Electric Vehicle Transportation Center

Electric Bus Systems

Dr. Nan Qin
Dr. R. Paul Brooker
Dr. Ali Raissi
Electric Vehicle Transportation Center
Florida Solar Energy Center
1679 Clearlake Road
Cocoa, FL 32922-5703
Email: nqin@fsec.ucf.edu

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Submitted to: Ms. Denise Dunn
Research and Innovative Technology Administration
1200 New Jersey Avenue, SE Washington, DC 20590
E-mail: denise.dunn@dot.gov
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The objective of the Electric Bus Systems project was to study the adoption and operation of an electric bus fleet, analyze cost savings, and identify challenges and methods to overcome these challenges. The work was conducted by Dr. Nan Qin, Principle Investigator, Dr. R. Paul Brooker, and Dr. Ali Raissi of the Florida Solar Energy Center. We would also like to thank Mr. Ralph Wilder, Superintendent of Transit Maintenance at Tallahassee StarMetro Transit for providing the information of the bus implementation strategies and the bus operational data.

Final Research Project Report

Electric Bus Systems

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1.0 Abstract

Pure electric buses (EBs) offer an alternative fuel for the nation's transit bus systems. To evaluate EBs in a transit setting, this project investigated the five electric bus fleet of the StarMetro transit system of the city of Tallahassee, FL. For the study, the implementing strategy, route distances and timings, charging times, fuel economies, impact of chargers, and maintenance and operational characteristics were analyzed. The results were compared to a baseline five diesel bus fleet. The results showed that even with a four-fold improvement in fuel efficiency, the operational costs of electric buses were only 10% lower than that for diesel buses. The results showed that for EBs, the electricity cost due to demand charges was identified to be a major contributor to the electricity cost. To mitigate the high demand charges, researchers developed a method that can reduce the demand charge by optimizing the charging strategy. By using the optimized charging schedule, the demand charges can be reduced by up to 45%.

2.0 Background

There are over 70,000 transit buses operated by about 800 transit agencies in the United States. Most of these buses operate with diesel fuel and present environmental concerns, thus, alternative fuel buses such as compressed natural gas (CNG), biodiesel, and hybrid diesel-electric buses offer a cleaner option. The percentage of alternative fuel buses increased from 8% in 2000 to 41% in 2012. As of 2012, the CNG and hybrid buses are the most widely adopted alternative buses and have a 50% and 33% market share, respectively.[1] However, a study revealed that CNG buses produced more wells-to-wheels greenhouse gas (GHG) than diesel buses in all types of driving conditions.[2] The same study showed that the hybrid buses were more efficient in the city driving cycles because the regenerative braking could be better utilized, but performed similarly to diesel buses in non-city cycles. The pure electric bus (EB) is a new player in the transit bus arena. It consumes only electricity and uses an electric motor for propulsion. In addition, the electricity prices are much more stable than those of diesel as shown in Figure 1.[3] Also there are zero tailpipe emissions of a pure electric bus.

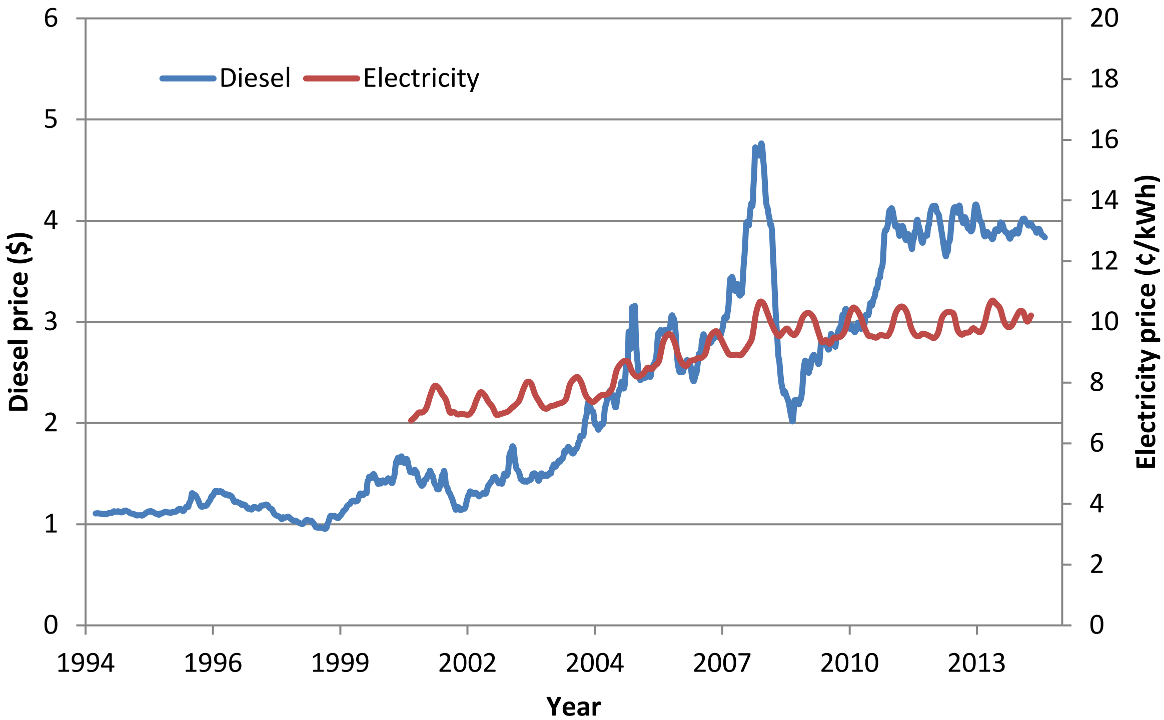

Figure 1. Historical national average diesel and electricity prices.

