: SBMTD/ETI

Figure 19. Range Extender Test Configuration

The accumulated test data for the eight-day focused evaluation is presented in Table 25. The data is arranged in ascending order of duration of range extender operation. It should be noted that all DC energy parameters (discharge, regen, and recharge) are metered at a position between the batteries and controller. *Regen* energy reflects all energy flowing toward the battery during the period of vehicle operation, while *discharge* energy represents energy leaving the battery. *Recharge* energy indicates the DC energy delivered by the charger at the end of the run in order to restore the batteries to a full state of charge. The three columns on the right present the data normalized on a per mile basis.

Table 25. Range Extender Test Data

RECORDED DATA								DERIVED DATA		
Date	Driver(s)	Route	Miles Driven	Duration of Rng Xtndr Operation (hours)	Discharge (DC kWh)	Regen (DC kWh)	Recharge (DC kWh)	Energy Discharged Per Mile (DC kWh/mi)	Energy Regen'd Per Mile (DC kWh/mi)	Energy Recharged Per Mile (DC kWh/mi)
8/30/94	Maya/Acosta	4	44	0.0	51.978	11.546	57.684	1.18	0.26	1.31
8/31/94	Maya/Acosta	4	45	0.0	55.658	12.438	N/A	1.24	0.28	N/A
8/9/94	Maya/Acosta	4	53	4.9	56.172	13.541	59.700	1.06	0.26	1.13
8/23/94	Maya/Acosta	4	54	7.6	54.866	14.160	55.073	1.02	0.26	1.02
8/22/94	Maya/Acosta	4	59	8.6	55.892	16.616	60.100	0.95	0.28	1.02
8/25/94	Maya/Acosta	4	71	10.6	69.241	21.906	68.246	0.98	0.31	0.96
8/29/94	Maya/Acosta	4	71	10.7	65.066	23.537	58.179	0.92	0.33	0.82
8/10/94	Maya/Acosta	4	72	10.8	67.381	20.085	62.638	0.94	0.28	0.87

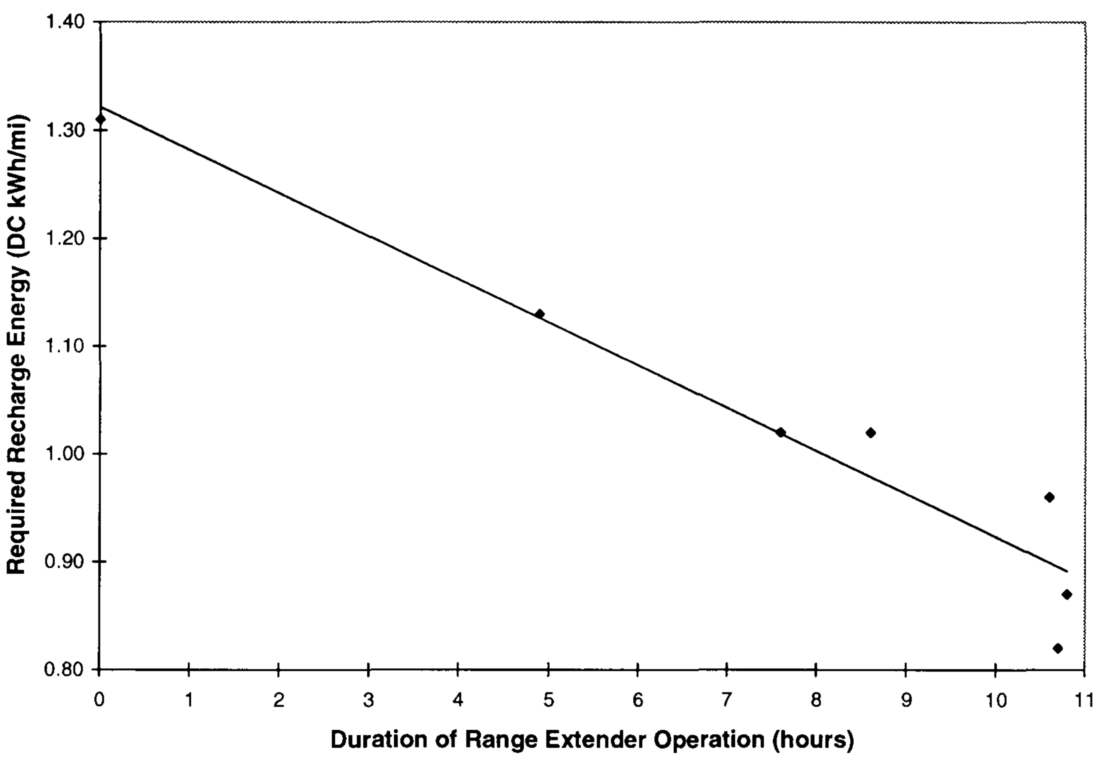
Source: SBMTD/ETI

It may be noted that the *energy regenerated per mile* value is virtually independent of the duration of range extender operation. This indicates that virtually none of the power output from the range extender has been directed toward the batteries for in-operation recharge. Inspection of *energy recharged per mile* does show an inverse dependency upon the duration of generator operation, as is graphically illustrated in Figure 20, thereby demonstrating that range extender operation does result in reduced battery discharge per mile driven.

The implication is therefore that the output from the range extender is utilized to power the traction motor rather than to charge the batteries, thereby supplementing the power output from the batteries and, in the process, reducing the rate of battery discharge. This is actually the preferred energy path because the energy produced by the generator is not subject to the inefficiencies associated with a round-trip through the battery.

By referring to Table 25, it is evident that vehicle operation without range extender use results in a battery discharge rate that requires 1.31 DC kWh/mi of battery recharge.

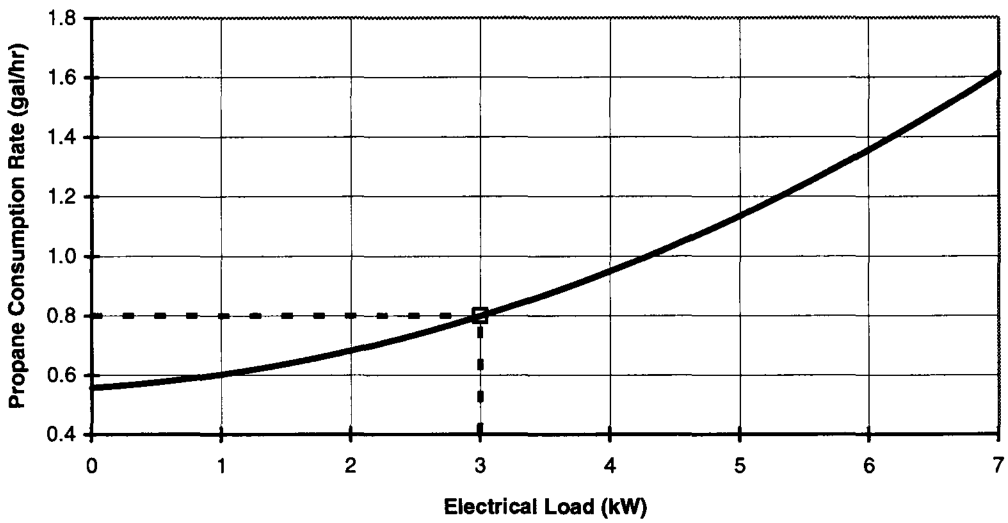
Under continuous range extender use (10.7 hours average operation period), the battery is discharged at a rate that requires an average of 0.88 DC kWh/mi of battery recharge. The actual recharge necessary after 71 miles of vehicle travel under continuous range extender use averages 63 kWh. The bus is not capable of traveling 71 miles on this route without the contribution of the range extender; if it were, however, the duty cycle would result in a battery discharge level that would require 93 kWh of recharge (71 miles x 1.31 kWh/mi). The contribution of the range extender under continuous operation is therefore 30 kWh in a 10.7 hour period, yielding an average power output of 2.8 kW. The extension to range produced by continuous operation of the on-board generator is approximately 50% (1.31 kWh/mi ÷ 0.88 kWh/mi).



Source: SBMTD/ETI

Figure 20. Required Battery Recharge vs. Duration of Range Extender Operation

The calculated average power output of 2.8 kW is less than anticipated given the tapered power output charge profile of the generator. A cross-check of this calculation can be made by consulting the fuel consumption rate vs. electrical load relationship for the generator (Figure 21). The MTD application results in a propane consumption rate of 0.8 gallons per hour (11 gallons consumed in 14 hours of operation), which suggests an average electrical load of approximately 3 kW, thereby demonstrating close correlation with the previously developed average power output value.



Source: Onan Advanced Power Systems, SBMTD/ETI

Figure 21. Range Extender Fuel Consumption Rate vs. Electrical Load

8. BATTERY CHARGERS

8.1 INTRODUCTION

A dedicated battery charger is assigned to each electric vehicle in the Santa Barbara MTD fleet. Two additional charge stations are also available as spares. Three separate charger topologies are presently utilized: ferroresonant, 3 SCR / 3 diode, and 12 SCR. All MTD chargers are configured either to directly accept 240-volt, 3-phase power, or are provided with external step-up transformers to supply the required voltage input.

The methods by which rectification and regulation are accomplished defy simple explanation, as do the various charger performance parameters. An effort has been made to summarize and simplify these issues, but unfortunately this effort falls short of avoiding technical jargon on the one hand, or providing complete technical descriptions on the other. Nevertheless, it is hoped that the following brief discussions will provide the non-technical reader with some insight into the operation and performance of various charger variants. The technical reader is encouraged to consult other sources for a more thorough treatment of these issues. A charger performance summary is provided in Table 26; technical issues are discussed in the following sections.

Table 26. Battery Charger Performance Summary

	Chloride Electro Networks	Chloride Spegel	LaMarche	LaMarche	Chloride Motive Power	Enerpro
Charger Type	Ferroresonant	Ferroresonant	3 SCR / 3 diode	3 SCR / 3 diode	3 SCR / 3 diode	12 SCR
Model Number	EV-05 108V0325M3D	BS3P 108/85	A70B-60-108L-B(DC)3	A70B-105-80L-C3	23S 216V40	EVBC-2
EV Station	EV 2, 3, 4, 5, 7, 8	shop, spare	EV 1, 6	Electric Villager	EV 22	EV 9, 10
Charge Profile Adjustability	none, other than at termination. Ni-Cd incompatible.	none, other than at termination. Ni-Cd incompatible.	relatively unsophisticated multi-stage profile.	relatively unsophisticated multi-stage profile.	relatively unsophisticated multi-stage profile.	programmable to any desired charge profile
Energy Efficiency (AC to DC)	0.96	0.87	0.92	(~0.92)	0.94	0.92 (incl. 6-phase xfrmr)
THD (%) (AC input current)	11.9	8.6	58.5	60.5	55.9	7.9
True Power Factor	0.99	0.81	0.70	0.72	0.67	0.75
DC Ripple Current	58 A peak-to-peak @ 180 Hz	not available	60 A peak-to-peak @ 180 Hz	not available	not available	8 A peak-to-peak @ 720 Hz
Cost	$3,350	(obsolete)	$3,533	$4,045	$2,000	$7,200 chrgr (on-brd) $1,300 xfrmr (single) $3,344 distr. box $11,844 total

Notes: 1. Power Factor evaluation conducted with the assistance of Southern California Edison.
2. THD and Ripple Current analyses performed by Enerpro Corporation.
3. Energy efficiency of LaMarche A70B-105-80L charger not measured, but presumed equivalent to that of LaMarche A70B-60-108L.

