Lessons Learned: Battery-Electric Transit-Bus Opportunity Charging

Interim Report

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REPORT SUMMARY

This document details the results of a study of battery-electric bus opportunity charging. This document is an interim report pending conclusion of further experiments with at least one other rapid-charging system and battery type.

Background

Battery-electric buses have shown to be an economical and ecologically sound alternative to conventionally fueled transit buses in many applications. Limited on-board energy stores restrict the useful range of battery-electric buses and constrain their use of on-board climate control systems. Air-conditioning systems can reduce the useful range of electric buses by up to 30%, making the buses unattractive to transit operators for many applications. Heretofore, the only practical way to extend the range of battery-electric buses has been to schedule breaks in service to swap the discharged batteries for fully charged units. This battery swapping technique takes the buses off their routes, requires the use of trained maintenance personnel to accomplish the change, and inflates program expenses by the cost of the extra batteries and necessary infrastructure. Operators have recognized that an alternative to battery swapping would be to use short layover periods in route schedules to partially recharge the bus batteries. Unfortunately, the battery chargers normally furnished with battery-electric buses take from six to ten hours to accomplish a full charge and cannot accomplish a meaningful recharge in the short periods usually available during scheduled service. Battery chargers with higher charging rates (over 40 kW) can return a useful quantity of energy to bus batteries during reasonable layover periods though. Doubts regarding the utility of operating with such a duty cycle have prevented the widespread adoption of opportunity charging. Other questions, not yet definitively answered, involve the relationships between the charging and maintenance protocols and the longevity of opportunity-charged traction batteries, infrastructure, labor, and energy costs.

Objectives

To develop a guidance document for organizations considering the planning and implementation of electric-bus opportunity charging.

Approach

Review previous and ongoing opportunity/rapid-charging projects at the Santa Barbara Metropolitan Transit District (MTD) and the Santa Barbara Electric Transportation Institute. Survey recent and current literature on the topic and review pertinent articles. Synthesize the major lessons learned to date and produce a document illustrating their importance by illuminating their relationships to the economic, operational, and technological constraints under which battery-electric transit buses are deployed.

Results

Opportunity charging is a developing technique with considerable potential for extending the service capabilities of battery-electric buses. Study has revealed the need for an appropriate relationship between equipment capabilities and operational procedures in order to sustain an acceptable battery cycle life and consequent control of program costs.

EPRI Perspective

Interest Categories

Electric transportation operations

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1 EXECUTIVE SUMMARY

Battery-electric buses do not generally have all of the performance capabilities of fluid-fueled buses. The performance differences between the fuel types result from the weight and volume required to store a given amount of energy on-board the vehicles. Fortunately, battery-electric bus performance is adequate to allow their substitution for fluid-fueled buses in a significant portion of transit bus operations. That proportion of transit operations appropriate for electric-buses can be appreciably expanded through adaptations of equipment and operational tactics, most especially through tactics such as opportunity charging where layovers in scheduled route service are used to partially recharge the bus batteries. Several demonstration projects have shown that opportunity charging increases electric-bus utility, but developing efficient solutions for any particular application remains a difficult engineering task.

Properly implemented, an opportunity charging or battery swapping tactic will extend the operational margins of a bus/battery combination, extending its otherwise limited range. Improperly implemented, opportunity charging and battery swapping schemes can marginalize the capabilities of an electric-bus program and make an otherwise promising system too costly or too unreliable for provision of an essential public service.

Three "keys" characterize all successful electric-bus programs, and they are especially important to programs where the technology's limits are regularly challenged, such as with opportunity charging. The crucial principles are an organizational commitment to program success, undertaking a significant enough program to justify that required commitment, and operating with duty cycles appropriate to the technology. These three principles are kept in the forefront when considering new techniques such as opportunity charging.

Charging is normally conducted at a low rate that will return 60% to 70% of the battery's discharged energy within six hours, returning it to a state-of-charge of about 80% to 90% of its capacity. The normal charging then reverts to an even lower rate to complete the charging (to 100% state-of-charge or SOC) in another 2 to 4 hours (8 to 10 hours total charging). Opportunity charging is a range extension technique that should be distinguished from the terms "rapid" or "fast" charging which refer to a charging rate higher than normal charging. Making opportunity charging a useful technique for transit operators will usually involve charging at higher rates (greater amperage) than conventional overnight battery charging.

Most battery types appear to exhibit increased lifetime energy throughput in partial state-of-charge (PSOC) operation compared with traditional deep cycling in which the battery is cycled between a full (100%) state-of-charge and its minimal (20%) state-of-charge. Charging at currents higher than two to three times normal rates may produce similar effects but also produces heat that can shorten battery life if not effectively removed. Development of effective battery cooling systems and their integration into electric buses remains a significant engineering challenge.

The operational tempos potentially allowed by opportunity charging can amplify weaknesses in electric buses at a rate that may overwhelm maintenance expertise and budgets that would otherwise be sufficient. Planning of extended-range operations should include consultation with manufacturers of the bus, battery, and charger at an early stage. Inexperienced electric-bus operators should contemplate gaining at least minimal familiarity with maintenance and operations at a less intensive tempo before implementing extended-range procedures.

The higher costs of electric-bus operations compared with their diesel-fueled counterparts are often cited as a barrier to their wider use. Analyses of the costs of avoiding emissions are a useful tool in the planning of electric-bus programs as they bring into focus all aspects of the prospective operation and provide useful metrics for quantifying costs and benefits. Cost/benefit analyses of electric-bus operations will often show that they produce a greater air quality improvement per unit cost than other alternative fuels. Such studies can also be useful in helping operators choose between alternative technological approaches.

Quantifying avoided emissions is a complicated task. Electric transit buses substituted for diesel-fueled buses avoid all of the tailpipe emissions of the smoky units. One common procedure is to assume that the certification emissions of the fluid-fueled engine are representative of its in-service emissions and calculate the emissions for the routes of interest. Alternatively, one could use measured emission rates from a representative engine/bus/duty-cycle combination and calculate the daily and yearly emissions. Typical emissions factors are presented for both procedures. Comparing the emissions attributable to electric buses with those of other alternatively fueled buses does not present a fully representative picture of the air-quality benefits and congestion abatement that electric-buses bring. The experience of most agencies that have introduced electric buses into service is that they generate ridership well beyond what would be expected from introducing new fluid-fueled buses. Calculating emissions avoided by recruiting ridership from automobiles is discussed.

Projecting costs of electric-bus programs is similar to costs estimating for long-term capital programs. Programs utilizing opportunity-charging will present a less certain picture of maintenance and operating costs than conventional programs due to the uncertainties regarding rapid-charging’s impact on battery cycle-life.

An appendix outlining the basic considerations of electric-bus battery maintenance and selection is presented for readers unfamiliar with the technology. A brief, annotated bibliography is also included.

Determining if opportunity charging is appropriate for a particular application is a difficult engineering task that is complicated by a shortage of reliable data concerning many of the factors known to be pertinent. While enthusiasm for the concept of opportunity charging appears to be well founded on the results of several successful demonstration projects, there are too many complicating factors involved for any prudent transit operator to rely on the tactic without a convincing demonstration that it is appropriate for the particular buses, batteries, charger, routes, schedules, climate, and maintenance procedures that a proposed application will employ. Potential users of the technology should keep the shortcomings in battery technology clearly in view when considering range-extension strategies, especially potential users without some experience in the maintenance and operation of electric buses. Battery swapping as a range-extension strategy is, at present, more easily implemented and presents less technical risk than opportunity charging, although impact on schedule structures can be more pronounced.

2 INTRODUCTION: ELECTRIC-BUS FUEL

Increased concern with the quality of life in urban settings and government mandates requiring improvements in air quality have invoked considerable interest in alternative-fueled transit vehicles. Among the alternative fuels presently available, battery-electric power has the greatest potential to reduce the emissions attendant to transit bus operation. Electric buses are also more energy efficient than diesel buses. Because electric-power generation utilized to recharge the batteries is in general not reliant on petroleum fuels, the use of such buses supports a reduction in the national dependency on imported oil. Equally important, the deployment of electric buses in-lieu of buses driven by internal-combustion engines often leads to an increase in bus ridership, reducing privately owned vehicle traffic. This displacement of privately owned vehicles both improves local air quality and reduces congestion on local roadways. Displacement of internal-combustion engine buses and automobiles from highly congested locales has multiple benefits and can be a catalytic element in redevelopment of pedestrian friendly commercial, tourist, or campus areas.

The experiences in Santa Barbara, Chattanooga, Miami Beach and other cities over the past eight years have conclusively demonstrated that electric bus programs attract ridership. While the urban bus is generally viewed as the product of a stagnant technology, the experience of these forward-looking cities shows how a creative repackaging and re-powering of transit buses serves to increase interest in public transit and helps overcome the psychological resistance that prevents many Americans from patronizing such services.

While the psychology behind rider support for the electric bus is not fully understood, the vehicle's quiet operation and absence of exhaust odor and smoke are obviously important factors, as is the general public's affinity for and support of "environmentally friendly" products. Although a CNG-, LNG- or alcohol-fueled bus offers a reduction in exhaust smoke, it does not possess the other attributes of the electric bus.