Because of battery types, there are two distinctive types of all electric transit buses available in the market. One uses lithium iron phosphate batteries of 200-300 kWh and can drive up to 155 mile between charges. After the battery is depleted, the bus goes off the route to recharge which takes up to 5 hours. The other type uses lithium titanate batteries of 55-72 kWh and has ranges up to 30 miles. Due to the unique chemistry and relatively small battery, these buses can be charged in less than 10 minutes.

3.0 Case Study

For this case study, the five lithium titanate electric bus fleet of the StarMetro transit system of the city of Tallahassee, FL, was used. For the study, the implementing strategy, route distances and timings, charging times, fuel economies, impact of chargers and maintenance and operational characteristics were analyzed. The results were compared to a baseline of five diesel buses.

3.1 StarMetro Electric Bus Fleet

StarMetro is the transit agency of the City of Tallahassee. It operates more than 70 vehicles in 12 cross-town routes, as well as university shuttles for Florida State University and Florida Agricultural & Mechanical University. The purchase of five EBs was made possible by a Transit Investment for Greenhouse Gas and Energy Reduction (TIGGER) II grant, awarded to StarMetro in January 2011. The total award was $6.47 million which was separated into four parts: $4.9 million for the bus purchases, $1.17 million for infrastructure, $50k for vehicle introduction promotion and $350k for program management, data collection and reporting. The EBs were manufactured by Proterra which specializes in electric bus technologies with fast charging capabilities. The revenue service of the EBs started in July 2013. Prior to the introduction of the EB fleet to the public, StarMetro launched a series of public awareness campaign to raise the awareness of this new technology. StarMetro Marking Specialist issued a series of press releases, web and email newsletters, and social media updates to alert the public of the EB arrival and construction details of the charging station. StarMetro also contracted a marketing firm to produce three television commercials.[4]

To enable the fast charging ability of the EBs, a fast charging station was installed. Site survey and engineering design was carried out in concurrence with the EB purchasing process. The details are described in Section 3.3. The FastFill charging station took a large area footprint with an enclosed area for the hardware. For aesthetic purposes, a concrete wall featuring an abstract art designed by a local artist was installed around the enclosure.

3.2 Electric Buses Technical Specifications

The all battery electric EcoRide™ BE-35 buses were designed and manufactured by Proterra which was founded in 2004. The EB is shown in Figure 2. According to the manufacturer data sheet, the bus features a light weight, composite bus body with a TerraVolt™ battery energy storage system which is capable of fast charging due to advanced lithium titanate battery technology. The bus is propelled by the rear wheel electric motors. The engine compartment is easily accessible from the back of the bus (Figure 2). The core technologies that differentiate this bus model with conventional diesel buses are the TerraVolt™ energy storage system, the ProDrive™ system, and the composite body.

The TerraVolt™ energy storage system includes a total of eight lithium titanate battery packs, each of which includes eight, 1.15 kW-hr battery modules for a total of 72 kWh of usable energy (Figure 3a). The battery modules include ten serially connected nano-titanate cells for a total of 23 volts and 50 amp hour each. The energy storage system is placed beneath the bus floor, providing a low center of gravity and even weight distribution (Figure 3b).

The lithium titanate battery was supplied by Altairnano. It utilized nano-structured lithium titanate spinel oxide anode materials instead of conventional graphite anode materials used in many Li-ion batteries. Due to its operating voltage, the titanate anode does not react with the electrolytes, thus no solid electrolyte interface (SEI) barrier will be formed around the electrode, rendering it easier for lithium ions to reach the surface of the electrode and the nanostructure allows the fast access of lithium ions to the active sites. These characteristics give the Altairnano lithium titanate batteries the advantages of:

1) a full charge can be completed within ten minutes;

2) a wider temperature window for charging, nearly 90% of room temperature charge retention can be realized at -30 °C to 65 °C range;

3) the battery is safe up to 240 °C, more than 100 °C above the temperature at which graphite-based batteries can catch fire or explode; and

4) the battery presents enhanced calendar and cycle life.

Figure 2. Proterra BE 35 and its engine compartment.

The ProDrive™ system is a vehicle control system developed by Proterra to effectively manage the energy supply and demands of the vehicle. It continuously monitors all vehicle conditions and adapts each subcomponent/subsystem to maximize energy efficiency in conjunction with the entire vehicle system. The systems employ a heavy-duty (HD) series hybrid electric drive architecture. TerraVolt™ then supplies energy to the traction motor, which in turn drives the wheels of the host vehicle. Because of the TerraVolt™ System's ability to absorb most of the kinetic energy it has available to it, it is able to recapture up to 92% of the available regenerative braking energy. The ProDrive system also includes a route memory, a global positioning system (GPS), and a remote monitoring system.

The basic structure of the bus is resin laminate fiber glass reinforced (composite). This structure, according to the manufacturer, results in a 20-40% weight reduction, 40% longer life, lower maintenance cost, and improved safety as compared to metal counterparts.

The other technical specifications such as weight, top speed, electric motor peak power are listed in Table 1.