Source: SBMTD/ETI

8.2 THEORIES OF OPERATION

Battery recharge can be accomplished in various manners. Charge profile strategies include constant-current, constant-voltage, taper, and combinations. The basic function of all charger types is to rectify alternating voltage to direct voltage format, and to regulate the charge profile (current and voltage) applied to the battery. Various charger types utilize different components to perform these tasks. Summaries of the various theories of operation are presented below:

8.2.1 Ferroresonant Transformer/Rectifier

The ferroresonant charger consists of an input transformer, diode bridge rectifier, filter capacitor, and bleeder resistor.[19] In addition to providing isolation and voltage stepdown, the transformer has an additional winding that is connected to a capacitor. This inductive-capacitance circuit resonates at line frequency, saturating the transformer core for a portion of each input power cycle. The result is a flat-topped secondary voltage with a peak amplitude that does not change with the alternating primary voltage. The initial charging current is set by the transformer impedance and the final charging voltage is determined by the secondary winding voltage taps.[20] Charge termination time is the only possible control variable. The simple design of the ferroresonant charger results in few components and low manufacturing cost. Disadvantages of the ferroresonant charger are the lack of voltage and current adjustment, poor regulation at high charge rates, and the use of limited life, high-voltage capacitors.

8.2.2 Three SCR / Three Diode Rectifier

The silicon controlled rectifier (SCR) is a semiconductor device that acts as a current switch. The SCR only conducts current when biased in one direction, and then only after a gate signal is applied. Current control is accomplished by regulating the portion of the 180° half-cycle during which the SCR may pass current.[21]

The advantage of the SCR charger is that it is a low cost, electronic approach to achieving current control, voltage regulation, and limited profile adjustability. Disadvantages include a large number of components for those models that use discrete circuits rather than microprocessor control, a relatively high harmonic distortion, and relatively low power factor.

8.2.3 12 SCR Rectifier

The 12 SCR rectifier consists of two 6-pulse rectifiers powered from 6-phase AC power (the 3-phase input transformer is wound to provide the required 6-phase power to the rectifier).

[19] Ronald Khol, Basics of Design Engineering, 1991 Reference Volume, Penton Publishing

[20] Report No. R160, Battery Charger Testing at the Santa Barbara MTD Shop, Enerpro Corporation, June, 1993

[21] Comparison of Industrial Battery Chargers, LaMarche Manufacturing Company

The advantages of the 12 SCR charger are full programmability to any desired charge profile, low harmonic distortion for an electronic charger, and low DC ripple current.[22] The charge system is relatively expensive, however.

8.3 CHARGE PROFILES

The charge profiles delivered by the various chargers in use at MTD are presented in the Appendix. The presented profiles are those associated with the charging of 216-volt battery systems.

8.4 INFLUENCE ON BATTERY ENERGY EFFICIENCY

Battery energy efficiency is defined as the ratio of the energy delivered by a battery during discharge to the total energy required to restore it to a full state-of-charge. As discussed earlier in Section 6.8, the charge profile has an influence upon battery energy efficiency. Relevant data is presented again in Table 27 for quick reference. These data were developed by monitoring electric shuttle vehicle EV1 during recharge by both a 3 SCR / 3 diode charger and a ferroresonant charger (seven battery recharge events for each charger).

Table 27. Influence of Charger on Battery Energy Efficiency

Vehicle / Battery Set	Charger Type	Battery Energy Efficiency
EV1 / C-6 (flooded lead-acid tubular cell)	3 SCR / 3 diode	77%
	Ferroresonant	69%

Source: SBMTD/ETI

Energy efficiency during the first portion of the recharge process is high. This means that for every DC kWh of energy delivered by the charger, the battery state-of-charge increases by nearly the same amount. Towards the end of the charge process, each kWh that is delivered by the charger results in a less than one kWh increase in the battery state-of-charge. This less efficient portion of the recharge process is an inevitable component of bringing the battery to a full state-of-charge, however. The fact that a battery recharged with the ferroresonant charger exhibits a lower energy efficiency than when charged by the electronic charger suggests that for this particular evaluation, the ferroresonant charge process results in a longer duration in the inefficient energy-transfer regime.

[22] Report No. R160, Battery Charger Testing at the Santa Barbara MTD Shop, Enerpro Corporation, June, 1993

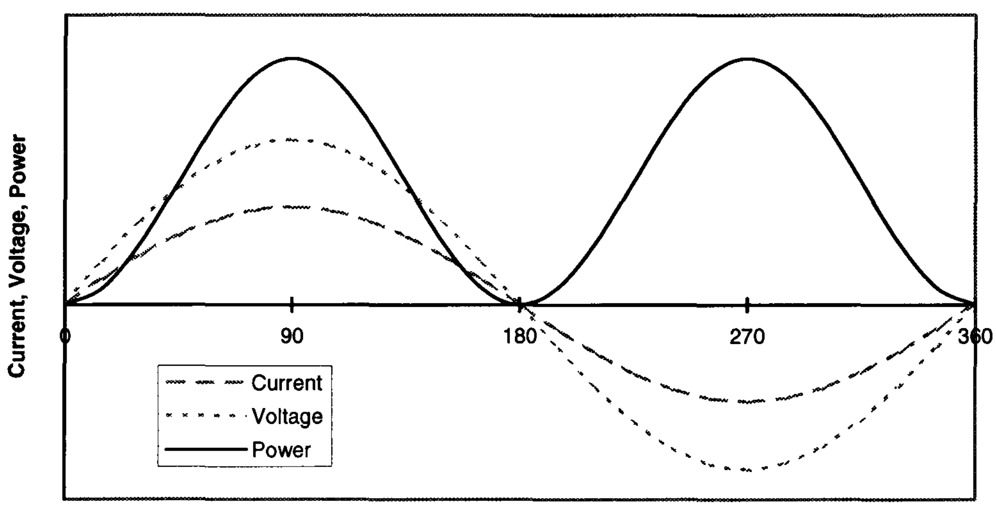
8.5 AC TO DC EFFICIENCY

The rectification of the alternating voltage supplied by the electric power grid to direct voltage and current (as is required to recharge a battery) is accompanied by energy conversion into heat, thereby yielding an efficiency ratio of less than unity. This conversion process is relatively efficient, however, and reference to Table 26 indicates that all battery chargers in use at MTD have an AC to DC efficiency ranging from 87% to 96%.

8.6 POWER FACTOR

Electric power is the time rate of transforming or transferring electric energy, and is measured in watts. *True power* (or "*active power*") is the product of voltage times current averaged over a cycle, and determines the rate of energy utilization by the consumer. *Apparent power* in Volt-Amperes (VA) for a 3-phase AC circuit is obtained by multiplying the rms (root mean square) voltage by the rms current, times √3. *Reactive power* in Volt-Amperes-Reactive (VAR) for a 3-phase AC circuit is obtained by multiplying the rms (root mean square) voltage by the rms current and by the sine of the angular phase difference by which the current leads or lags the voltage, times √3.

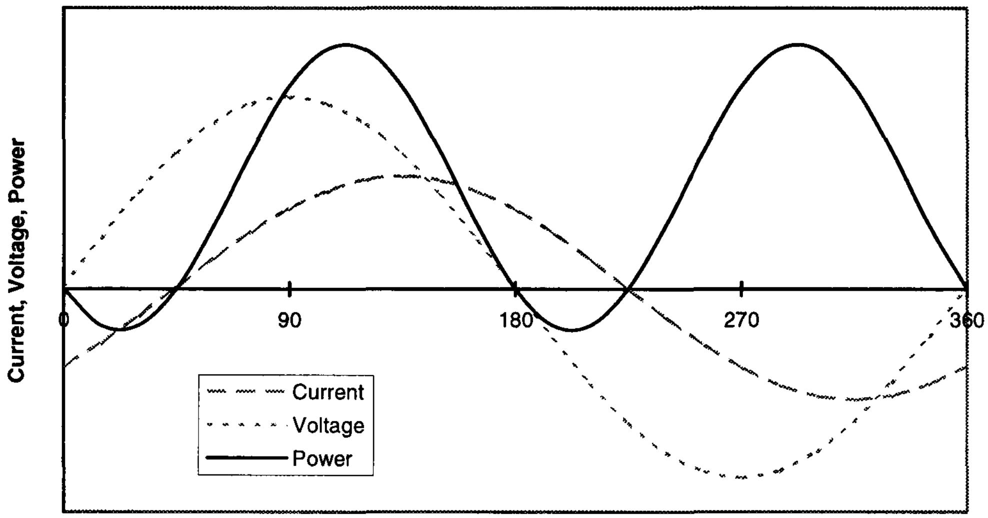
When electrical energy is produced by induction in an alternator, a sinusoidal voltage is produced that causes a sinusoidal current to flow in a linear external circuit. In a circuit consisting of only resistive elements, the voltage and current waveforms are "in phase", meaning that they both transition from positive to negative at the same instant, as depicted in Figure 22. Since current and voltage are of the same algebraic sign in the absence of any phase displacement, the resulting power is always positive, and true power is equal to apparent power.



Source: SBMTD/ETI

Figure 22. Time Graph of Alternating Current: No Phase Displacement

The presence of capacitance (storage of energy in the form of separated charge or in the form of an electric field) and inductance (storage of energy in the form of moving charge or in the form of a magnetic field) in a circuit may cause phase displacements between the voltage and current waveforms (Figure 23). Such displacements result in periods during which the voltage and current have different algebraic signs; the power during these intervals is therefore negative. Because of these negative values, the true power is less than the apparent power.