The "attractiveness" to riders of the various fuel types defies credible quantification. Whether the bus styling is characterized as open-air shuttle, classical streetcar tram, or modern low-floor transit, electric buses are perceived as being more comfortable than conventionally fueled buses. Even in congested traffic, electric-bus riders perceive the vehicles to be islands of relative tranquility and pleasant shelter from a hectic world.

Electricity is recognized as a cleaner fuel than other alternative fuels. This usually refers to electric vehicles' lack of tailpipe emissions, but is even more encompassing when comparing all of the emissions attendant to refueling of conventional vehicles. The logistics involved with the production, transport, storage, and dispensing of fluid fuels is characterized by significant pollutant emissions, direct costs, hazard to public safety, related potential liabilities, and burden on management resources. Electrical energy is delivered only as needed to the users' meters and the costs of distributing and “dispensing” that energy on the customer’s side of the meter are a small fraction of those associated with liquid and gaseous fuels.

Unfortunately, battery-electric buses do not generally have all of the performance capabilities of liquid-fueled buses. The performance differences between the two fuel types result from the weight and volume required to store a given amount of energy on the vehicles. Even the most advanced batteries do not yield, weight-for-weight and volume-for-volume, the energy available from liquid or gaseous fuels and their required tanks or pressure vessels.

Fortunately, battery-electric bus performance is adequate to allow their substitution for liquid-fueled buses in a significant portion of transit bus operations. That proportion of transit operations appropriate for electric-buses can be appreciably expanded through adaptations of equipment and operational tactics, most especially through tactics such as opportunity charging. This preliminary report examines those adaptations of equipment and tactics necessary to implement transit-bus opportunity charging within the context of operational utility, life-cycle costs and environmental impacts.

3 MAKING ELECTRIC BUSES WORK

There are a number of factors common to all of the electric-bus operations that have progressed beyond the status of technology demonstrations. The first key to a successful electric bus program is the integration of electric bus services in appropriate applications within the community transit system. The operation and maintenance of electric buses require somewhat different routines than those which have been used with conventionally-fueled fleets. The limited energy stores of electric buses require that assigned routes and schedules be within their capabilities. Drivers must learn and practice energy management skills and mechanics need to add a new set of safety assurance and diagnostic skills. Dispatchers, drivers and shop supervisors need closer coordination than with conventionally-fueled fleets to ensure that buses are ready for service when dispatched.

The additional skills and tasks associated with the operation of electric buses are part of the cost that must be paid to realize the benefits of an electric-bus program. These additional requirements are not trivial and touch on virtually all aspects of a transit operation. Quite often, demonstration programs involving one or a few electric buses have failed because the operating organization was unable or unwilling to commit the extra personnel resources necessary to ensure that the demonstration would succeed while simultaneously maintaining the effort needed for ongoing operations. Very few transit operators can add such dissimilar vehicles to their fleets and operate them properly without providing the affected staff with the time and other resources required by electric buses. Without such time and resources, electric-bus programs are likely to be poorly received and perceived as burdensome by the personnel most responsible for keeping the buses on route and on schedule.

The commitment required to make an alternative fuel program work must extend from the governing board throughout the organization. Such a commitment is a major undertaking; maybe too big a commitment to make for the benefits provided by only one or two buses. All of the successful alternative-fuel transit programs have been founded on “make it work” determination and have involved enough vehicles to make the required commitment worthwhile. A principle of mass, of using enough buses to provide significant service, is required of programs intended to reap the benefits of using any alternative fuel and especially to using electric buses. The necessary combination of personnel skills, infrastructure, and a reasonable number of spares needed for minimal capability argues for several buses being considered the minimal electric-bus fleet size. This is one of the major lessons learned from many demonstration programs, but this has often been overlooked. Few organizations can learn enough with one or two electric buses to generalize lessons for larger fleet operations, especially since the most important considerations deal with organizational “culture” rather than specifics of the bus technology.

It is impossible to over-emphasize the importance of these three “keys” to successful electric-bus programs, and they are especially important to programs where the technology’s limits are fully-utilized. The principles of organizational commitment, of undertaking a significant enough program to justify that required commitment, and of operating with appropriate duty cycles must be kept in the forefront when considering new techniques such as rapid charging.

4 RANGE EXTENSION

For a given route and schedule structure, the limited daily range of battery-electric buses can be extended by two methods, replacing a discharged battery with a freshly charged unit or recharging the installed battery. Where in-service episodes are interspersed with idle periods, opportunity charging between scheduled runs to keep batteries topped up may allow vehicles to attain daily ranges well in excess of what they could attain in continuous operation. Opportunity charging may also be used in systems where the level of service requires continuous operation if a “float” or spare vehicle is available to substitute for “line” vehicles while they are charging. Similar considerations also apply to the use of battery swapping as a range extension tactic.

Either of these range extension techniques may be used to provide electric-bus services on routes where the duty cycle is otherwise too rigorous, such as extremely hilly routes, or routes where high speeds are necessary for traffic safety. Both methods have been shown to extend the daily range capabilities of electric buses. Only the battery-swapping tactic has been demonstrated for periods longer than the service life of a single battery set. Combining the two tactics in a formal program designed to optimize bus range, operational availability, and life-cycle costs has not been reported, but could offer advantages over either particular method.

The use of idle periods between scheduled runs for rapid battery charging may add enough energy to an electric bus’s on-board store to allow operation under a duty cycle otherwise too rigorous to attempt with just the battery energy replenished during regular charging. The added capabilities might be realized in the form of additional hours of service, or service on routes that are too hilly or with too high an average speed for the un-augmented on-board energy stores. Opportunity charging may allow the use of electric buses where high ambient temperature requires the use of air conditioning.

Charging is normally conducted at a low rate that will return 60% to 70% of the battery’s discharged energy within six hours, returning it to a state-of-charge of about 80% to 90% of its capacity. The normal charging then reverts to an even lower rate to complete the charging (to 100% state-of-charge or SOC) in another 2 to 4 hours (8 to 10 hours total charging). Opportunity charging is a range extension technique that should be distinguished from the terms “rapid” or “fast” charging which refer to a charging rate higher than normal charging. Making opportunity charging a useful technique for transit operators will usually involve charging at higher rates (greater amperage) than conventional overnight battery charging.

When cost and reliability issues are carefully considered, however, it will become apparent that there are duty cycles that may have initially appeared to be workable but that are not appropriate for electric-bus technology. Determining the level where a duty cycle becomes too severe for a particular bus, or battery, or operational tactic should not be a difficult task. Provision of robust margins of bus, battery, and personnel capabilities over normal conditions are the only prudent means for ensuring that transit services continue when operating under less than optimal conditions or with degraded performance. Properly implemented, an opportunity charging or battery swapping tactic will extend the operational margins of a bus/battery combination, extending its otherwise limited range. Improperly implemented, opportunity charging and battery swapping schemes can marginalize an electric-bus program's capabilities and make an otherwise promising system too costly or too unreliable for provision of an essential public service.

Electric-bus technology is not at a level of maturity resembling that of similarly-sized diesel buses. The operational tempos potentially allowed by opportunity charging can amplify weaknesses in electric buses at a rate that may overwhelm maintenance expertise and budgets that would otherwise be sufficient. Planning of extended-range operations should include consultation with the bus, battery, and charger manufacturers at an early stage. Inexperienced electric-bus operators should contemplate gaining at least minimal familiarity with maintenance and operations at a less intensive level tempo before implementing extended-range procedures.

Determining if opportunity charging is appropriate for a particular application is a difficult engineering task that is complicated by a shortage of reliable data concerning many of the factors known to be pertinent. While enthusiasm for the concept of opportunity charging appears to be well founded on the results of several successful demonstration projects, there are too many complicating factors involved for any prudent transit operator to rely on the tactic without a convincing demonstration that it is appropriate for the particular buses, batteries, charger, routes, schedules, climate, and maintenance procedures that a proposed application will employ.

The notion that all aspects of a proposed opportunity charging program must be considered in determining its feasibility cannot be overstated. Opportunity charging is a technique for maximizing the utilization of electric buses and may stress systems beyond prudent levels of utilization. The performance of several specific battery products is well documented,, however, so few batteries have been studied that generalizations should be well qualified. Even when limiting consideration to just the batteries, the effects of these stresses are not well enough understood to generalize much beyond the experiences reported from demonstration projects.

The commercial availability of well-engineered high-rate battery chargers appears to have convinced some bus builders that opportunity charging for battery-electric transit buses is a potential solution to limitations imposed by shortcomings in battery technology. Potential users of the technology should adopt a more prudent viewpoint and keep those shortcomings clearly in view when considering range-extension strategies, especially potential users without some experience in the maintenance and operation of electric buses. Battery-swapping as a range-extension strategy is, at present, more easily implemented and less technically risky than opportunity charging, although impact on schedule structures can be more pronounced.