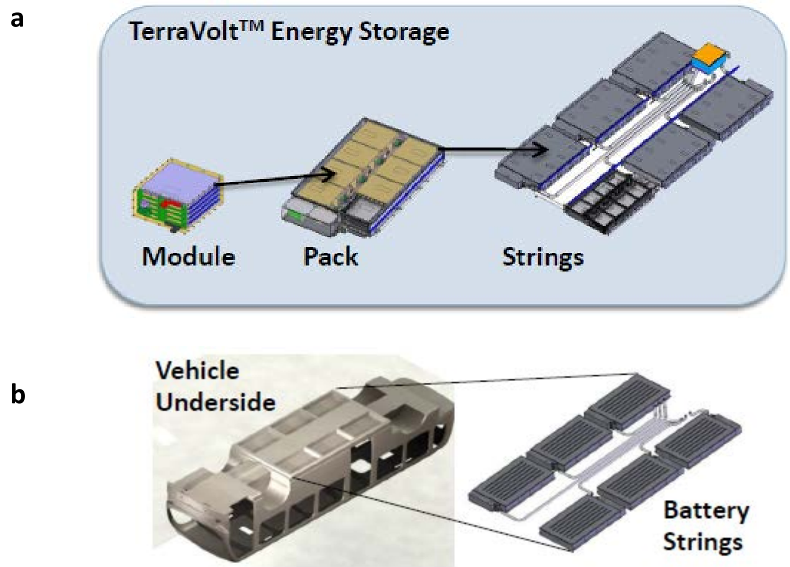

Figure 3. The energy storage system of a Proterra electric bus.

Table 1. Technical specifications of the Proterra EcoRide™ BE-35 buses.

Design Element	Description
Body construction	Resin laminate fiber glass reinforced (composite)
Length/width/height	35ft 8 5/8 in./102in./134in.
Wheel description	22.5X8.5 dura-flange
Steering Description	Electrically Driven Hydraulic
Motor description	UQM, Model PP15permanent magnet, 150 kW (200 HP) peak power
Transmission	BorgWarner P/N 6666
Battery	Altairnano Lithium titanate battery 72 kWh
Battery safety & preservation strategies	Glycol cooled, nano-safe chemistry 260 °C melting point, 8000-25000 cycle life
Inverter Capacity	150 kW
Gross Vehicle Weight Rated(GVWR)	35660 lbp
Curb Weight	27250 lbp
Acceleration (0-60mph)	60 seconds
Passenger Capacity	35 seated/27 standees
Top Speed	55 MPH
Operating Range	30 miles

3.3 Fast Charging Station

Transit buses are designed to service a fixed route. During a duty cycle, the bus returns every hour or two to a fixed location for the operator to take a break (known as a layover) and to re-align the schedule to coincide with the fixed route time points. These layovers are normally 10-15 minutes long and supply the opportunity to recharge the EBs.

The fast charging ability of the BE35 bus is realized by pairing the EB with a Proterra FastFill™ charging station. This charging system is comprised of the software and hardware to rapidly charge the energy storage from 10% to 95% in 10 minutes or less. The charging station is comprised of a charger, a charger head, and a bus communication system. When a BE-35 approaches, the station recognizes the bus and takes over control from the driver for the last 30-40 feet propelling the bus under the catenary arm, lowering the head and guiding it into its docking position. Charging begins when the driver engages the parking brake.

The installation of the rapid charging station was one of the critical tasks in the early implementation of the EB fleet. The task involved efforts from the Tallahassee City Utility, Proterra, StarMetro, and the construction and installation sub-contractors. The complete installation is covered in the following four steps:

1. Site Choice -- The site location had to satisfy the following requirements:
    - must be placed at a transit stop on an existing route,
    - must be on city-owned property,
    - must be located near high voltage lines,
    - must be accessible to multiple transit routes, and
    - must be in a high-visibility site.

    Satisfying all the above criteria, the C.K. Steele Plaza was selected to host the charging station location (see Figure 4 for the site location and the StarMetro routes). In addition, the C.K. Steele Plaza is the stop of 6 of 12 of StarMetro service routes which makes future expansion of the electric bus route possible.
2. Structure/Architectural Construction -- The chargers needed to be housed in a structure that restricts the public access to the high voltage electronics. The charger weighs about 10,000 pounds and has a footprint of 22 feet by 20 feet, thus, subsurface soil exploration and geotechnical engineering evaluation was conducted to provide recommendations regarding site preparation and foundation support. The construction of the bus canopy extension and supporting structure for the charge head was also part of the installation plan. The charge head is fully automated and communicates with the bus via Bluetooth technology. Figure 5 illustrates the model and the actual placement of the charger (enclosed in concrete walls). The charger head is located at the northwest corner of the C.K. Steele Plaza.
3. Electrical Installation -- To accommodate the 500kW chargers, a series of electrical installations and modifications took place. An 800A MCB panel board, a 15 kVA 120/208V transformer, a 50A MCB 120/208 V, and a 3-phase, 4w panel board were installed in the charger enclosure. Some existing electrical systems such as paging sound system, arrival/departure signage system, and lighting systems were relocated.
4. Heating, Ventilation and Air Conditioning (HVAC) System Installation -- A “mini-split” system consisting of an exterior heat pump with interior ductless air handling cassettes to handle the HVAC loads in the charging enclosure was installed.

As an alternative option to the Steel Plaza, several 50 kW DC charging stations were installed at the StarMetro Headquarters to provide for manual charging, if needed.