Source: SBMTD/ETI

Figure 23. Time Graph of Alternating Current: 45° Phase Displacement

Power factor is an expression of the reduction in power that occurs as a result of phase displacement or waveform distortion, and is calculated by taking the ratio of true power to apparent power. The true power, integrated over time, determines the quantity of energy consumed, and therefore the monthly electricity bill. The utility company must deliver both the required voltage and the required current independent of the phase difference between the two. Since the consumer pays at the true power rate, the power factor is of concern to the utility company. As a result, some electric rate schedules require that sites that exhibit high power demand also be metered for reactive power (see Section 4.14).

The power factor values presented in Table 26 represent cumulative values metered over the entire charge period. The closer the power factor is to unity, the smaller the difference between true power and apparent power. Typically, the ferroresonant chargers exhibit higher (more favorable) power factor values than do the electronic chargers.

8.7 Total Harmonic Distortion

Commercial electricity is carried by sinusoidal waveforms described by two main features: amplitude and frequency. Variation in either feature can impede or destroy circuits connected to the supply, although such variations or line faults are common on factory-floor power networks and are a "given" when designing industrial electronics.[23]

Resonances caused by circuit capacitance and reactance "ring" at different frequencies. In essence, a circuit can act as a generator and produce voltages fluctuations that may travel along the power line and cause waveform noise "pollution" for neighboring users. The propagation of such noise can adversely impact the performance of solid-state electronic devices, particularly those that are micro-processor based, such as computers. Fortunately, such noise may be dampened by transformers and other appropriate circuit elements, thereby keeping the effect localized.

The aggregate sum of all the generated harmonics produces a complex profile that distorts the basic 60-Hz sinusoidal waveform. The relative magnitude between the generated voltage harmonics and the basic sinusoidal voltage determines the *total harmonic distortion*, or THD. Reference to Table 26 reveals that THD is in the 10% range for the ferroresonant and 12 SCR chargers, but up to 60% for the other electronic chargers.

In general, customers should produce less than 5% THD in order to minimize potential interference with sensitive equipment utilizing the same power source. The higher THD resulting from some of the charger equipment in place at MTD has not created a problem to date because the equipment creating the distortion is used between midnight and 6 a.m., when other sensitive instrumentation is not in use. If a problem ultimately develops, the utility company could require MTD to reduce THD, a condition that could be addressed by the connection of 1:1 transformers and other appropriate circuit elements to the supply lines near the problematic equipment.

8.8 DC RIPPLE CURRENT

The process of converting (rectifying) alternating current to steady-state direct current is not perfectly accomplished by battery chargers. Although the resulting output current is unidirectional, the waveform magnitude fluctuates about an average value at a frequency predetermined by the charger construction. Such fluctuation is expressed as *DC ripple current*. Two DC waveforms, each with an average current of 60 amperes, are plotted in Figure 24. The waveform represented by the dotted line fluctuates between 30 and 90 amperes and therefore exhibits a peak-to-peak ripple of 60 amperes. The waveform represented by the solid line fluctuates between 55 and 65 amperes and therefore exhibits a peak-to-peak ripple of 10 amperes. Although both waveforms have an average value of 60 amperes, they have different rms (root mean square) values. The rms value (sometimes referred to as the "effective" value) of a waveform is equal to the square root of the average value of the squares of the instantaneous values. It may be noted that the rms value of the 60 ampere peak-to-peak waveform is 63.7 amperes, whereas the rms value of the 10 ampere peak-to-peak waveform is 60.2 amperes.

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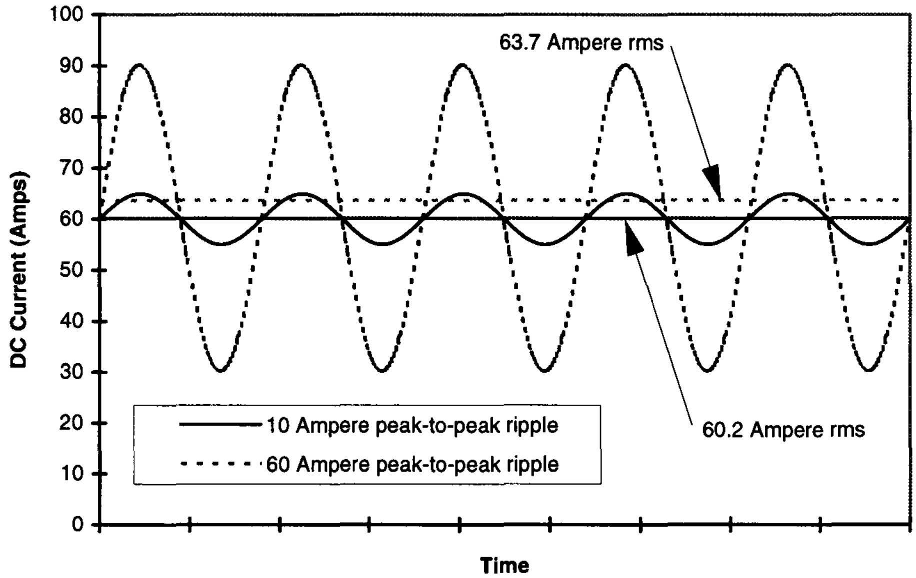
[23] Ronald Khol, Basics of Design Engineering, 1991 Reference Volume, Penton Publishing



Source: SBMTD/ETI

Figure 24. DC Ripple Current

The average current determines the charge accumulated by the battery, while the rms current determines the total energy delivered to the battery. It can be seen from the above analysis that the presence of DC ripple raises the rms value of current above the average value of current; the resulting differential may result in heating of the battery, and can be deleterious to battery health and longevity. Therefore, all else being equal, chargers exhibiting lower ripple current may lead to longer battery life. MTD is monitoring this issue, although there are many other variables, such as the influences of charge profile and operational conditions, that may obscure the comparative evaluation.

8.9 SUMMARY

The selection of the optimal charger for a given application is a function of several parameters. The variables that most directly influence the user are charge profile adjustability, AC to DC efficiency, and cost. The DC ripple current level may also have an impact on battery life. Power factor and harmonic distortion values are also of concern, but their potential for direct impact on the user is dependent upon the electric rate schedule and the use of sensitive equipment on the same circuit.

9. POWERTRAIN SYSTEMS

9.1 AC VS. DC SYSTEMS

The MTD battery-electric transit vehicle fleet utilizes powertrain systems that incorporate DC shunt motors (separately excited) and AC induction motors. Because batteries produce direct current, DC motor systems are able to directly utilize battery energy; AC motor systems, on the other hand, must have the DC battery current "inverted" to alternating current prior to utilization.

Early electric vehicle designs made use of DC-based powertrains because of the relatively simple design of the attendant speed control devices. The separately excited DC motor exhibits moderate efficiency but is larger and heavier than an AC motor of comparable power, and it is more likely to produce radio-frequency interference. The AC induction motor, on the other hand, exhibits high efficiency, a favorable power to size/weight ratio, is more robust and less expensive than a DC motor, and can produce more regenerative braking energy than the DC motor. The inverter electronics can also be used in some designs to rectify an AC signal, thereby also allowing operation as a battery charger. The cost of the inverter/controller associated with an AC powertrain is far greater than that for the DC-based system, however.

9.2 CONVERSION OF 22-FOOT ELECTRIC BUS FROM DC TO AC DRIVE

MTD is presently in the process of retrofitting its 22-foot electric transit bus with an AC drive. A comparison of the salient features of the two powertrains is presented in Table 28.

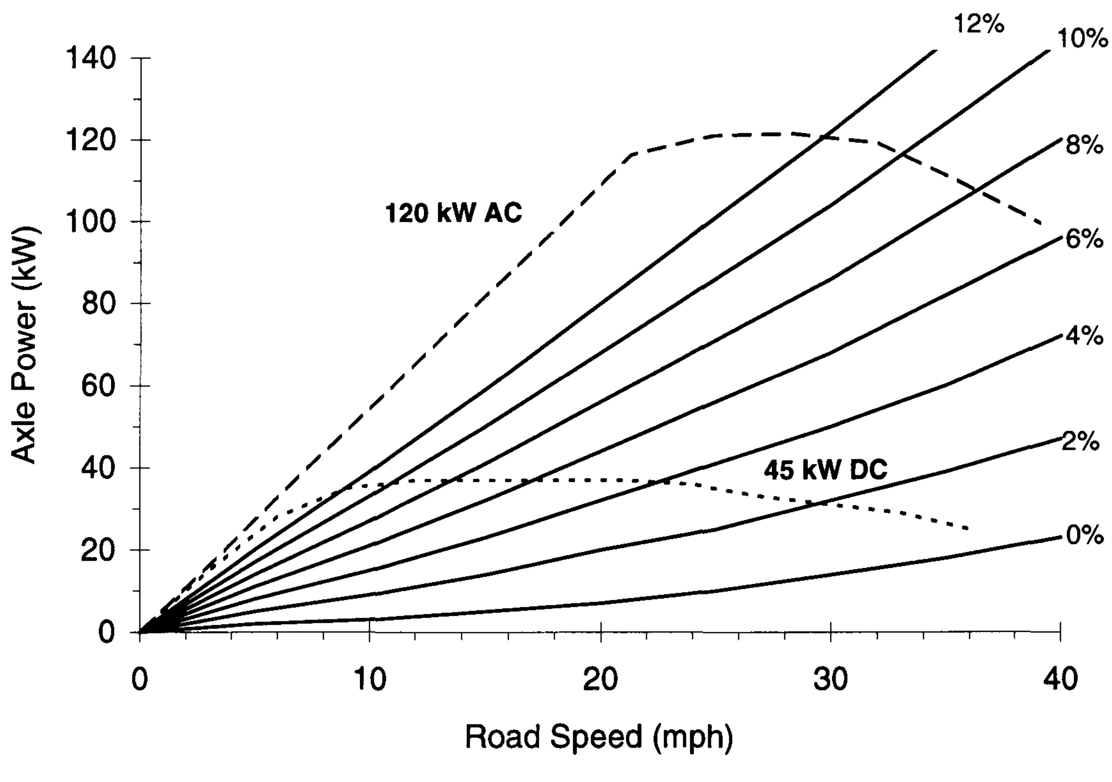
Table 28. Comparison of DC and AC Powertrains for 22-Foot Electric Bus

	DC (Separately Excited)	AC (Induction)
Peak Power Rating	45 kW	120 kW
Continuous Power Rating	30 kW	50 kW
Weight		
Motor	385 lbs.	360 lbs.
Controller / (Inverter)	99 lbs.	110 lbs.
Power Distribution Unit	---	35 lbs.
Total	**484 lbs.**	**505 lbs.**

Source: Nelco, Power Control Systems, SBMTD/ETI

A motor's power rating determines the time-rate at which electrical energy can be converted to mechanical energy. Higher power output translates into greater achievable speeds and acceleration. The power necessary to propel a vehicle under constant velocity conditions is a function of rolling resistance, incline resistance, and aerodynamic drag. An analysis of required power includes such parameters as tire rolling resistance coefficient, drag coefficient, vehicle frontal area, vehicle weight, road gradient, and vehicle speed. The capacity of a drivetrain to deliver power to the vehicle drive axle at any given road speed is a function of the motor shaft torque and rotational speed, the gear reduction ratio, the tire rolling radius, and the drivetrain power transmission efficiency.