5 OPERATIONAL CONSIDERATIONS

Normally electric-bus battery charging is conducted during off-duty hours at a rate that will complete the restoration of discharged energy in six to ten hours; roughly a time comparable to the period that the bus is in service. Such a charging episode consists of two or three distinct stages. The initial or bulk charging stage has a moderately high rate of charge return to approximately 80% to 85% state-of-charge. Whether conducted with constant voltage or constant current, this stage is characterized by high efficiency of charge return to the battery. Typically, over 90% of the energy put into the battery in the bulk-charging phase can be recovered on discharge. After the initial stage, charge rate is much reduced and the state-of-charge increases slowly toward a full state-of-charge. Charge efficiency falls dramatically as the charge process nears completion. Beyond the inefficiency of the late stages of conventional charging, some charge protocols can call for as much as 20% overcharge (charge input in excess of the previous discharge) to ensure that the battery is fully recharged.

The efficiency of the conventional recharging process as a whole depends on several factors. These include:

- Magnitude of the bulk charge return
- Magnitude of the finish charging including the extent of overcharging
- Battery temperature
- Battery cycling history
- AC-to-DC efficiency of the charger (typically proportional to the charger output)

Because opportunity charging brings the battery to a full state-of-charge much less frequently per unit of energy throughput than conventional deep cycling, the energy efficiency of the overall process is higher. This added energy efficiency usually is not be reflected in reduced costs as increased energy demand charges and charging during peak rate periods offset the energy savings. Deep cycling in which the battery is cycled between a full (100%) state-of-charge and its minimal (20%) state-of-charge requires traversing the low-efficiency finishing stages of charging with each battery cycle.

The least efficient portion of conventional charging, from the end of the bulk-charging phase, requires several hours to bring the battery up to a full state-of-charge. This is the portion of charging when batteries suffer the most deterioration associated with normal cycling. Finish charging of maintenance-free batteries must be very carefully controlled because excessive overcharge will result in gas evolution and permanent capacity loss. Flooded-cell batteries are more forgiving in this respect as electrolyte water lost during overcharge can be easily replaced. This phase of charging is minimized during partial-state-of-charge operations, described below.

DUTY CYCLE AND PARTIAL STATE-OF-CHARGE BATTERY CYCLING

Most opportunity charge tactics are intended to work in the charge-sustaining mode after discharging the top 20% to 10% of battery capacity. Alternatively, significant range extension may also be achieved in a charge-depleting mode, whereby the state-of-charge after each successive charge episode falls throughout the service day. After the day's service is finished, the battery is recharged to a level high enough to begin the next day's service. Opportunity charging in a charge-depleting mode may simplify battery thermal control in appropriate applications by allowing the battery to cool before beginning the after-service charge episode.

Discharge/charge cycling, while keeping the battery state-of-charge between about the 80% and 40% levels, is known as partial-state-of-charge (PSOC) cycling. Most battery types appear to exhibit increased lifetime charge and energy throughput in PSOC operation compared with traditional deep cycling. Periodic topping-up and equalization charges are required to maintain battery capacity when utilizing a PSOC cycling strategy. PSOC cycling minimizes overcharge and maximizes charge efficiency. The figure below shows a steadily declining series of peaks in

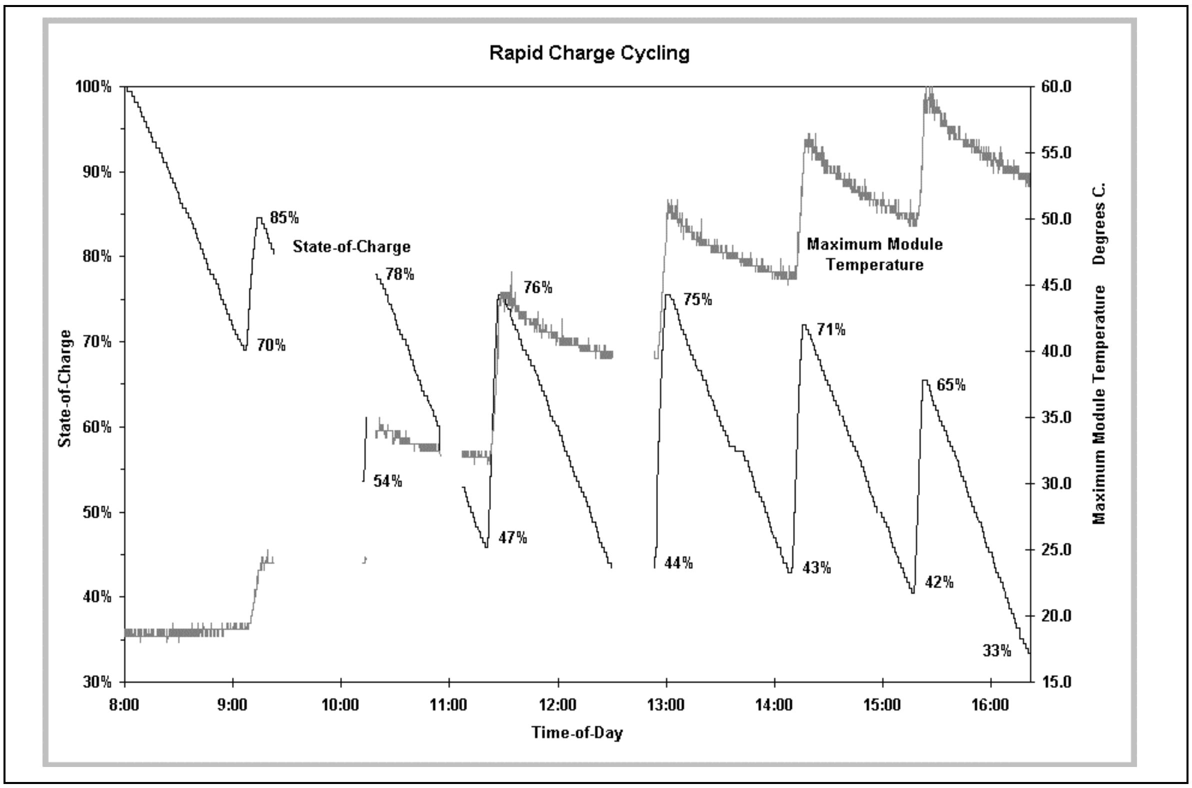

FIGURE 5-1. STATE-OF-CHARGE AND MAXIMUM BATTERY-MODULE TEMPERATURES DURING OPPORTUNITY CHARGING

the state-of-charge after charge episodes, a charge depleting strategy. Research has shown that the optimal intervals between topping-up (and equalization) charges varies with both battery construction and cycling history. The illustrated day's cycling started at a full state-of-charge and was terminated when the battery temperature became too high to allow continued rapid charging between driving episodes.

Rapid charging results in battery heating. High battery temperatures above the battery reference temperature result in reduced cycle life. Initial battery temperatures, charging rates, ambient temperature, and cooling system effectiveness are critical parameters in determining the feasibility of rapid-charging scenarios for transit operations. In the near term, the thermodynamic limitations that will be encountered with most existing battery designs will determine maximum charging rates and episode frequencies. Battery module and pack designs optimized for rejection of excess heat offer a more effective solution, but such optimization will have to be closely integrated with overall vehicle design.

The effects of opportunity charging on the cycle life of traction batteries is not so much unknown as it is difficult to evaluate. Indeed, there is not a consensus regarding exactly how to measure the usage of batteries in opportunity charging scenarios. Possible methods include totaling battery throughput in ampere-hours or in kilowatt-hours, counting full-charge (20% to 100% SOC) equivalents, or totaling overcharge in ampere-hours or in kilowatt-hours. All these methods have merits and drawbacks. Studies have produced evidence that various high-rate charging methods can have a beneficial effect on battery life if battery temperatures and overcharge are well controlled.

Several demonstration projects have shown that opportunity charging increases electric-bus utility, but developing efficient solutions for any particular application remains a difficult engineering task. Prospective users should understand that estimating the costs and gains in performance attributable to some application of opportunity charging without performing the pertinent experiments will only yield enough accuracy for very preliminary evaluations.

Integration of the hardware used in opportunity charging with the operational and maintenance procedures required to make an extended-range electric-bus program cost effective will require substantial commitment of resources. Most importantly, intensive coordination between maintenance, transit planning, and operational departments will be necessary to ensure that battery health considerations are recognized as the critical factors for success of the program. Battery health bears directly on bus availability and reliability, and battery longevity is a major cost driver in opportunity charging operations.

One view of opportunity charging holds that the most efficient use of the tactic involves discharging the bus battery to a 20% state-of-charge before recharging, and then recharging to the 80% SOC level. In order for this tactic to succeed one presumes quite a long layover, benign battery thermal behavior, and highly reliable equipment. Prudence requires demonstrations that these presumptions are reasonable.