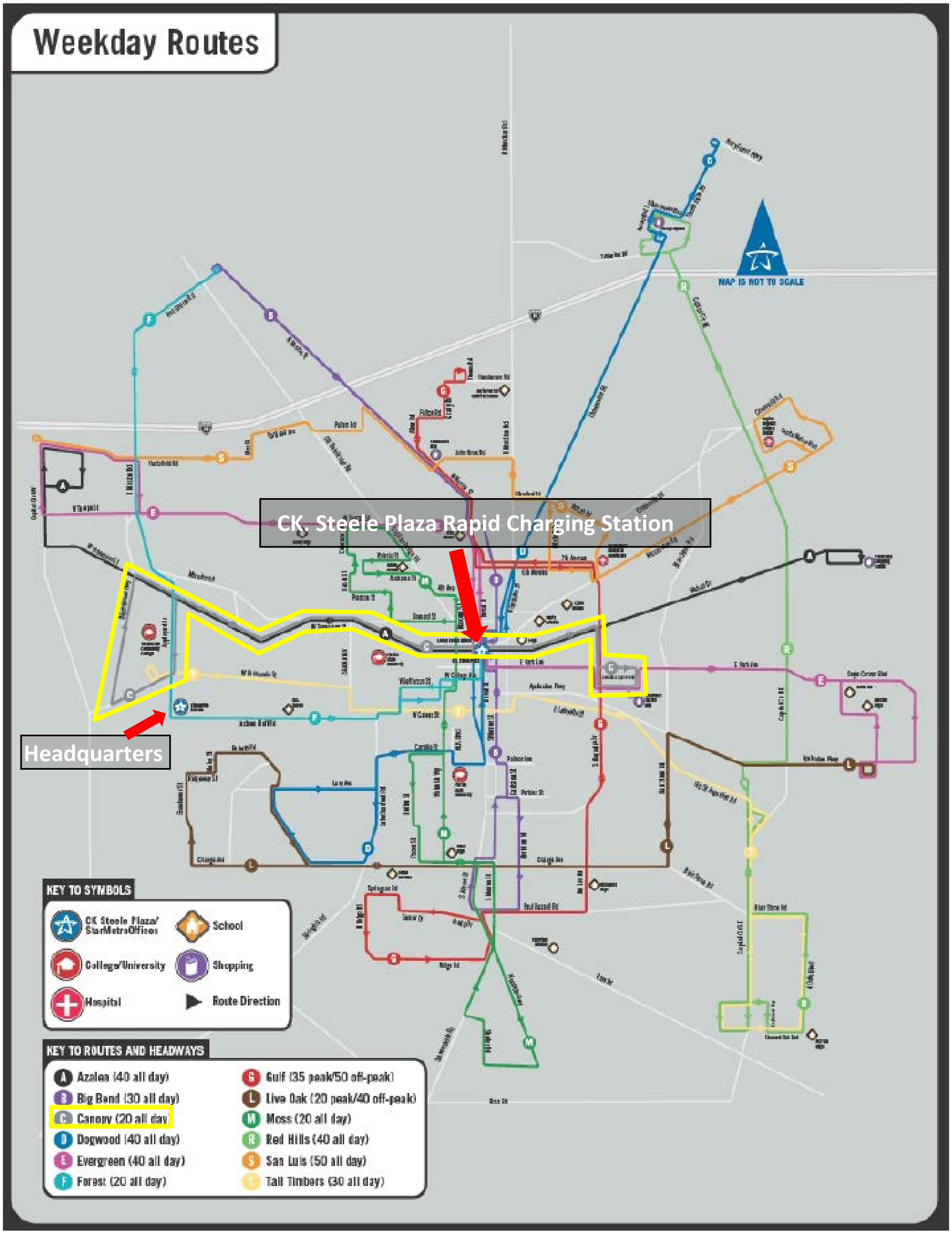

Figure 4. The StarMetro route map and the location of the rapid charging station.

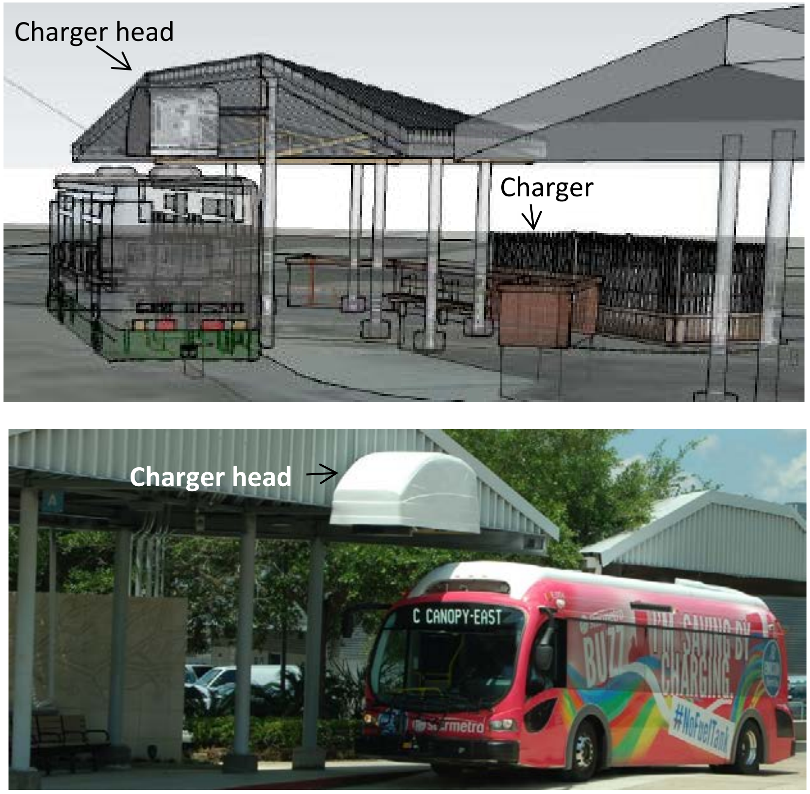

Figure 5. The model and actual picture of the FastFill^{TM} charger and the charger head.