A plot of required and available axle power is presented in Figure 25 for the 22-foot transit bus traveling at constant velocity under full-seated load conditions. The dashed lines represent the power that can be delivered to the axle on an intermittent basis by both the DC and AC powertrains as a function of road speed. The family of curves depicted by the solid lines represent the necessary axle power to climb the indicated road gradient as a function of road speed. The region under each dashed line represents the vehicle speed on gradient that can be achieved by the respective drivetrains. For example, it is evident from this analysis that on an 8% gradient, the 120 kW AC powertrain can maintain a speed of 37 mph, while the 45 kW DC powertrain can deliver a vehicle speed of only 14 mph (it may be noted from Table 28 that the two motors are of approximately the same weight).



Source: Nelco, Power Control Systems, SBMTD/ETI

Figure 25. Required/Avail. Power vs. Road Speed/Gradient for 22-Foot Electric Bus

In addition to influencing the speed with which a vehicle can travel under a given road/load condition, the powertrain also dictates the efficiency at which electrical energy is converted to rotational kinetic energy, and will therefore also influence the range of the vehicle. The energy consumption rate of the AC system is expected to be more favorable than that of the DC system given its higher inherent efficiency and its greater anticipated production of regenerative braking energy. The objective of the forthcoming test evaluation is to demonstrate such performance issues under real-world conditions, however, and to provide important comparative data.

10. ACCESSORY EQUIPMENT

10.1 Importance of Energy Efficiency

As previously discussed, the lack of abundant on-board energy is the bane of battery-electric vehicle technology. Consequently, accessory equipment of interest to the EV industry centers primarily on energy efficient components and systems.

10.2 Heaters and Air Conditioners

The accessory components that consumes the greatest quantities of energy, and therefore that affords the greatest potential savings from efforts to improve energy efficiency, are those relating to vehicle climate control.

At least two companies are presently developing advanced, compressor-driven, high-efficiency air conditioning systems that will purportedly operate at energy consumption levels 50% to 75% less than that achievable with conventional automobile systems. While such systems offer the potential for successful application to electric-bus climate-control requirements, the present stage of development renders such systems cost prohibitive.

MTD has also explored evaporative cooling systems as a potential solution to air-conditioning requirements. This technology utilizes the reduction in temperature that accompanies the phase change of water from the liquid state to the vapor state. Air is forced by a blower through a saturated media whereupon cooling accompanies the evaporation process. Because the air humidity increases upon passage through the media, the air is not recirculated but instead is ventilated to the vehicle exterior, thereby preventing an unacceptable increase in humidity level. In addition to the evaporative cooling unit that contains the saturated media, a water tank is required. A typical transit bus system would consist of 600 pounds of equipment (1225 pounds when filled with water), would draw approximately 2 kW of power, and would achieve 116,600 BTU/hr cooling capacity at 95°F dbt / 65°F wbt. It is questionable whether such a system would be effective in high-humidity climates, however.

Internal-combustion engine powered vehicles warm the passenger compartment by the utilization of waste heat from the engine. Because of the increased efficiency with which an electric vehicle operates, less waste heat is available for this purpose. The electric vehicle must therefore rely on other means to achieve passenger-compartment heating. As discussed in Section 4.8, the energy consumption associated with resistance heating elements is very high. As a result, liquid-fuel fired heaters are frequently used in EVs to perform space-heating and defrost functions. The electric power load for a 16,000 BTU/hr unit is only 80 watts. Unfortunately, the regulations concerning the incorporation of such devices in EVs are not settled. Present policy requires that in order for electric vehicles under 8,000 pounds to maintain ZEV certification, an integral fuel-fired heater must be provided with an interlock that prevents heater operation at ambient temperatures greater than 40°F. The regulations for the transit bus class vehicle have not yet been formulated with respect to this issue, however.

Several developments are underway in which space heating and cooling functions are integrated into a single system. One alternative incorporates a reversible heat pump, as is utilized on GM's Impact. Transfer of such technology from a two-seat automobile to a transit bus application may involve more than simple scaling, however.

Another integrated systems approach, proposed by Amerigon Corporation, strives to heat and cool the occupant directly, rather than the entire vehicle interior. This is accomplished by convective heat transfer resulting from the delivery of heated or cooled air directly to the occupant's body via a variable temperature seat. The system is based upon Peltier thermoelectric heat pumping; no refrigerants are used, and the only moving parts are blower and fan motors. Energy consumption is estimated at 120 to 300 watts per seat. This technology is still in the prototype stage, however, and the attendant cost is presently impractical for all but demonstration programs.

Until such time that energy efficient climate control systems mature and become commercially affordable, passenger heating and cooling tasks are probably best handled by fossil fuel driven apparatus, despite the potential loss of ZEV consideration.

11. ENERGY CONSUMPTION

11.1 OVERVIEW

The respective energy contents [24,25] of several storage elements is presented in Table 29. The energy storage capacity of a rubber band has been included for reference because it is a storage medium with which most readers are familiar (i.e., rubber-band-powered toy propeller airplanes). Unfortunately, it is readily apparent from Table 29 that chemical batteries are closer to the rubber-band end of the energy storage spectrum than to the fossil-fuel end. Given such disparity in energy content, the fact that battery-powered vehicles can be successfully integrated into any transportation applications at all is testament in part to the relatively high efficiency with which the electric powertrain converts electrical energy to mechanical energy (as well as to the increased mass and volume allocated for batteries in an EV relative to that allotted for fossil fuel in an internal-combustion vehicle).

Table 29. Energy Capacity of Various Storage Elements

Storage Element	Specific Energy	Energy Density
Natural Rubber Band	9 Wh/kg	10 Wh/L
Pb-Acid Battery	40 Wh/kg	110 Wh/L
Ni-Cd Battery	52 Wh/kg	114 Wh/L
Ni-MH Battery	71 Wh/kg	172 Wh/L
Zn-Air Battery	215 Wh/kg	252 Wh/L
Gasoline	11,600 Wh/kg	8,650 Wh/L
Diesel #2 Fuel	11,600 Wh/kg	10,000 Wh/L

Source: Marks' Stnd Hndbk for ME's, Chloride, Trojan, Saft, GM Ovonic, Electric Fuel, API, SBMTD/ETI

11.2 ELECTRIC VEHICLE ENERGY CONSUMPTION

The BTU energy consumption per mile associated with electric vehicle operation is equal to the product of the AC energy consumption per mile times the BTU energy content of an electrical kWh (3,412 BTU per kWh[26]). For MTD's electric shuttle vehicle,

$$Energy\ Consumption_{\text{electric shuttle vehicle}} = \left(\frac{1.34\ AC\ kWh}{mile}\right)\left(\frac{3{,}412\ BTU}{AC\ kWh}\right) = \frac{4{,}570\ BTU}{mile}$$

[24] Theodore Baumeister, ed., Marks' Standard Handbook for Mechanical Engineers, Eighth Edition, McGraw-Hill

[25] API Publication 4261, Second Edition, American Petroleum Institute

[26] Theodore Baumeister, ed., Marks' Standard Handbook for Mechanical Engineers, Eighth Edition, McGraw-Hill

For MTD's 30-foot Electric-Villager bus conversion,

$$Energy\ Consumption_{\ 30'\ Electric\ Villager\ Conversion} = \left(\frac{1.90\ AC\ kWh}{mile}\right)\left(\frac{3{,}412\ BTU}{AC\ kWh}\right) = \frac{6{,}480\ BTU}{mile}$$

11.3 Diesel Vehicle Energy Consumption

Energy consumption associated with diesel vehicle operation is equal to the product of the diesel fuel consumption per mile times the energy ("heat") content of diesel fuel (129,000 BTU per gallon). For MTD's standard 30-foot diesel Villager bus,

$$Energy\ Consumption_{\ 30'\ diesel\ Villager} = \left(\frac{1\ gal.\ diesel\ \#2}{5.8\ miles}\right)\left(\frac{129{,}000\ BTU}{gal.\ diesel\ \#2}\right) = \frac{22{,}000\ BTU}{mile}$$

11.4 Energy Consumption Comparison

Referring to the foregoing calculations, it is evident that the replacement of a diesel propulsion system with an electric one on the 30-foot Villager bus reduced the vehicle's energy consumption rate by approximately 70%. The energy consumption rate of the electric shuttle vehicle is 80% less than the diesel Villager which it replaced on the Downtown-Waterfront service route.[27]

[27] This simplified energy consumption analysis does not evaluate the entire energy chain, but rather contemplates "point-of-use" consumption only. For example, prior to diesel fuel combustion, a barrel of crude oil must first be refined and then transported to the subject vehicle's fuel tank. Likewise, prior to electrical energy consumption by a battery charger, a barrel of crude oil must first be processed in a power plant, and the generated electricity must then be transported over transmission lines and through distribution networks.

12. EMISSIONS

12.1 OVERVIEW

The transportation sector has primarily been built upon the internal-combustion engine and fossil fuels. Fossil fuels consist of hydrocarbon chains of variable length, depending on fuel type. Other chemical elements, such as sulfur, may also be present. Perfect combustion in air would convert all of the carbon present to carbon dioxide (CO_2) and all hydrogen to water (H_2O). Unfortunately, perfect combustion is not realizable in an internal combustion engine. The result is that some hydrocarbon burns incompletely to form carbon monoxide (CO), while some hydrocarbon may not burn at all, thereby producing volatile organic compounds (VOCs), also referred to in California as reactive organic gases (ROGs). Any sulfur in the fuel will convert to sulfur dioxide (SO_2). Furthermore, high combustion temperatures cause some of the nitrogen in the air to combine with oxygen to form nitrogen oxides (NO_x).[28]

Water and CO_2 are generally considered harmless emissions. Although CO_2 has no direct adverse effect on people, animals, or plants, there is some concern that substantial increases in CO_2 will promote the Greenhouse Effect (heating of the earth's atmosphere). All other combustion gases are clearly harmful, however. Carbon monoxide deprives the blood of oxygen, SO_2 forms sulfurous and sulfuric acids that deteriorate lung tissue, plants, and paint (particularly if accompanied by small particulates), and the NO_x and ROGs (hydrocarbons) combine in sunlight to form harmful ground-level ozone.[29]

Obviously, the emissions associated with electric vehicle operation are produced at the power generating facility that is producing the electrical energy necessary to accomplish recharge of the vehicle's batteries; no emissions are produced at the vehicle itself. The precise emissions profile associated with a kWh of electricity is dependent upon the fuel ("power mix") used to produce the electric power. Further complicating any analysis is the fact that the power mix often fluctuates with time of day. Therefore, the actual reduction in emissions achievable with the utilization of electric transportation is sensitive to the particular emission component, the fuel mix associated with the power generation facilities, and the time of day during which battery recharge is effected. Given the spectrum of power generation sources (including coal, oil/gas, nuclear, hydroelectric, geothermal, wind, solar, cogeneration, and biomass), the actual EV emissions picture is variable and dependent upon regional power sources.