Knowledgeable transit professionals argue that an opportunity charging tactic should make provision for missed or curtailed charging opportunities. At a maximum then, the duty cycle between opportunity charging episodes should consume no more than 30% of rated battery energy so that on a normal cycle the state-of-charge would fall from 90% to 60% leaving a 40% reserve (above the minimal 20% SOC level) for a missed charging opportunity. Battery reliability problems become prominent when operating at low states-of-charge and are largely avoided with this strategy. A duty cycle using 30% of rated energy and starting a discharge/charge cycle at an 80% state-of-charge would leave no margin above the 20% state-of-charge after the driving cycle following a missed charging opportunity.

This may be too simplistic, however, as it leaves little margin for battery degradation, for excessive energy consumption enroute, or for many other possible contingencies. Even plans to use 25% of rated battery energy between recharges may not provide sufficient margins unless the fleet size is sufficient to warrant enough spare buses and chargers to allow for substitutions in the event of malfunctions. Spare buses and chargers would also have to be sited appropriately in order to continue service without disruption in the event of malfunction. Fortunately, battery chargers are generally highly reliable. Conversely though, the connectors and receptacles used to couple chargers and buses are somewhat less robust than desired and have been problematic in some demonstration projects.

The full-discharge-before-recharging tactic will require either an interruption of service for the duration of the charge episode or substitution of another vehicle in service. Provision should be made in scheduling for the time required by a driver to switch buses if this is necessary. Many jurisdictions require that a driver conduct and document a pre-operation inspection before placing a vehicle into service. Labor contracts and insurers may also require such inspections and documentation. Opportunity charging tactics that make provision for a missed or curtailed charging episode would seem to be more likely to maintain a transit schedule than those without such provision.

ROUTE EVALUATION AND PLANNING

The first step in route planning is to characterize potential routes by the net energy required to service them. Energy consumption figures used for planning should be conservative as a great deal of variance can be encountered in actual operations. The best method of determining energy consumption on a route is to actually drive the route with the buses that will be used. Bus suppliers can estimate the energy requirements of their buses for a particular route and schedule. Their estimates may be adequate for preliminary planning purposes, but before committing to a particular bus model, prospective purchasers should require that the performance (and actual energy consumption) of candidate buses be demonstrated on the planned routes. Care should be taken to ensure that accessory loads, especially energy required by climate control systems are taken into account. The least efficient driver in an electric-bus program will be much more influential in the program’s success than the most efficient drivers. Passenger loading, traffic congestion or its lack, and battery deterioration with aging will also affect energy consumption.

Some useful services may operate during morning and evening commute times to provide access to inexpensive parking lots peripheral to a crowded downtown, or to move commuters between industrial campuses and rail stations. At least one community has experimented with a circulator service to provide industrial park workers with access to downtown restaurants and shopping at lunchtime. Crowded university student housing neighborhoods may be best served by shuttle services to campus centers coordinated with class schedules. These types of service include many occasions for brief layovers amenable to opportunity charging.

Reasonable service frequency is a matter of perception and governed by the relative ease of waiting, walking, or fetching an automobile from a parking lot. High service frequency can be attained with short route circuits or with more buses on the circuits if ridership levels are adequate to justify the level of service. Quite often, electric buses can be usefully employed for services which operate during just a few busy hours when congestion is at its peak or when ridership is available.

Operators should be careful that “making schedule” does not cause drivers to waste energy with high speeds and accelerations when a minute saved doesn’t really make a huge difference. A few energy-wasting episodes a day can keep a bus from finishing its assigned duty cycle. Quite often drivers or supervisors can hold a connecting bus for a minute or two, impress passengers with their concern, maintain the system’s overall timeliness, and help ensure adequate on-board energy margins with a simple radio call.

MODIFICATIONS FROM CONVENTIONALLY-CHARGED BUS CONFIGURATIONS

Batteries

Many of the batteries used for electric buses are not suitable for high-rate charging, or their suitability has not been systematically investigated. The few investigations conducted to date have focused mainly on maintenance-free (sealed) lead-acid cells and their applicability to transit operations has not always been clear. The few batteries that have been systematically tested in a fast-charging regime have only been tested in a few configurations. It is unlikely that variations from the duty cycles, battery arrangements, chargers and management systems used in the demonstration projects will be useful in different transit applications.

Battery manufacturers have not generally been willing to warrant batteries used in high-rate charging applications (few, if any have explicitly granted a warranty of any sort for bus batteries in a fast-charging application). Several manufacturers have stated that they would consider warranting their batteries in a fast-charge application if sufficient research showed it were reasonable. An application that did not exactly replicate a successful demonstration would probably not receive warranty support from the battery maker.

Battery Management/Monitoring Systems

Battery-management or battery-monitoring systems are not commonly fitted to electric buses, but are a necessary component of any fast-charge design. At a minimum, a management system must present battery chargers with signals governing the allowable charge rate and voltage. Such a management system would account for the battery’s discharge history and current state-of-charge, temperature, cell or module imbalances within and between battery strings, and the rates of change of these parameters. A simpler monitoring system would report summarized discharge history, selected temperatures and cell or module voltages to the chargers for calculation of appropriate charging parameters. Both the simpler and more autonomous battery monitoring/management systems communicate with their chargers throughout charging episodes to ensure that control is maintained.

The continuous communication between battery management systems and high-rate chargers is the primary indication that the battery management system is functioning. Most battery management systems feature a display indicating the general status of the battery. Most battery management systems are also able to communicate with diagnostic programs running on PC-type computers. The presence of sensible data on the driver's display is usually a sign that the system is functioning well, but close examination of data retrieved by the diagnostic program is necessary to determine that the management system is fully functional.

Frequent examination of the system's diagnostic output is a good practice both to keep track of battery condition and of management system functionality. Unfortunately, most battery-management systems do not monitor battery condition at the individual cell or module level. Because most battery-management systems used in electric buses have been adapted from systems originally designed for automobiles or lift-trucks, they lack the ability to monitor the number of battery components (cells or modules) needed for a bus-sized battery. Adaptations to the limited number of components monitored are usually made by combining a group of components (such as six two-volt cells, or two six-volt modules). This joining together of several battery components can conceal minor malfunctions that would be monitored by systems fully capable of monitoring a bus battery. Largely this shortcoming of available monitoring systems is a function of the small market presented by transit applications that applies as well to battery components that are not optimized for the battery sizes typically used in buses. Therefore, regular checks of battery condition on a cell-by-cell or module-by-module basis are still required on systems that do not monitor all battery components.

Trouble shooting of battery-monitoring systems is also not a simple task as they are by and large "black boxes." Testing for circuit continuity and verification of voltage and temperature readings is possible when malfunction is suspected, but replacement of suspect "black boxes" with known-good units is both the diagnostic and repair method of choice, however expensive.

Battery Thermal Management

Cooling systems for batteries are perhaps the most problematic subsystem on buses used in opportunity charging programs. Battery heating in rapid charging results mainly from the resistance of conductors within the battery. Heating is proportional to the square of the current applied and takes several minutes to spread throughout battery elements. Removing the heat takes much longer due to the thermal resistance of the battery case materials. When battery temperatures become high enough to compromise battery longevity, the best course of action is to suspend charging until the temperature falls. There is little that an operator can do to enhance battery cooling, but the potential for battery damage from overheating in a rapid-charging program is high enough to warrant continued vigilance.

Operators considering rapid charging should be especially wary of claims that a battery cooling system will keep battery temperatures within bounds. The ambient temperature of "cooling" air over urban streets in the summertime is often higher than battery temperature. The efficiency of blown-air cooling systems for available batteries is marginal under the best conditions due to the poor thermal properties of battery case materials. Poorly maintained or engineered systems can be worse than no system at all if they cause temperature imbalances within the battery assembly. Temperature imbalances in a battery cause differences in charge acceptance that create charge imbalances, decrease the efficiency of the charge process and can dramatically shorten cycle life. High-rate charging accelerates such damage. Battery management systems with a small number of temperature sensors can exacerbate this condition if the sensors are not properly located. Fan function is not monitored by any of the battery management systems known to be used on electric buses. Operators should frequently verify that cooling system fans are functioning properly, that all required ducts and seals are intact and properly positioned, and that temperature sensors are reasonably accurate.

On-Board Circuits

Charging circuits of electric buses may need upgrading to be suitable for high-rate charging. The charge receptacle, fuses and holders, contactors, and associated wiring must be engineered to accommodate the charging current with prudent safety margins.

Charge receptacles and connectors for rapid charging must comply with the specifications of the charger manufacturer. Only one manufacturer's products are used as a conductive interface for bus rapid-charging applications. Receptacles and connectors offered to date have proven less than fully satisfactory, but the manufacturer has been responsive and has introduced several improvements in design and materials. Potential operators considering opportunity charging should specify their buses be fitted with the appropriate receptacle.

Infrastructure

High-rate charging equipment suitable for use with bus batteries are offered by three makers. These manufacturers have necessarily focused their development efforts on applications with more market potential than transit buses, but have shown that they are willing to expend considerable effort to service the industry.

Because integration of high-rate charging with transit bus operations is such a complex and unexplored field, prospective users should consult with their bus and battery manufacturers before initiating discussions with the charger builders. While the charger manufacturers proficiency lies in electronics design and production, they nonetheless have a considerable knowledge base pertaining to batteries and battery applications that may be useful. They all operate applications laboratories and have personnel available to tailor their products to particular uses.