3.4 Operational Data Analysis

The data regarding the electric bus implementation and operation were collected through many methods that included site visits, interviews, phone conferences, frequent email exchanges and discussions with bus manufacturers including Proterra, and their competitor, BYD. The collected data included the original manufacturer technical specification data sheet, Altoona Bus Test reports on BE-35 buses, the StarMetro charger installation work plan, public awareness campaign documents, driver and maintenance personnel training materials, and operational data spreadsheet including monthly mileages, energy consumption, electricity bills, maintenance record, and out of service reasons. Most operational data was collected between July 2013 and July 2014, with some exception of early operational data prior to July 2013. All data were supplied by StarMetro and do not contain confidential or proprietary information.

The first electric bus started on revenue service on the designated Canopy route (see Figure 4) in July 2013. EBs 2 and 3 were placed in service in late August 2013 and the last two soon after. Five diesel buses (DBs) placed in service in 2010 were chosen as the baseline comparison buses. These diesel buses were compliant to the 2010 EPA emission standard. For the results, the five EBs fleet were compared to the five baseline DBs.

Data of miles driven, fuel consumption, fuel costs, out of service reasons, and maintenance costs were collected. Figure 6 shows the monthly average driving distance of both the EBs and DBs from July 2013 to July 2014. The data showed that the DB transit bus drove 2279-5105 miles per month with an average of 3470 miles per month, typical to a transit bus. In contrast, the EBs drove 309-1869 miles per month with an average of 861 miles per month, significantly lower than that of a DB. The low usage of the EBs was attributed to several reasons as follows:

1) the EBs did not start service at the same time;
2) StarMetro drivers struggled with familiarity and confidence in the technology;
3) three EBs were needed in the Canopy route, thus, two EBs were idle in the beginning. A fourth bus was added to the route to accommodate a traffic congestion issue; and
4) both the charger and EBs experienced intermittent technical issues which caused down time.

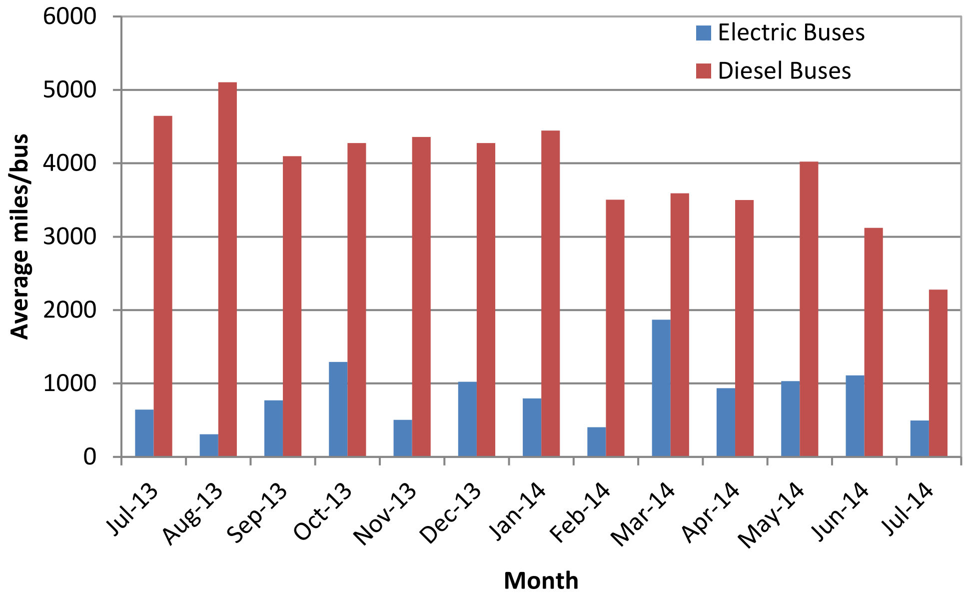

Figure 6. Average monthly driving distances for EBs and DBs from July 2013 to July 2014.

Analysis of the out of service causes of the EBs between July 30, 2013 and September 30, 2014, showed a total of 350 out of service days were reported which was approximately 17% of the total days that the EBs had been in service. The causes related to the core EB technologies such as charging issues, battery issues, and electric issues contributed to 29% of out of service days. The Proterra's onsite technician was able to resolve most of the charging related problems and the charging has since been more consistent. About 47% of out of service days were related to other bus issues such as air conditioning system, doors, windshield wipers, coolant leak, and service bulletin. As the Proterra EBs were designed from ground up, these technical issues were resolved with retrofitting and then did not occur. For example, the door issues were only associated with EB 1-3 which was the first generation Proterra all electric bus. A redesign of the doors was performed and this problem does not exist in EB 4 and 5. The issues with windshield wipers, coolant leak, and service bulletin were also corrected in Proterra's second generation EBs. The remaining 24% of the out of service days were caused by non-manufacturer specific reasons such as accidents and scheduled maintenance.

The average monthly fuel efficiency of the EBs and DBs from August 2013 to March 2014 are shown in Figure 7. The fuel efficiency of the DBs is presented as kWh-e/mile which is calculated using 37.3 kWh/gallon of diesel equivalent. The fuel efficiency of EBs was 2.57±0.35 kWh-e/mile while the DBs operated at 9.78±0.97 kWh-e/mile. The EBs demonstrated a fuel economy about four times higher than the DBs.