Electric vehicles are considered advantageous even in regions where relatively "dirty" fuels are used to produce electric power, however. In Hong Kong, for instance, where electric power is produced by coal, battery-electric transportation is still deemed highly desirable because of its ability to displace emissions away from the highly populated urban center.[30] Also, emissions attendant to EV recharge are often produced at night,

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[28] George Beakley, Introduction to Engineering Design and Graphics, Macmillan Publishing Co.
[29] Ibid.
[30] Private communication: Raymond Leung (Environmental Protection Department, Air Services Group, Hong Kong) to P. Griffith, February 1995

thereby reducing the formation of harmful ozone, a photochemical process that requires the presence of light.

The following analysis covers emissions associated with MTD's diesel and electric bus fleet. Emission components evaluated are NO_x, ROGs, PM10 (particulate matter of 10 microns or larger size), and CO. SO_2 has not been addressed because data concerning diesel vehicle SO_2 generation was not available.

12.2 DIESEL-POWERED VILLAGER

12.2.1 Local Diesel Emissions

The emissions associated with the operation of MTD's diesel-powered vehicle can be calculated as follows:[31]

$$\text{Emissions (g / mi)} = \text{Emission Rate}\,\frac{\text{Fuel Density}}{\text{(Brake Specific Fuel Consumption) x (Fuel Efficiency)}}$$

where:

$$\text{Fuel Density} = 7.16 \text{ lb / gal}$$

$$\text{Brake Specific Fuel Consumption} = 0.4 \text{ lb / bhp - hr}$$

$$\text{Fuel Efficiency} = 5.8 \text{ mi / gal}$$

The grams per brake horsepower-hour (bhp-hr) emission rates for the 8.2 liter turbocharged diesel engine utilized in the Villager bus are presented in Table 30.[32]

Table 30. Emission Rates for 1988 8.2L Diesel Engine

Emission	NO_x	HC (ROG)	PM10	CO
g / bhp-hr	8.3	0.5	0.41	2.0

Source: General Motors Powertrain Division, SBMTD/ETI

The resulting gram per mile emissions attendant to the diesel-powered Villager operation are presented in Table 31.

[31] The above reflects only tailpipe emissions. Air pollution control districts are also concerned with emissions that evaporate from the vehicle, refueling emissions, diesel tanker truck emissions, and refinery emissions.

[32] M. J. Bonello, 8.2L Diesel Certification for 1988 Model Year, General Motors Powertrain Division

Table 31. Emissions Associated with Diesel Villager Bus Operation

Emission	NO_x	HC (ROG)	PM10	CO
grams per mile	25.6	1.5	1.27	6.2

Source: General Motors Powertrain Division, SBMTD/ETI

12.3 Electric Vehicle Emissions

12.3.1 Local EV Emissions

There are no tailpipe emissions and no Southern California Edison power plants in the Santa Barbara Air Pollution Control District (SBAPCD). Therefore, the operation of MTD's electric bus fleet does not result in any local emissions.

12.3.2 Regional EV Emissions

Data concerning estimated emissions generated in the South Coast Air Quality Management District (SCAQMD, Greater Los Angeles Area) associated with electric energy consumption during off-peak periods is presented in Table 32. This information, provided by Southern California Edison,[33] is developed from 1993 data and has been weighted to account for the percentage contribution of the various fuels in use during the off-peak period when the MTD vehicles are recharged.

Table 32. Estimated Off-Peak Power Generation Emissions in SCAQMD in 1993

Emission	NO_x	ROG	PM10	CO
Weighted lbs/MWh	0.256	0.014	0.007	0.051

Source: SCE, SBMTD/ETI

The conversion from pounds per megawatt-hour (MWh) to grams per mile entails accounting for the AC kWh energy consumption per mile driven, the power transmission line loss factor from the power plant to the recharge facility, and a conversion factor:

$$\text{Emissions (g / mi)} = \frac{\text{Weighted Emission Factor (lbs / MWh) x (EV Energy Consumption Rate) x (Conversion Factor)}}{\text{(Transmission Line Loss Factor)}}$$

where:

Transmission Line Loss Factor = 0.91 (9% power loss)

Conversion Factor = 0.454 (454 grams / pound; 1,000 kWh / MWh)

The emissions associated with the recharging of two of the vehicle types in MTD's electric bus fleet is presented in Table 33.

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[33] Private communication: Dean Taylor (Southern California Edison) to P. Griffith, February 1995

Table 33. SCAQMD Emissions Associated with MTD Electric Bus Recharge

Emission	NO_x	ROG	PM10	CO
Electric Shuttle Vehicle (@ 1.35 AC kWh/mi)	0.166 g/mi	0.009 g/mi	0.005 g/mi	0.034 g/mi
Electric Villager (@ 1.90 AC kWh/mi)	0.233 g/mi	0.013 g/mi	0.007 g/mi	0.048 g/mi

Source: SCE, SBMTD/ETI

Southern California Edison estimates that approximately 34% of the off-peak power used to recharge the electric buses comes from Los Angeles area power plants; the balance of the power is generated out of state.

12.3.3 Total EV Emissions

As previously stated, only 34% of the off-peak power used to recharge the electric buses is generated within the greater Los Angeles basin. Unfortunately, computation of the total emissions from all power generation facilities is more complicated than a simple tripling of the regional emissions because of a different, but unknown, power mix associated with out-of-state off-peak power generation. A previous study conducted by MTD that assumed *average* emissions analysis (on-peak, mid-peak, and off-peak power generation) rather than marginal emissions (off-peak power period only) suggested that under average emission conditions, the total emissions (NO_x, ROG, PM10, and CO) associated with operating the Electric Villager Bus are only approximately 5% that of its diesel-powered counterpart. Actual emissions associated with off-peak charging would be somewhat less.

12.4 Emissions Comparison

12.4.1 Diesel Villager vs. Electric Villager

Emissions associated with operation of the Diesel Villager and its electrified counterpart are presented in Table 34.

Table 34. Comparative Emissions from Diesel and Electric Powered Villager Buses

Emission	Diesel Villager	Electric Villager		
	Local	**Local**	**Regional**	**Total**
NO_x	25.6 g/mi	0	0.233 g/mi	n/a
ROG	1.5 g/mi	0	0.013 g/mi	n/a
PM10	1.27 g/mi	0	0.007 g/mi	n/a
CO	6.2 g/mi	0	0.048 g/mi	n/a
Total	34.6 g/mi	0	0.301 g/mi	<5%
Comparative	**100%**	**0%**	**0.9%**	**<5%**

Source: SBMTD/ETI

12.4.2 Diesel Villager vs. Electric Shuttle Vehicle

Emissions associated with operation of the MTD Electric Shuttle Vehicle and the vehicle that it replaced on the Downtown-Waterfront Route, the Diesel Villager, are presented in Table 35.

Table 35. Comparative Emissions from Diesel Villager and Electric Shuttle Vehicle

Emission	Diesel Villager	Electric Shuttle		
	Local	**Local**	**Regional**	**Total**
NO_x	25.6 g/mi	0	0.166 g/mi	n/a
ROG	1.5 g/mi	0	0.009 g/mi	n/a
PM10	1.27 g/mi	0	0.005 g/mi	n/a
CO	6.2 g/mi	0	0.034 g/mi	n/a
Total	34.6 g/mi	0	0.214 g/mi	<3%
Comparative	**100%**	**0%**	**0.6%**	**<3%**

Source: SBMTD/ETI

During the 279,679 miles traveled by the Electric Shuttle Fleet on the Downtown-Waterfront Route from January 1991 through December 1994, the emissions reductions achieved by the replacement of the Diesel Villager by the Electric Shuttles is presented in Table 36.

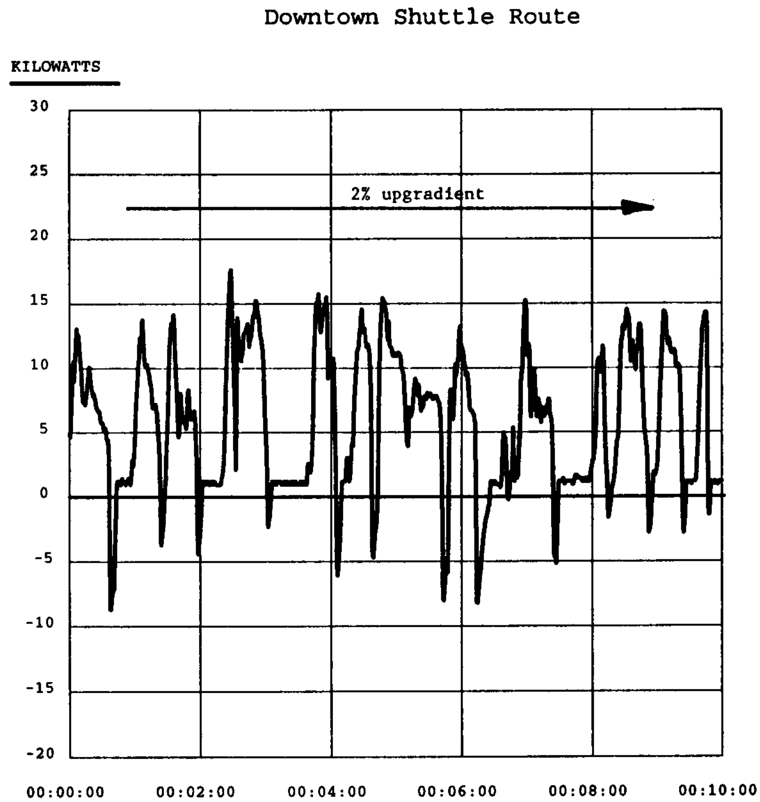
Table 36. Emissions Reduction from 279,679 miles of Electric Shuttle Operation

Emission	Diesel Villager	Electric Shuttle		
	Local	**Local**	**Regional**	**Total**
NO_x	15,800 lbs.	0	102 lbs.	n/a
ROG	920 lbs.	0	6 lbs.	n/a
PM10	780 lbs.	0	3 lbs.	n/a
CO	3,800 lbs.	0	21 lbs.	n/a
Total	**21,300 lbs.**	**0**	**132 lbs.**	**<3% (600 lbs.)**

Source: SBMTD/ETI

It is clearly evident from Table 36 that in addition to creating a marketing success, the implementation of the Electric Shuttle on MTD's Downtown-Waterfront Route has also had a phenomenally positive impact on the environment, having prevented the generation of over 10 tons of pollution during the four years of operation.