The manufacturers with experience in transit-bus applications are:

Norvik Traction
2486 Dunwin Drive
Mississauga, Ontario
Canada, L5L 1J9
(905) 828-7700

AeroVironment Inc.
222 East Huntington Drive
Monrovia, CA 91016
(626) 357-9983

Ferro Magnetics Corp.
P.O. Box 4039
Hazelwood, MO 63042
(314) 739-1414

Operators planning installation of high-rate charging equipment should contact their utility's service planner as early as possible to allow sufficient time for upgrading of electrical service if required. If the utility needs to install additional capacity to service high-rate battery chargers the user may find that the associated installation fees marginalize the project's cost effectiveness. Similar considerations may also apply to monthly demand charges. These fees and charges are based on the utility's need to recover the substantial capital costs of making high-power service available and should be viewed in the light of the relatively minor revenues from energy charges for bus fuel.

6 ECONOMIC AND ENVIRONMENTAL CRITERIA FOR PROJECT EVALUATIONS

The higher costs of electric-bus operations compared with their diesel-fueled counterparts are often cited as a barrier to their wider use. Analyses of the costs of avoiding emissions are a useful tool in the planning of electric-bus programs as they bring into focus all aspects of the prospective operation and provide useful metrics for quantifying costs and benefits. Cost/benefit analyses of electric-bus operations will often show that they produce a greater air quality improvement per unit cost than other alternative fuels. Such studies can also be useful in helping operators choose between alternative technological approaches.

BENEFITS

Transit buses are most prominent as a transportation resource in the urban areas where tailpipe emissions are most hazardous to health. Incremental reductions in the most harmful tailpipe emissions from buses may be achieved by use of some alternative fluid fuels, but the elimination of the tailpipe, and all local emissions, is accomplished only with the use of electric buses. This chapter discusses quantifying the emissions attributable to and avoided by electric bus operations and with estimating their costs.

State and local air quality management agencies have adopted regulations tailored to the specific conditions that characterize their jurisdictions. While varying in detail, these regulations are generally similar, as they must comply with EPA guidelines. These regulations typically specify procedures for calculating the emissions savings generated by substitution of alternatively-fueled buses for conventionally-fueled units. Credit is only allowed for emissions reductions in excess of those necessary to comply with federal, state and local regulations. In areas with emissions banking programs, emissions credits have a specified lifetime that is usually equal to the design life of the source vehicle type. Accelerated retirement of aging, high-emissions buses may generate relatively short-lived emissions credits. Substitution of small, zero- emission or low-emission buses for larger, high-emission buses will generally entail a case-by-case analysis to determine the quantity of emissions to be credited.

In areas with severe pollution problems, the avoided oxides of nitrogen (NO_x) may be especially valuable; $10,000 per ton has been cited by some sources. Calculated against the emissions of 1998-standards diesels, if these avoided emissions are valued at $10,000 per ton the shuttle buses studied in Santa Barbara each avoid annual NO_x emissions worth $1,300 per year, or $0.12/mile ($0.20/km). These values are impressive when compared to their annual fuel costs of $948 for the shuttle buses with flooded-cell lead-acid batteries. When considering the emissions of the gasoline-fueled private automobile trips needed to transport the 750,000 elective passengers the

Santa Barbara electric-bus program moves each year, the electric buses avoid emitting 18 tons of regulated pollutants in the downtown area (including 1.8 tons of NO_x, worth about \$0.15/mile (\$0.25/km)). While the valuation now placed on NO_x emissions avoided through the use of electric-buses does not yet equal the marginal cost of operations, there may be opportunities for program sponsors to receive offsetting emissions credits in return for their subsidies.

Although pricing of avoided emissions is not yet widely accepted, these discussions give some indication of the importance attached to avoiding emissions in some pollution-control jurisdictions. Marketable or not, avoided emissions have a tangible value as an indicator that the sponsoring or operating agency is a responsible neighbor. This value is necessarily difficult to quantify but is clearly derived from more substantial grounds than the novelty of using electricity as fuel. The novelty may play some part in the public support for electric buses, but quietness and lack of offensive exhaust are most readily noted. For its most suitable applications, the electric bus' complete lack of local emissions and nearly silent operation gives it a particular utility unmatched by other vehicles.

Quantifying avoided emissions is a complicated task. Electric transit buses substituted for diesel-fueled buses avoid all of the tailpipe emissions of the smoky units. One common procedure is to assume that the certification emissions of the fluid-fueled engine are representative of its in-service emissions and calculate the per-mile, per-day, and annual emissions for the routes of interest. Alternatively, the procedure is to use measured emission rates from a representative engine/bus/duty-cycle combination and calculate the daily and yearly emissions. Unfortunately, certification emissions are not representative of real-world emissions and the in-service emissions of very few heavy-duty engines have been reported in the open literature. Consequently, neither method is likely to yield highly accurate estimates of the emissions of diesel buses in route service. The method using figures from engine-certification testing seems to yield emissions estimates that are erroneously low. More representative emissions estimates can be made by using figures generated by simulating en-route conditions with real buses on a chassis dynamometer. Even when representative engine/bus/duty-cycle combinations have not been tested it is possible to generate plausible emissions estimates by weight scaling from similar chassis-dynamometer generated data. Scaling for bus-weight is relatively straightforward, but should be limited to use of a duty-cycle similar to the targeted route service. Such scaling should be validated by and, if necessary, adjusted with fuel-consumption figures for the buses of interest operating on the actual routes being evaluated.

Comparing the emissions attributable to electric buses with those of fluid-fueled buses does not present a fully representative picture of the air-quality benefits that electric-buses bring. The experience of most agencies that have introduced electric buses into service is that they generate ridership well beyond what would be expected from introducing new fluid-fueled buses. The emissions avoided by taking elective riders out of cars are substantial. A car trip normally carries 1.4 persons (national average basis), consequently a car trip is avoided for every 1.4 elective passengers riding the bus. Electric buses avoid the automobile's normal tailpipe emissions as well as the excess classified as "cold start" and "hot soak" evaporative emissions for short trips. Engines using fluid fuels emit excessive pollutants (mostly unburned fuel) until they reach operating temperature (cold start) that are totally avoided by battery-electric buses. Similarly, vehicles powered by conventional and other alternatively-fueled engines continue to emit pollutants long after being turned off (hot soak). A 22-foot electric bus can produce less than a tenth of the emissions of a single average car for the 3.7 miles (6 km) of an average bus trip

(44.28 grams of local, regulated emissions vs. 4.33 grams of remote emissions–see table 6-1). The automobile emissions typical of an area have often been cataloged by local or state air-pollution control authorities. These figures will present the most accurate picture of privately-owned vehicle emissions displaced by electric buses The use of national-average emission factors may also be useful in quantifying the environmental benefits of electric buses if local or regional factors are not available. Tables 6-1 and 6-2 illustrate these discussions.

TABLE 6-1. MEASURED EMISSIONS AND FUEL CONSUMPTION

	Typical 40-Ft,38-seat 1994 DIESEL-Fueled Transit Bus	Typical 40-ft, 38-seat 1996 CNG-Fueled Transit Bus	CARS AND LIGHT TRUCKS Typical 1998 Calif. County LDA/LDT Composite Fleet (1964-1998 model year vehicles)		Typical 22-Ft, 19-seat Battery-Electric Bus
EMISSION	grams per mile	grams per mile	Running Emissions (incl. running loss evaporative emissions) grams per mile	Starting & Hot-Soak Emissions grams per trip	Local Emissions (Remote Emissions) grams per mile
PM_{10}	0.66	0.025	0.05		0 - Local (0.03 - Remote)
NOX	31.5	20.8	0.72	0	0–Local (1.0–Remote)
Hydrocarbons(HC), Non-Methane Volatile Organics (NMVOC)	0.12	15.8	0.85	1.65	0–Local (0.01–Remote)
CO	5.2	9.0	9.0	3.34	0–Local (0.13–Remote)
CH4 & NMHC (not regulated)	--------	14.45	-------		0–Local (0–Remote)
Bus Weight	32,843	32,843			16,500
Total grams per 1 mile trip	37.48	60.08	Combined Running, Starting, & Hot-Soak Emissions --- 15.61		0–Local (1.17–Remote)
Total grams per average trip (3.7 miles)	138.68	222.28	Combined Running, Starting, & Hot-Soak Emissions --- 44.28		0–Local (4.33–Remote)
MPG	3.40 MPG	2.80 MPG	8-28 MPG		1.5 AC kWh/mi.
BTU/mile	38,735 BTU/mi.	45,836 BTU/mi.	4,300-15,000 BTU/mi.		5,630 BTU/mi.
Fuel Density:	7.16	4.80	lb/gal	6.24	---
Brake Specific Fuel Consumption:	0.40	0.375	lb/bhp-hr	0.25	---
Fuel Efficiency:	3.4	2.8	mi/gal	15	1.5 AC kWh/mi
Work efficiency:	5.26	4.57	bhp-hr/mi	1.66	1.01bhp-hr/mi

Bus Emissions on Central Business District Test Cycle (per SAE J-1376) reported in SAE Technical Paper 973203 Natural Gas and Diesel Transit Bus Emissions: Review and Recent Data, Nigel Clark et al., November 1997. Light duty automobile (LDA) and truck (LDT) emissions per Santa Barbara County Association of Governments, MVE17G Emission Factors Scenario, March 1998. Note: National average LDA/LDT emissions are very high, local emissions profiles should be used in computing potential emissions displacements. Electric-bus emissions calculated from data in California Air Resources Board Technical Support Document Zero Emission Vehicle Update, April 1994, @ 1.5 AC kWh / mi. and 10% transmission losses.