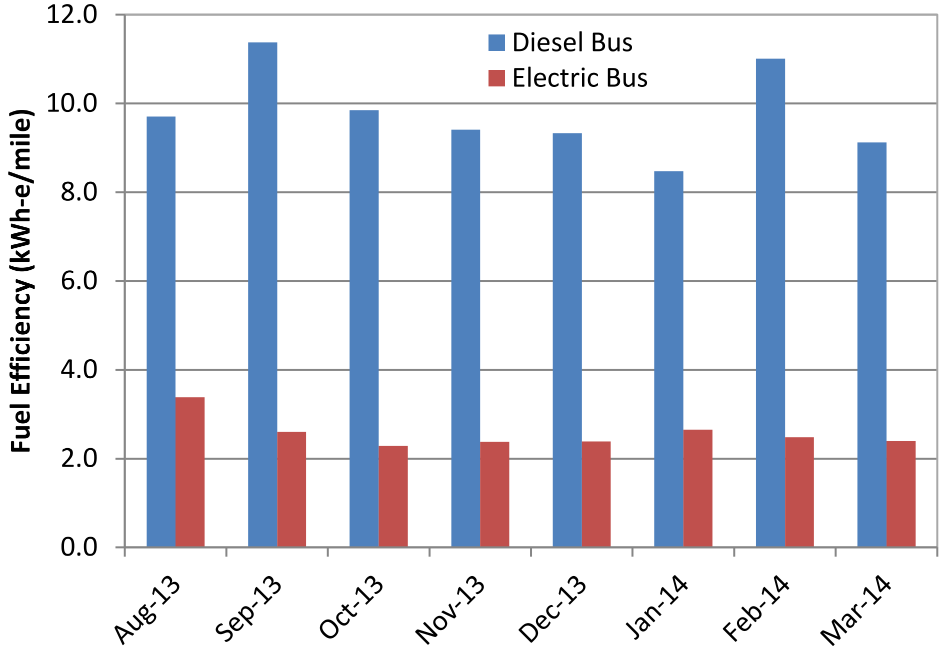

Figure 7. Fuel efficiency comparison of EBs and DBs from August 2013 to March 2014.

The environmental impact of EBs was next assessed by using their fuel economy. These CO_2 emission calculations were done on a U.S. basis and used U.S. electrical generation numbers. Although the tailpipe emissions for a pure electric bus is zero, the upstream CO_2 emission associated with the electricity generation must be taken into consideration.

According to the U.S. Energy Information Adminstration, U.S. electricity was generated from an energy mix of coal, natural gas, nuclear, and renewable energy sources.[5] Table 2 shows the 2015 national electricity energy source mix and the CO_2 emission associated with each source. The CO_2 emissions of the DBs and EBs were calculated using the average fuel economy data mentioned above.

Table 2. 2015 energy sources, percent share, and CO_2 emission of U.S. electricity generation.

Source	Share	CO_2 emission (kg/kWh)
Coal	33.0%	0.94
Natural Gas	33.0%	0.55
Nuclear	20.0%	0
Hydropower	6.0%	0
Other Renewable	7.0%	0
Petroleum	1.0%	0.77

These CO_2 values are compared with emission data obtained from a separate study based on Altoona test of New Flyer buses on city cycles.[2] The New Flyer buses include a compressed natural gas (CNG) model, a diesel model, and a hybrid model which are all compliant with the

2010 EPA emission requirements. The results are shown in Figure 8. The StarMetro diesel buses show similar CO_2 emission levels as the New Flyer CNG and diesel buses, while the EBs demonstrate significantly lower CO_2 emission than other bus types including the hybrid bus model.

Assuming a typical 500,000 miles lifetime service of a transit bus, the use of an EB would produce 655 tons less CO_2 than a diesel bus counterpart. If the electricity generation consist of a higher percentage of renewable energy sources, the CO_2 saving would be even higher.

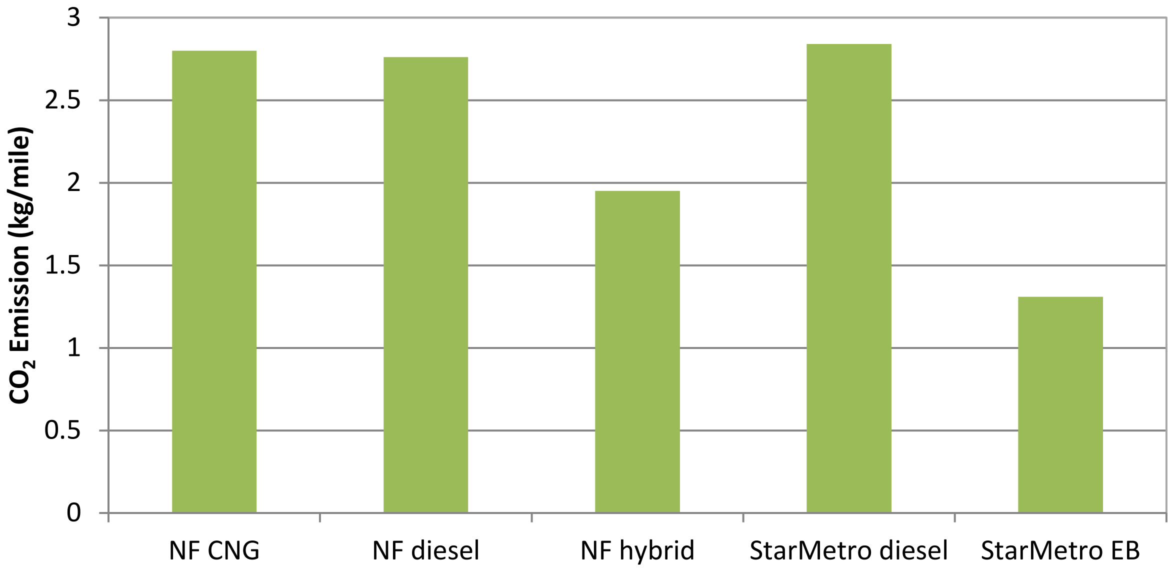

Figure 8. CO_2 emission of StarMetro buses and New Flyer buses.