APPENDIX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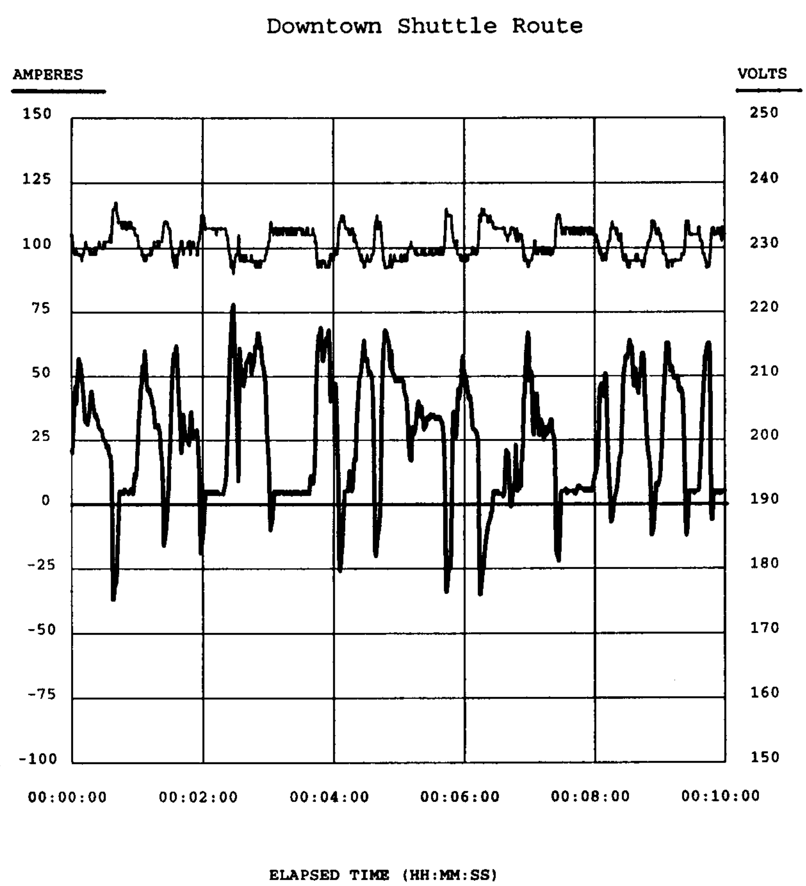
Downtown Shuttle Route
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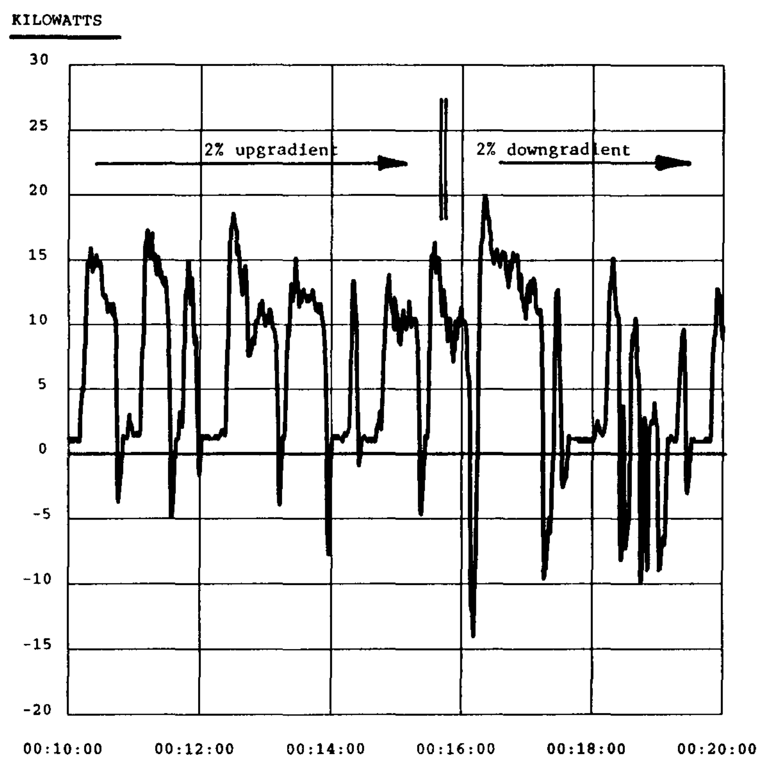
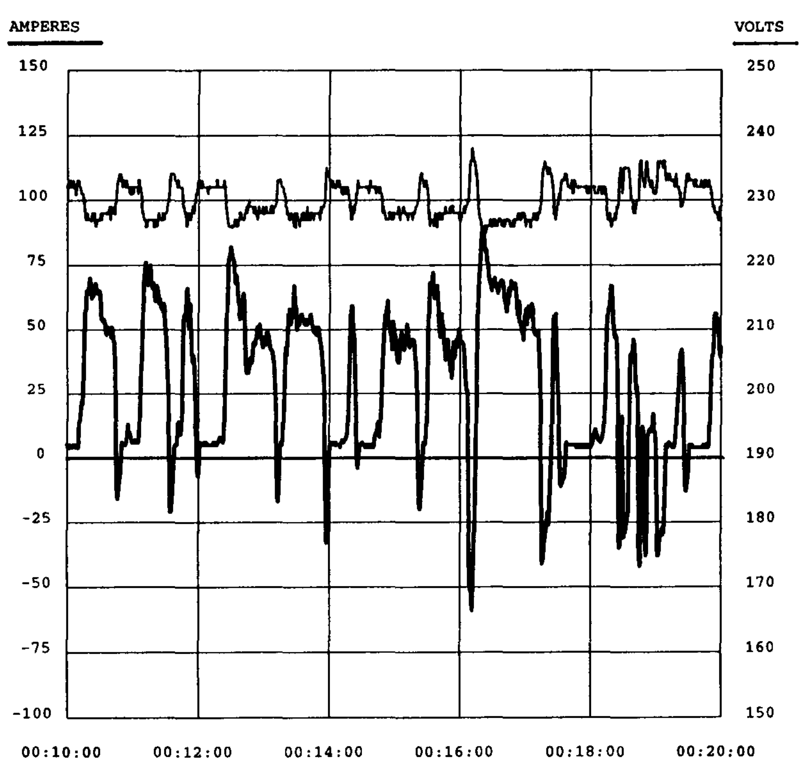
Downtown Shuttle Route



Downtown Shuttle Route



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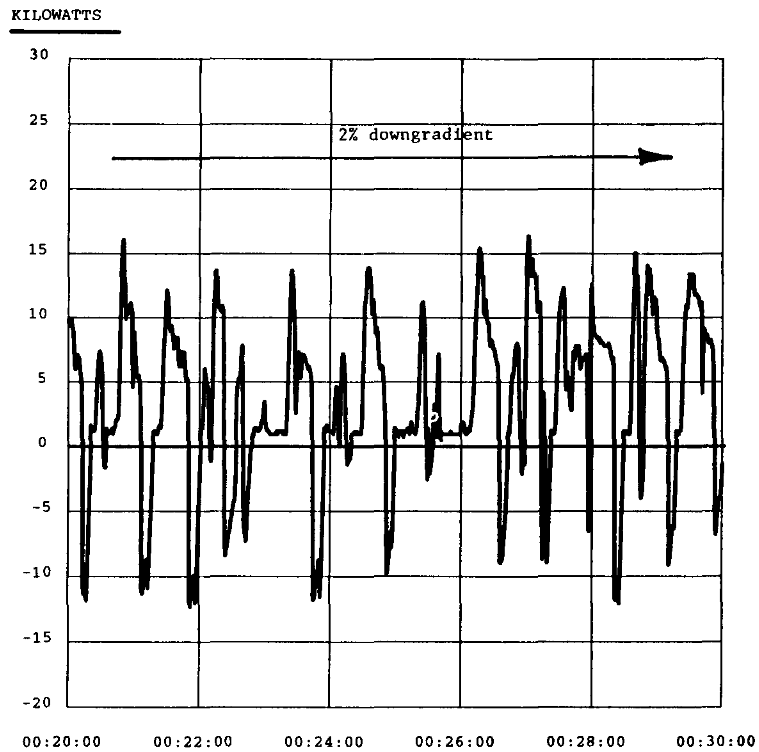
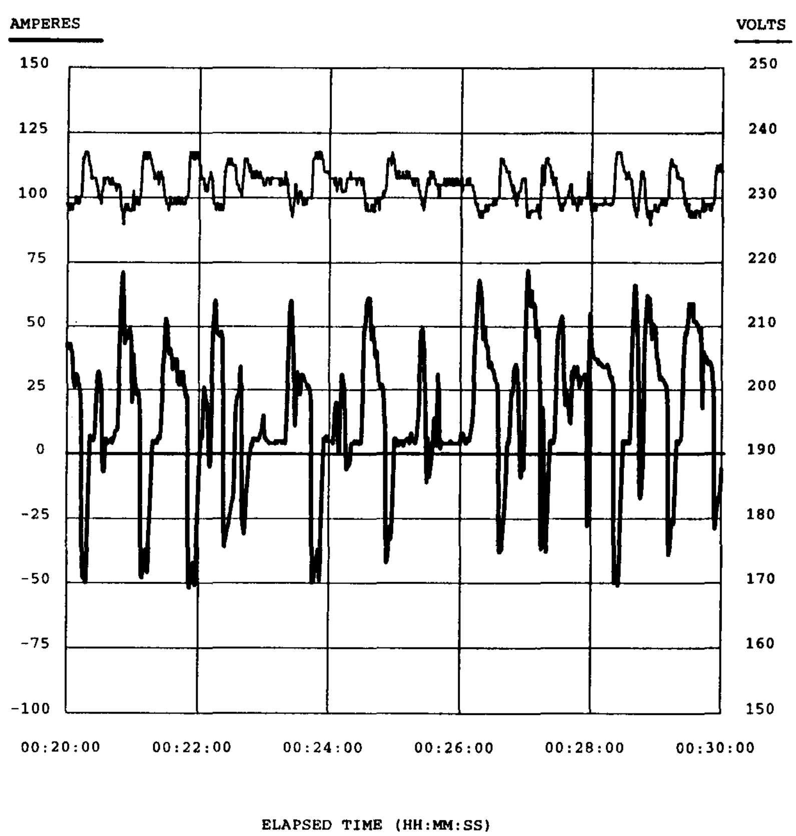
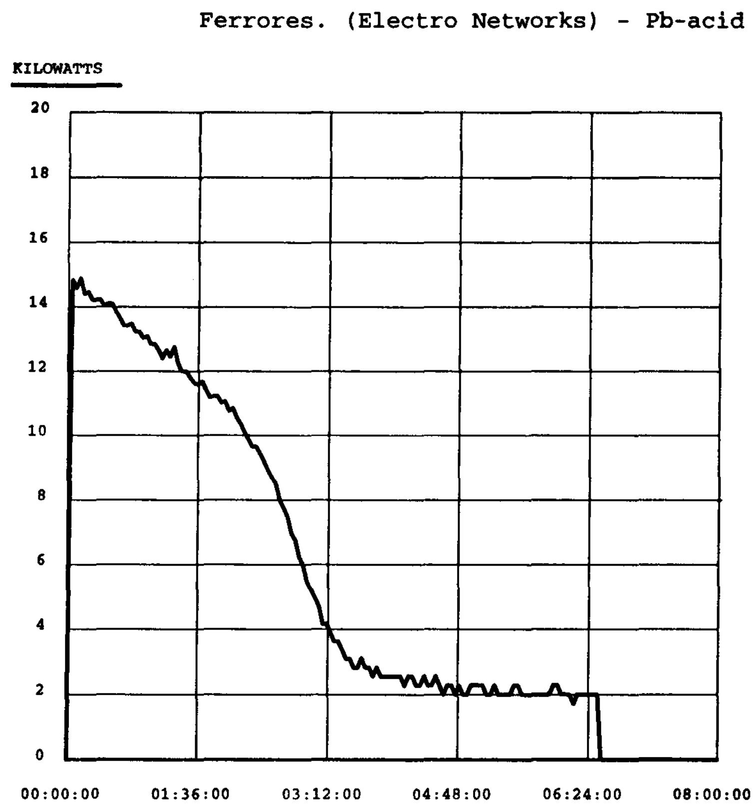