TABLE 6-2. EMISSIONS STANDARDS AND FACTORS

		Emission	PM#	NOx	HC	CO	Total	
	1998 EPA Urban Bus Standards:	g / bhp-hr	0.05	4.00	1.20	15.50	20.75	g / bhp-hr
	Diesel at 4.3 bhp-hr/mi	g/mile	0.22	17.20	5.16	66.65	89.23	g / mile
	CNG at 4.1 bhp-hr/mi	g/mile	0.21	16.40	4.92	63.55	85.08	g / mile
	bhp/mi numbers for full-size (40') transit buses (average wt. 38,500 lbs)							
	1996-2003 EPA Passenger Cars & Light Truck Standards:	g / mile	0.08	0.40	0.25	3.40	4.13	g / mile
		Emission	**PM#**	**N0x ***	**HC ***	**CO**	**Total**	
(most recent)	**National Emission Factors - Light-Duty Vehicles - 1995**	g / mile	est. 0.05	1.63	2.49	20.64	24.76	g / mile
(most recent)	**National Emission Factors - Light-Duty Trucks - 1995**	g / mile	est. 0.05	1.99	3.39	27.58	32.96	g / mile
	Averaging these two sets of emission factors does not give a fair representation of the on-road vehicle mix. As a fair approximation, consider 2X light-duty vehicles per 1X light-duty trucks.	g / mile	est. 0.05	est. 1.75	est. 2.79	est. 22.95	est. 27.5	g / mile
	National Emission Factors - Heavy-Duty Diesel - 1995	g / mile		14.11	2.54	12.28	28.93	

Approximately 0.01g/mi for tire and brake-wear particulates for light-duty vehicles, and 0.03 g/mi for tire and brake-wear particulates for urban buses and trucks should be added to the exhaust particulates.

* NOx and HC starting and hot-soak emissions are calculated for an average trip. These emissions are understated for short-trip, urban driving cycles.

On a national basis the average length of an urban bus trip is 3.4 miles, yours may be different. On an averaged, national basis each car carries 1.4 passengers. So each 1.4 bus passengers displaces one car for an average trip.

Determining the power-plant emissions attributable to electric-bus operations can also be a complex task. Measuring the actual energy consumption of electric buses on a particular duty cycle is preferable to making estimates, however buses are often not available to prospective users. In such a case, scaling by weight from similar duty cycles is usually accurate, but only when the duty cycles are similar in terms of average and peak gradients, accessory loads, average and peak speeds, and start/stop frequencies. These energy consumption figures are corrected for transmission losses to establish gross energy consumption figures. On- and off-peak proportions of these figures are established for the proposed charging schedules. Establishing the emissions attributable to on- and off-peak generation is a very complex task where the pertinent data is often closely held by the utilities concerned. Often, the only credible source of this data is state energy regulatory authorities if utilities are reticent to release their emissions profiles. For example, Table 6-3 is drawn from data prepared by the California Air Resources Board and has been used to calculate regional and remote emissions attributable to electric vehicle operations in Southern California.

TABLE 6-3. ELECTRIC POWER PLANT EMISSIONS - SOUTH-COAST AIR BASIN (SCAB)

California Air Resources Board (CARB) staff estimates 33% of South Coast Air Basin (SCAB) off-peak demand is served by generating units in the basin, and 20% of SCAB on-peak demand is served by generating units in the basin.

	Estimate For Generating Sources in SCAB	
PM particulates	0.030	lbs./MWh
SO2 sulfur oxides, taken as sulfur dioxide	0.009	lbs./MWh
NOx oxides of nitrogen	0.150	lbs./MWh
ROG reactive organic gases	0.020	lbs./MWh
CO carbon monoxide	0.220	lbs./MWh
CO2 carbon dioxide	750	lbs./MWh
Transmission Line Loss Factor	9.0%	CARB estimate

Electric Power Plant Emissions (All Generation Sources Serving California)

	Estimate For All Generating Sources	
PM	0.046	lbs./MWh
SO2	0.893	lbs./MWh
NOx	1.324	lbs./MWh
ROG	0.016	lbs./MWh
CO	0.172	lbs./MWh
CO2	750	lbs./MWh
Transmission Line Loss Factor	9.0%	CARB estimate

Generating emissions estimates from California Environmental Protection Agency, Air Resources Board *Technical Support Document, Zero-Emission Vehicle Update*, April 1994

COSTS

The cost to a transit program for avoiding particular emissions may be useful when used in comparisons with the costs of other methods of removing pollutant sources from a locale. Projecting costs of electric-bus programs is usually a straightforward exercise, similar to costs estimating for other long-term capital programs. Programs utilizing opportunity-charging will present a less certain picture of maintenance and operating costs than conventional programs due to the uncertainties regarding the rapid-charging impact on battery cycle-life.

Capital costs

Electric buses are generally furnished with battery chargers that will accomplish a full charge within six to twelve hours. These chargers are usually rated at between ten and twenty kilowatts and cost from $3,000 to $6,000 when purchased separately. Prospective electric-bus operators should consult with their electrical energy provider to determine if proposed equipment installations are appropriate for their existing service or if changes are necessary. Charger installation usually costs at least $500.

High-rate or “rapid” chargers designed to replace a large portion of a battery’s charge in much shorter periods are also available from most bus builders. Use of these sophisticated products requires that the buses they will be charging are equipped with battery management systems, high-current charge-port wiring, and (usually) battery cooling systems. On-board equipment and modifications cost between $5,000 to $9,000 per bus, or more. A 120-kW charger costs over $72,000; a 60-kW charger costs over $40,000. Each rapid charger can service several buses in an opportunity-charging scenario, the number of buses depends on the scenario scheduling. Rapid charger installation can cost over $5,000 if adequate service panel capacity is not already available.

Prudent managers may have difficulty justifying the capital expenditures required for high-rate opportunity charging without substantial evidence that the life-cycle costs associated with its effects on battery cycle life will be satisfactory.

Prospective users in areas where the climate requires that battery charging take place within enclosed buildings should be aware that facility modifications may be required. Flooded-cell batteries release a mixture of hydrogen and oxygen in the later stages of battery charging. Explosive concentrations of hydrogen can accumulate in enclosed structures if appropriate ventilation is not provided (see Article 625 of the National Electrical Code - NEC®). Similar considerations apply to enclosed structures used for maintenance of CNG- and LNG-fueled vehicles.

Maintenance Costs

Table 6-4 lists the maintenance costs incurred by the Santa Barbara MTD electric-bus program for open-air shuttles using three different battery types during its first six years of operation.

TABLE 6-4. 22-FT SHUTTLE-BUS BATTERY MAINTENANCE COSTS

	Per Mile Costs (11,700 miles per year average)	
	Battery Maintenance	
	Maint. and single cell replacements only	Maint. Including battery replacement cost
Parts & Materials		
Flooded-cell Lead-Acid	$0.051	$0.293
Maint.-Free Lead-Acid	$0.016	$0.577
Flooded-cell NiCad	$0.011	$0.424
Direct Labor		
Flooded-cell Lead-Acid	$0.064	
Maint.-Free Lead-Acid	$0.007	
Flooded-cell NiCad	$0.030	
(Average labor wage and benefits cost $23.00/hour, national average is $19.00/hour.)		

Extrapolation of costs from another operator's experience can be problematic, but for similar buses and duty cycles should yield reasonable estimates. Scaling of labor costs to other operators can be directly proportional from Santa Barbara's $23.00 per hour for wages and benefits. Costing of parts and materials for battery maintenance and single-cell replacements on a per mile basis should be fairly accurate for the battery types listed for battery sizes between about 65-kWh and 90-kWh (at C/6 rates) for similar battery duty cycles. Cost estimates of parts and materials for battery maintenance including battery replacement costs are not so straightforward. Per mile costs for battery replacement will be quite sensitive to the duty cycle, and to the cycle life and price of the particular cells installed. Again it must be emphasized that the effect of rapid-charging on the cycle life, and life-cycle costs, of any particular battery are conjectural.