The operational cost of a transit bus consists of fuel and maintenance costs. To compare the fuel costs of EBs and DBs, the cost per distance driven ($/mile) was calculated from the fuel prices and average fuel efficiencies of DBs and EBs. For DBs, the diesel price was based on $ 3.44 per gallon as of December 2014. For EBs, the electricity cost was obtained from StarMetro monthly electricity bills which consist of two major components: energy cost and demand charge. Energy cost is directly related to how much energy (kWh) are used in a billing cycle, usually a month. Demand charge is a cost related to the peak demand of electricity (kW) in a given billing cycle. Peak demand is normally determined as the highest power in any given 15 or 30 minute window during the month. It is reset each month and normally applies to only commercial or industrial accounts. Thus, the total electricity cost is comprised of two parts and can be calculated using equation 1:

$$\text{Electricity Cost} = \text{Energy Consumption (kWh)} \times \text{Base Price} + \text{Demand (kW)} \times \text{Demand Charge Unit Price} \tag{1}$$

For the City of Tallahassee as of July 2014, the energy use charge was $0.06/kWh, and the demand charge was $10.97/kW. Using this process, the average cost per mile of EBs and DBs were calculated to be $0.72/mile and $0.90/mile, respectively. The difference in cost per mile between EBs and DBs is not as significant as the difference in their fuel economy and the main reason can be attributed to demand charges.

Figure 9 shows the monthly peak demand at the fast charging station from August 2013 to July 2014. Most peak demands are over 150 kW with the exception of August 2013 which was the beginning of the revenue service with only one EB in operation. The average demand for this period was 167.5 kW which added $1837 for demand charges to the monthly electricity cost. Note is made that the Proterra charging station has one electric meter, thus, the single meter accounts for only the EB power used.

Using equation (1), the monthly average EB electricity cost was calculated to be $0.28/kWh. The demand charges contributed to an added $0.22/kWh and accounted for 78% of the total cost, greatly impacting the fuel cost efficiencies of EBs. As a result, approaches to mitigate demand charges resulting from high speed charging need to be developed to lower the EB fuel cost. A method developed here and based on optimization of charging schedules is described in Section 4.0.

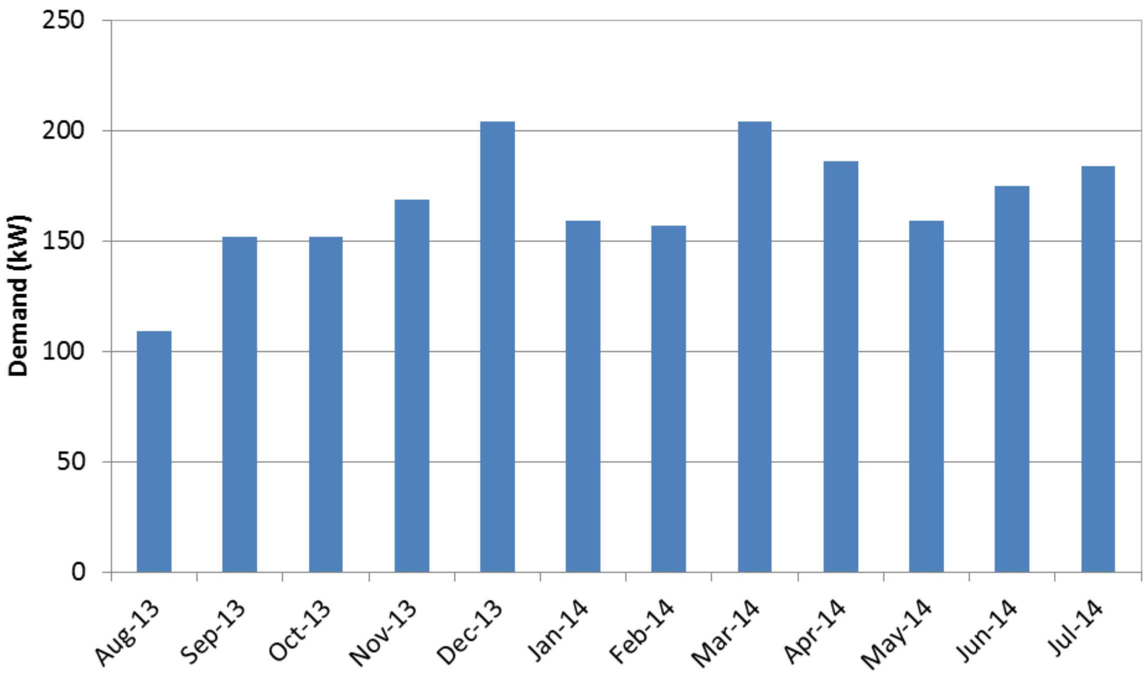

Figure 9. Monthly demand at the fast charging station

In addition to the fuel cost, the maintenance cost also contributes to the transit bus operation cost. Figure 10 shows the maintenance cost comparison of the EBs and DBs. The cost includes labor and parts for both preventative maintenance and repairs. The EBs average a $1000±$168 monthly cost and the DBs average a $1500±$266 monthly cost. The maintenance cost of the EBs was not only considerably lower than the DBs, but also more consistent. This could be attributed to the simpler electric powertrain of the EBs which has 30% less moving parts than the conventional powertrain used in the baseline DBs. It should be pointed out that the maintenance data of EBs were collected during the first year of their operation. The potential increase in maintenance cost to account for batteries aging and other power train degradation have not been evaluated.