Downtown Shuttle Route




Ferrores. (Electro Networks) - Pb-acid
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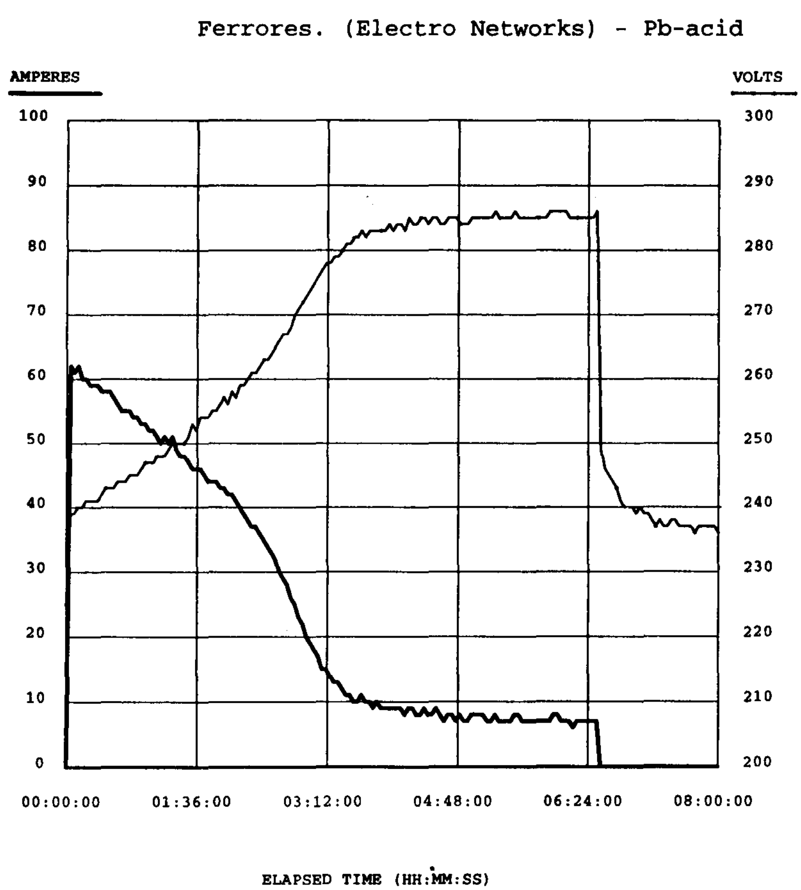
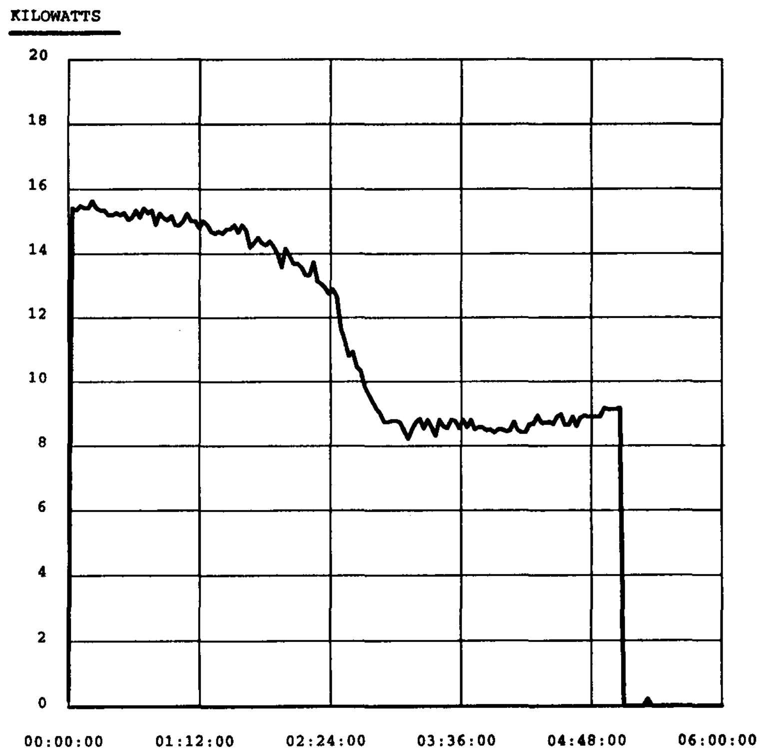
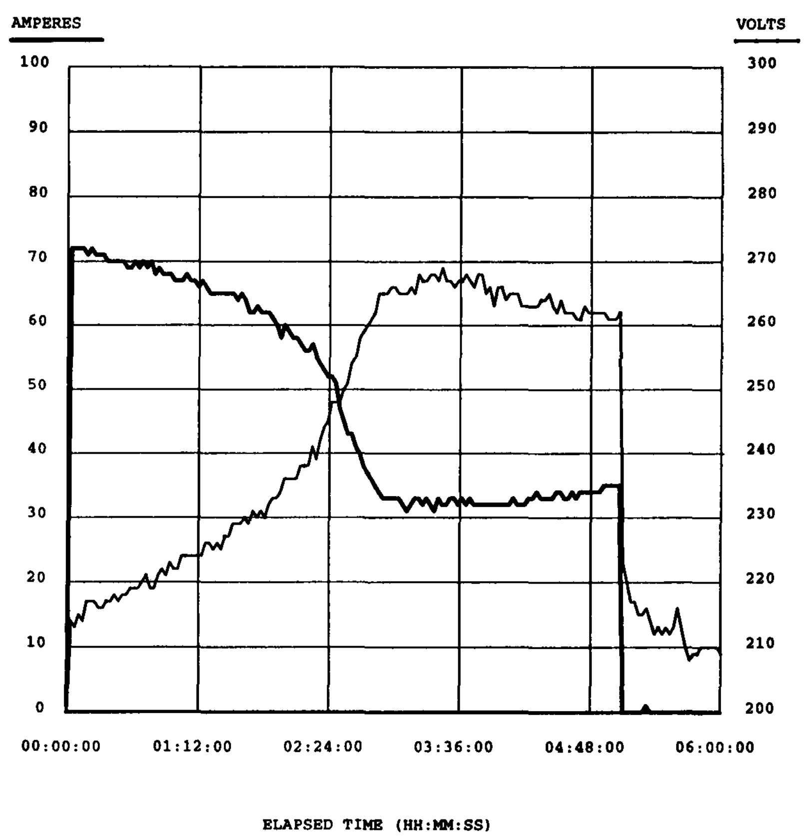
06:24:00
08:00:00


Ferrores. (Electro Networks) - Pb-acid
AMPERES
VOLTS
100
90
80
70
60
50
40
30
20
10
0
300
290
280
270
260
250
240
230
220
210
200
00:00:00
01:36:00
03:12:00
04:48:00
06:24:00
08:00:00
ELAPSED TIME (HH:MM:SS)