Total battery life-cycle costs (when operated in a 11,000 to 12,000 mile (18,000 to 20,000 km) per year duty cycle) were also derived in the study that produced the cost data above based on the per AC kilowatt-hour throughput. Exclusive of energy costs, flooded-cell lead-acid batteries cost $0.272/AC kWh, maintenance-free lead-acid batteries cost $0.523/AC kWh, and flooded-cell nickel-cadmium batteries cost $0.356/AC kWh. The use of these figures to project costs for an opportunity-charging program should be no less accurate than using the per-mile costs previously cited.

Fuel Costs

Energy costs of electric bus operations are typically from one-half to two-thirds the fuel costs of diesel buses operating on the same duty cycle. These costs are, of course, much less than those of other alternatives such as natural gas or alcohol based fuels. Care must be exercised in the planning stages of an opportunity charging program to ensure that all costs and fees that will be included in the electrical billing are anticipated.

Estimation of fuel costs is straightforward and a high degree of precision is not necessary because of the relatively minor contribution of fuel costs to total operational expenses. Adequate estimates are derived by multiplying required mileage by the estimated DC energy consumption per mile, factors accounting for battery efficiency (typically 0.60 to 0.80 but closely related to charger sophistication) and AC-to-DC conversion efficiency (typically 0.87 to 0.96), and local electrical energy prices. Meter or facility fees, demand charges, and seasonal or time-of-use energy price changes must be addressed when computing local electrical energy costs. The meter fees and demand charges will often dwarf the actual energy costs and potential operators should anticipate them. The local utility can assist planners with these estimates.

APPENDIX - BATTERY BASICS

Electric-vehicle batteries are composed of interconnected individual cells or of interconnected monoblocs (also called modules). Individual lead-acid cells operate at a nominal 2.2 volts and individual nickel-cadmium cells at 1.2 volts. Monoblocs are a number of cells packaged together. Lead-acid monoblocs are commonly made up of six cells connected in series to yield 13.2 volts. A “twelve-volt” automotive starting battery is a six-cell monobloc. Nickel-cadmium monoblocs or modules are usually made up of five cells connected in series for a nominal six-volt yield. The amount of active material available for the charge/discharge chemical reactions characteristic of the cell determine its energy storage capacity. This charge storage capacity is measured in ampere-hours.

A battery might be rated as having a capacity of 900 ampere-hours at a “C_5” or “C/5” rate. This means that if the fully charged battery was discharged at a constant-current rate over a five-hour period to the fully-discharged state it would give up 900 ampere-hours of current. The constant current in this case would be 180 amperes (180 amperes * 5 hours = 900 ampere-hours). A “C_3” (C/3) rating of the same unit might be 750 ampere-hours which would mean that a constant-current discharge over a three-hour period to 100% depth-of-discharge (DOD, the inverse of state-of-charge or SOC) would yield 750 ampere-hours. Here the rate or current would be 250 amperes (3 * 250 = 750). These two capacities of 900 ampere-hours and 750 ampere-hours, also illustrate that the capacity of a given cell or module is greater at a lower discharge rate.

Multiples of “C” rates are also used to specify current: 2C/5 is twice the C/5 rate, 2 * 180 or 360 amperes for the previous example. The “C” nomenclature is widely used, but can be misunderstood if used carelessly. The maximum continuous discharge rate of a cell or module is the “1 C” current. When used without a subscript or following numeral “C” is taken to mean the 1C rate, e.g. 2C as twice the 1C rate; but $2C_1$ (or 2C/1) is twice the rate needed to totally discharge the battery from a full state-of-charge in one hour.

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, experience suggests that the C/3 rate reflects a discharge condition that is more extreme than usually encountered with electric buses. A C/6 rate is probably more reflective of electric-bus applications with an 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 discharge, 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.

Another measure of a battery cell's capacity uses the energy units watt-hours or kilowatt-hours and takes the cell's voltage into account. A watt is a measure of power; it is the product of voltage and current (voltsXamperes or VA). Power produced over a period of time does work and consumes energy, hence watt-hours–a unit of both energy and work. As an example, a 200-volt battery discharging at a 250-ampere rate would be operating at a 25,000 watt (25 kilowatt) power level. If such a battery could sustain that power level for 3 hours before reaching its fully discharged state it would be rated as having a C_3 energy capacity of 75 kilowatt-hours.

In addition to a continuous maximum discharge rate, a battery maker will often specify a peak discharge rate. For the example cell's 1 C rating of 180 amperes, a peak rating might be "5 C for 15 seconds" or 900 amperes (180 * 5 = 900). Exceeding a cell or battery's peak discharge rate or maximum continuous discharge rate will probably damage it.

Lead-acid cells should not normally discharge more than 80% of their rated energy capacity and Ni-Cads no more than 95%. In general practice, nickel-cadmium batteries are not discharged past 80% DOD in order to maximize their cycle life. Adhering to these limits is necessary if the cells are to attain their advertised in-service life span. These limits relate to the concept of "accessible" energy or the amount of energy available from a battery in normal use as opposed to the total or rated energy capacity.

The cells or modules that make up a battery are connected together. A simple series connected battery string consists of cells connected positive terminal to negative terminal. The voltage of a series connected battery is the sum of the voltages of the individual cells or monoblocs. Its capacity rating is the same as the capacity rating of the constituent cells or monoblocs. Series strings can be connected together in parallel, positive end to positive end and negative end to negative end to increase the capacity rating of the assembly. Each additional parallel string in a battery adds the string's capacity to the battery assembly's capacity. An alternative battery arrangement is to connect monoblocs in parallel (adding capacity) and connect the paralleled pairs or triplets in series (to achieve required voltage).

Other measures describe the weight and volume of batteries relative to their energy capacities. *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, and the reader is therefore strongly encouraged to be aware of the difference between these parameters and their respective impacts on energy storage issues.

BUS BATTERIES

Battery selection for a particular application is subject to a number of constraints. Initial cost is often the primary factor in battery selection. However, life-cycle costs and the ability of a particular battery product to meet the demands of the required duty cycle may be more pertinent to the success of an electric-bus program.

Energy usage by electric buses is determined by a number of factors: bus weight and loading, start-stop frequency, average speed, route gradients (hilliness), and accessory usage (most especially heating and air conditioning). Estimated energy consumption rates for two of MTD's electric-bus variants are presented in Table A-1. These energy consumption estimates presume a fairly flat terrain, moderate speeds and a moderate stop/start frequency (7-10 stops per mile, 11-16 stops per kilometer).

TABLE A-1. ENERGY REQUIREMENTS

Bus Length	Curb Weight	Net DC kWh per mile	DC kWh necessary for 75 mi. range (no margin)	(10% margin)
22-foot	12,400 lbs	0.80	60	66
26-foot	17,400 lbs	1.05	79	87

The DC kWh requirements for the various bus and accessory load conditions have been tallied. The "Net DC kWh per mile" figures include a modest energy return from regenerative braking. A ten percent "safety" margin has been incorporated to accommodate variations in duty cycle, driver energy-management skills, and battery degradation with aging. Note that the energy consumption units are DC kilowatt-hours. AC energy consumption must take into account the losses involved in battery charging, inefficiencies in the charger and in the battery. These losses are commonly in the 20% to 25% range and the AC energy consumption for the buses described in Table A-1 would range from 0.96 AC kWh to 1.26 AC kWh per mile (1.57 AC kWh to 2.07 AC kWh per kilometer).

A more rigorous duty cycle would require more energy to achieve the same range and a lesser range requirement would, of course, require less energy. The energy parameter of interest in the consideration of operational range is net DC kWh per mile. Virtually all electric buses make use of regenerative braking, a process in which the electric motor acts like a generator during braking activity, briefly recharging the battery while retarding bus motion. The net DC kWh per mile figures reflect estimates for net energy discharged from the battery, after consideration of the *recoverable* component of regenerative braking energy. There are always some losses associated with storing energy in a battery, typically from 15% to 25%. Even with these losses, regenerative braking can result in up to a 20% increase in bus range over range without the feature. The energy consumption estimates presume the utilization of drivers with reasonable energy-management skills.

DC energy data for two routes served by MTD's 22-ft, 12,400-lb shuttles are presented in Table A-2. *Energy regenerated* represents the *recoverable* portion of the energy produced during braking, and has been reduced to reflect the losses associated with the round trip through the battery.

TABLE A-2. ENERGY USAGE RATE (22-FT SHUTTLE)

Stops per mile	Average. Gradient (%)	Energy Discharged (kWh/ mi)	Energy Regenerated (kWh/ mi)	Net Usage (kWh/ mi)
2.6	Level	0.77	0.11	0.66
12.8	2	1.12	0.17	0.95

At first glance, it may appear that a route with a low stop/start frequency is best suited for electric-bus application because of the lower energy-usage rate. It is important to recognize, however, that such routes tend to have disproportionately higher average speeds and will therefore consume energy at a higher rate *per unit time*. The net result is that an electric-bus can usually stay in service for a longer *period of time* between recharges if it is placed on a route that entails a high stop frequency, even though energy usage per unit distance will be greater. This is illustrated by Table A-3.