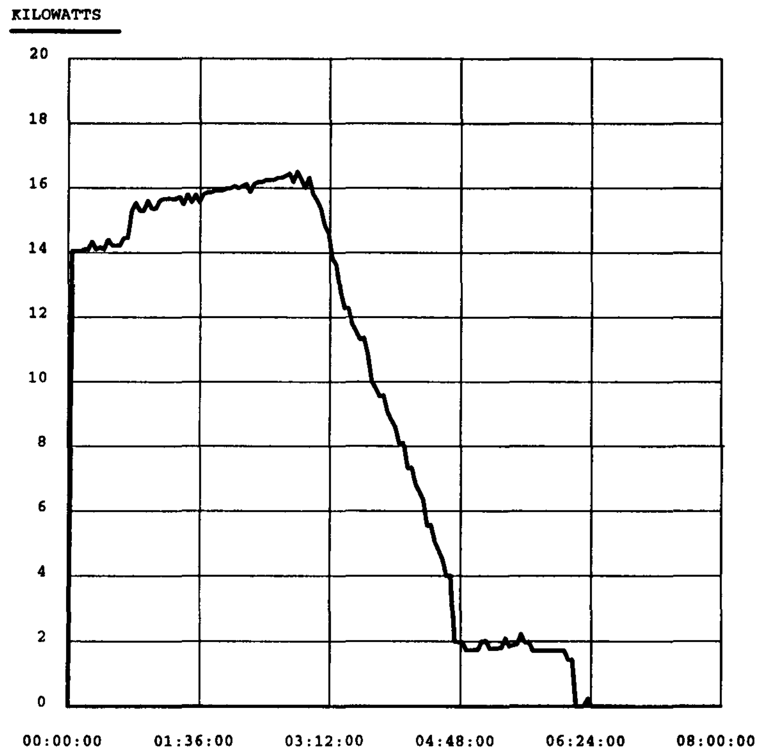
Ferrores. (Chloride Spegel) - Pb-acid



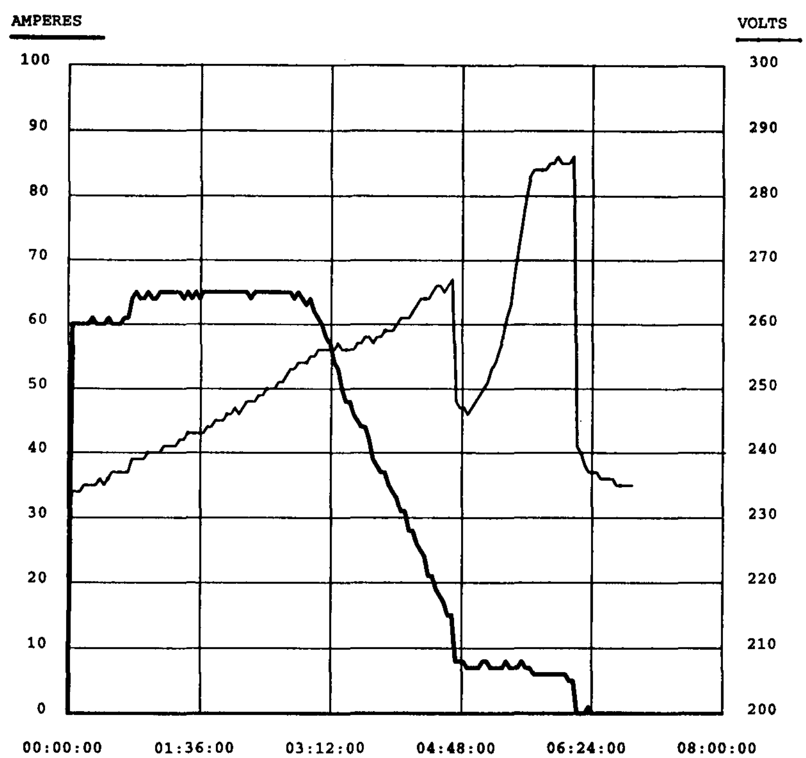
Ferrores. (Chloride Spegel) - Pb-acid



3 SCR (LaMarche) - gel Pb-acid

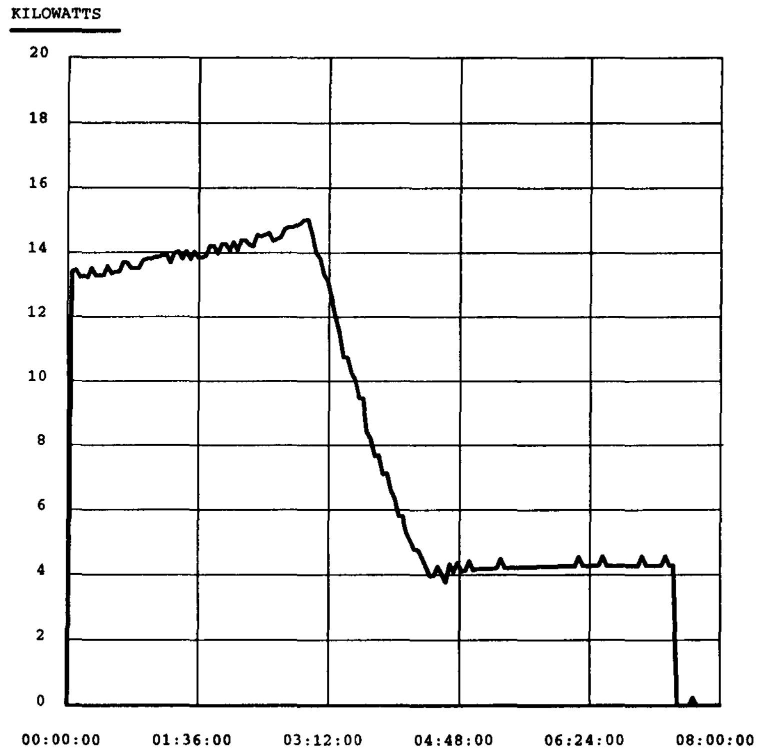


3 SCR (LaMarche) - gel Pb-acid

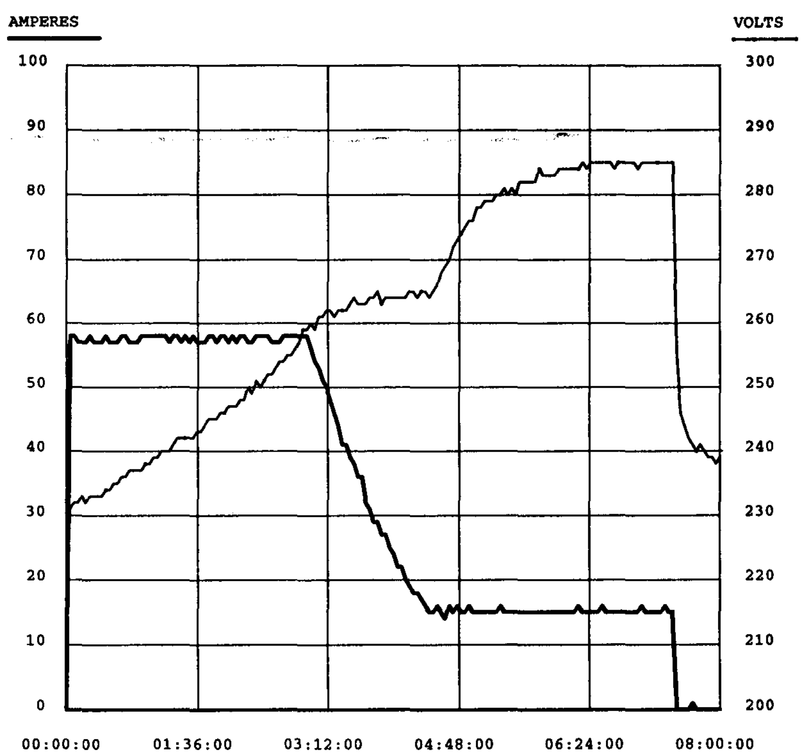


ELAPSED TIME (HH:MM:SS)

12 SCR (Enerpro) - Pb-acid

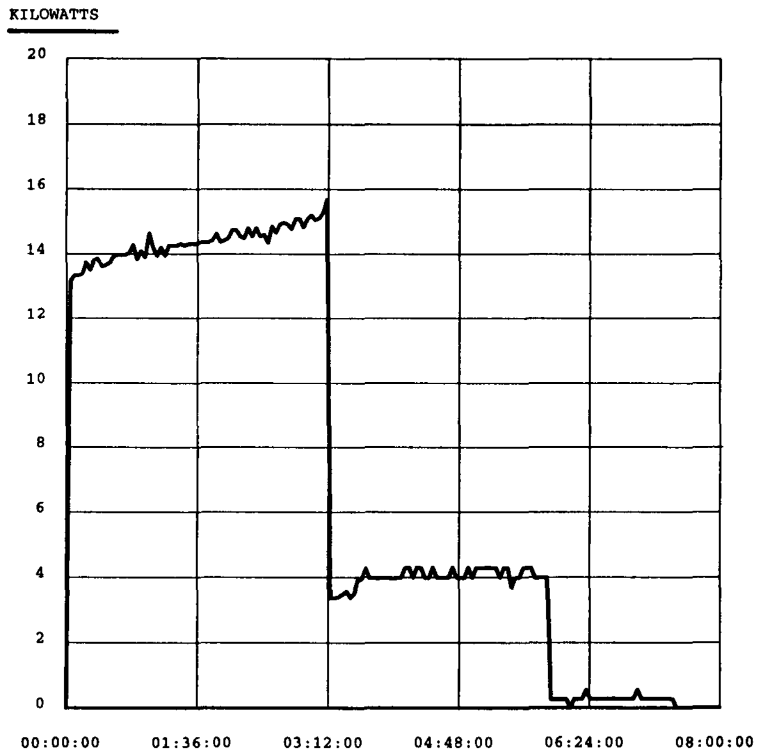


12 SCR (Enerpro) - Pb-acid

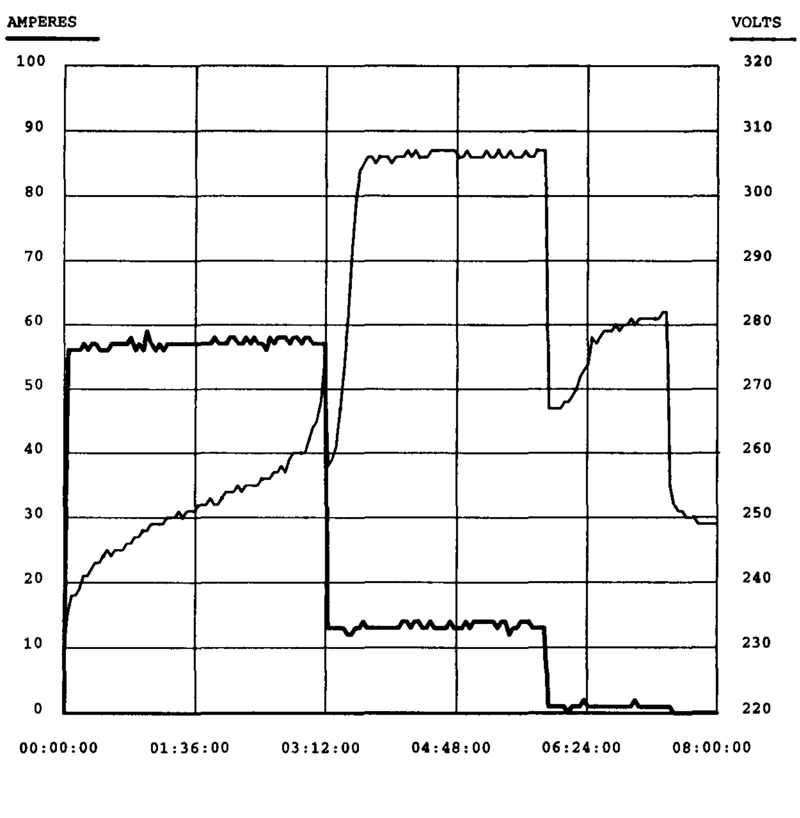


ELAPSED TIME (HH:MM:SS)

12 SCR (Enerpro) - Ni-Cd



12 SCR (Enerpro) - Ni-Cd



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