TABLE A-3. SERVICE RANGE AND DURATION

(22-ft Shuttle with 60 kWh usable energy)

Stops per mile	Net Energy Usage (kWh/mi)	Maximum Range (miles)	Net Energy Usage (kWh/hr)	Maximum Duration (hours)
2.6	0.66	91	6.1	9.8
12.8	0.95	63	4.8	12.5

BATTERY MAINTENANCE

All electric vehicles, regardless of whether they have provided service on any given day, should be coupled to their chargers. Battery charging is initiated in time to ensure completion of a full charge episode before buses are released to drivers. Once the integrity of the charge initiation process is confirmed (i.e., no blown fuses or tripped breaker switches), the process usually continues unsupervised. All chargers should be 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 will occur after relatively little recharge energy is delivered.

Buses equipped with flooded-cell batteries need to have electrolyte water replenished on a regular basis (two or four times a month). The task can be accomplished in a short period by a trained worker. Battery watering is a major component of the operational costs of flooded-cell batteries, but their increased cycle life and resistance to abuse more than compensates for these costs.

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 in operations without extended-range tactics, after “low power” episodes in which a bus is unable to complete its normal duty cycle, or whenever the open-circuit battery voltage after charge termination indicates that a full charge was not achieved. An equalization charge is also undertaken whenever cells or modules are replaced and subsequent to battery load testing. Cell and module replacements are made on an “as required” basis, with either new or reconditioned units being used depending on their availability. Often defective cells or modules can be reconditioned as individual units and either returned to their original battery assemblies or to other packs with approximately the same cycle life remaining.

Unscheduled repairs are a fact of life for all vehicles despite preventative maintenance programs. Those most commonly encountered in the operation of battery-electric buses involve the inability of the bus battery to deliver sufficient power or energy for the bus to complete its scheduled route service – a “low-power” event. Two possible causes of “running out of juice” are: insufficient accessible energy and excessive energy usage. In some cases one or the other of these general causes will explain the incident. After a low-power incident, the vehicle battery and charger involved are evaluated. Similarly, the operational aspects are scrutinized. The energy requirements of the route’s duty-cycle and/or the driver’s patterns of energy usage may be excessive. Only rarely are electrical or mechanical malfunctions responsible for a bus using excessive energy and being unable to complete a normal duty-cycle.

In some cases a low state-of-charge or the inability of a battery to deliver sufficient power is discovered prior to the bus leaving the charging facility. More commonly these symptoms appear while the malfunctioning bus is in service. Investigation of low-power incidents begins as soon as possible because diagnostic efforts are more likely to pinpoint malfunctioning battery components if begun before they cool or otherwise recover to some degree. Buses malfunctioning in service are usually able to “limp” home, or to a safe parking area, after a short recovery period. “Road service” is not usually able to rectify low-power incidents in the field. Buses suffering low-power incidents should be returned to the maintenance facility where their batteries can be removed and maintained.

Low-power incidents involving lead-acid batteries are often caused by a single cell malfunction. A common cause is the failure of a low-capacity cell in a high-impedance mode that restricts the flow of current from other cells in the string. Nickel-cadmium batteries are more rarely effected by this as their cells generally fail in a low-impedance mode where the battery output merely loses the contribution of the failed units.

A battery’s ability to deliver energy degrades with usage. Battery “end-of-life” is usually defined as that point at which the battery has suffered a 20% loss in capacity. The actual capacity loss that can be accommodated under operational conditions may deviate from the arbitrary 20% figure, and will depend upon the margin between available energy and energy required for the subject application. Experienced users have found that the incidence of outright failure of individual cells (and the resulting need to replace them) is a greater determining factor in end-of-life considerations than is loss of aggregate capacity. Several procedures for determining when to stop replacing individual cells and declare a battery "dead" have been proposed but operational commitments, budgetary considerations, and other exigencies seem to preclude the application of simplified rules.

Successful battery-electric transit operations are all characterized by the close match between the capabilities of their particular bus/battery combinations and the duty cycles to which they are applied. An appropriate duty cycle or operational regime for a particular bus/battery combination must make good use of the battery's energy storage capacity in order to show a decent return on investment and acceptable life-cycle costs. Duty cycles that are too demanding will result in buses unable to complete a route schedule, road calls to retrieve buses, greatly increased maintenance costs, and complaints from inconvenienced passengers. Minimizing maintenance costs for a battery-electric bus operation depends on attaining the maximum cycle life for the batteries. Replacement of batteries is the most significant cost in electric-bus maintenance programs. Premature retirement of batteries can destroy the cost effectiveness of an electric-bus program. Favorable comparisons with other alternative fuels on the basis of reduced emissions and customer satisfaction can be easily overlooked if battery replacement costs get out of hand.

Battery replacement costs, and the not insignificant costs of individual cell and module replacements, are minimized with an effective maintenance program that keeps minor battery degradation from progressing to premature loss of capacity and/or power-delivery capability beyond operational minimums. Variances between individual battery components will eventually cause premature battery failure if not attended to in a timely manner. Less than optimal operational regimes combined with any shortfall in driver energy management skills or deviations from ideal manufacturing tolerances virtually guarantee that a battery will fail prematurely if not aggressively maintained.

BATTERY CHEMISTRY AND CONSTRUCTION

Batteries using several different chemistries are under development, but only two have been widely used in electric buses to date: lead-acid and nickel-cadmium. The lead-acid chemistry is available in flooded-cell and "maintenance-free" variants in a range of packaging options and sizes. Availability of nickel-cadmium batteries is somewhat more limited; only the flooded-cell variety has been available in a few sizes appropriate for use in bus-size vehicles.

The flooded-cell lead-acid batteries commonly used in battery-electric buses are relatively inexpensive, both in terms of procurement and lifecycle costs. "Maintenance-free" batteries not only relieve the operator of watering duties, but also avoid the problems that accompany poor watering protocol. The term "maintenance-free" should not be taken literally however, as all batteries require regular surveillance and replacement or reconditioning of defective and deficient cells. "Maintenance-free" refers only to the replacement of electrolyte water lost during the final phases of charging. Maintenance-free batteries do not promote corrosion of the bus frame (they do not evolve gas and electrolyte mist in normal operation). Disadvantages of the maintenance-free battery are a reduced tolerance to abuse (overcharge, over-discharge, and thermal imbalances), and the need for programmable chargers (the flooded Ni-Cad battery also requires a programmable charger). The major disadvantage of the maintenance-free battery products, however, is their limited cycle life that results in high life-cycle costs.

The sensitivity of sealed or maintenance-free battery products to overcharging and over-discharging argues that they be fitted with “battery-management” systems to ensure that they are not inadvertently damaged in use. More sophisticated, and expensive, chargers are required by maintenance-free batteries than is the case with flooded-cell lead-acid batteries. Battery chargers promoted as “rapid chargers” generally require the use of battery management systems, or on-board “supervisory” systems. Procurement costs of maintenance-free lead-acid batteries are comparable to the flooded-cell variants, but despite no watering requirements, they have not yet exhibited the longevity, and the associated relative economy, of the flooded-cell variants.

The only economically feasible alternative to lead-acid technology in the near term is the nickel-cadmium chemistry. Nickel-cadmium batteries have several important advantages over the lead-acid variants that may overcome the cost differences between the chemistries. Nickel-cadmium’s advantages in mass per unit energy storage, allowable depth-of-discharge, and low-temperature capability often make it the chemistry of choice for some applications without seriously compromising life-cycle cost constraints. Attaining an “on-the-road” cycle life comparable to the “laboratory” cycle life demonstrated by NiCd battery manufacturers involves an appropriate operational regime and an effective maintenance program. An aggressive and comprehensive maintenance program for nickel-cadmium batteries is necessitated by their high replacement cost. Fortunately, flooded-cell NiCd batteries are more tolerant of some mishaps than other battery types.

Table A-4 summarizes some of the battery characteristics to be considered in selection of battery chemistry for electric-bus applications.

TABLE A-4. CONSIDERATIONS IN BATTERY APPLICATIONS

Battery Type : Condition:	Flooded-Cell Lead-Acid	Sealed-Cell Lead-Acid	Flooded-Cell Nickel-Cadmium
Low-Temperature <40°F	Severe Energy-Capacity Losses -15% @ 40°F, -25% @ 20°F		Slight Energy-Capacity Losses -3% @ 40°F, -6% @ 20°F
Low-Temperature <0°F	Severe Energy-Capacity Losses –40% @ 0°F Danger of Freeze Damage to Discharged Cells		Slight Energy Capacity Losses -10% @ 0°F
High-Temperature >100°F	Reduced Cycle Life		Reduced Cycle Life & Reduced Charge Acceptance
Over Discharge (Below 20% State-of-Charge)	Increased Cell Imbalances Within Strings		
	Increased Imbalances Between Paralleled Strings		
	Reduced Cycle Life Permanent Capacity Loss If Severe		Negligible Effects
Prolonged Idleness	Increased Cell Imbalances Within Strings		
	Increased Imbalances Between Paralleled Strings		
	Risk of Overdischarge Damage		Negligible Risk
	Sulphation Damage If Stored Discharged or If Self-Discharge Progresses To Low SOC		May Require Conditioning If Stored Discharged

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