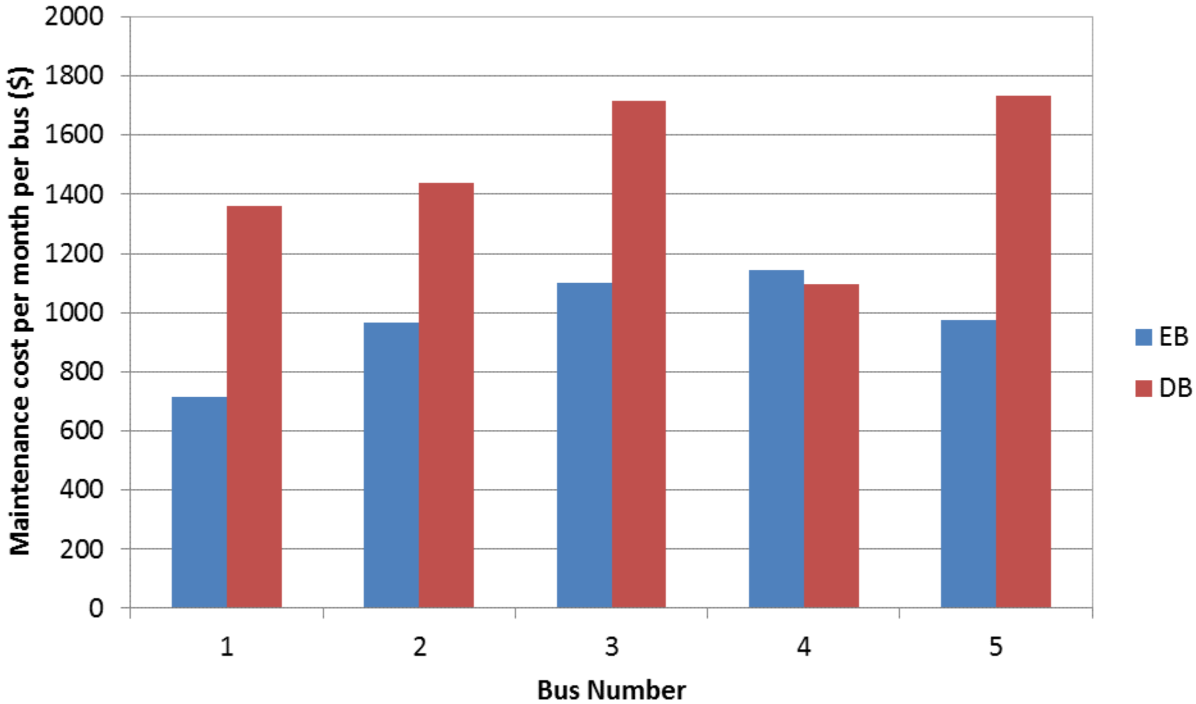

Figure 10. Maintenance cost comparison between EBs and DBs from Aug 2013 to Mar 2014

A simplified total cost of ownership (TCO) is calculated by considering only the initial cost plus the current fuel and maintenance costs. The total costs are shown in Table 3, assuming a life of 500,000 miles and 12-year service of a typical transit bus. The EBs exhibits a higher TCO than DBs, mainly due to the high initial purchase price. With the maturity of the technology and economy of scale, the capital cost of EBs are expected to continue to drop. For example, Proterra has since lowered the price of their second generation EBs by 13%. If the electrical demand cost can be further lowered by reducing demand charges, then EBs have the future potential to be lower than the DB TCO.

Table 3. The total cost comparison of EBs and DBs.

	Purchase price (k$)	Fuel Cost (k$)	Maintenance Cost (k$)	TCO (k$)
Diesel Bus	450	450	212	1112
Electric Bus	950	360	141	1451

4.0 Demand Charge Reduction by Charging Schedule Optimization

The case study results showed that EB fast charging resulted in high utility demand charges and, thus, they can cause a major barrier in the wide spread adoption of EB technology. For this research effort, a model was developed which can simulate daily charging patterns and demand charges of the StarMetro EB fleet. By running the model for various charging patterns and battery state of charge parameters, an optimal charging strategy was determined. The model assumption, parameters, and optimization methodology can be found in Reference 6.

The EB energy consumption model follows a selected driving cycle and back-calculates the energy needed to achieve the needed velocities and distances. The model was then validated by comparing the simulated fuel efficiency with actual operational data provided by StarMetro. The fuel efficiency predicted by this model is 2.69 kWh/mile while the operation data from August 2013 to March 2014 showed an average of 2.57 ± 0.35 kWh/mile. The model was considered successful since the simulation results are within 5% of the measured data.

The charging strategy developed is a decision making process in which an EB only charges when its state of charge (SoC) is below a certain charging threshold (CT) at the fast charger (FC). Within the decision making process, it is assumed that every EB in the fleet uses the same CT. The flow chart of the charging strategy is illustrated in Figure 11. Briefly, every time an EB arrives at the FC, the model checks its SoC. If the SoC is below a predetermined CT, the EB is charged to 95% SoC. If the SoC is above the CT, the model determines if the remaining SoC is sufficient to allow the EB to travel back to the FC in the next trip and return to the charging station with a SoC above 5%. If yes, the EB skips the charging. Otherwise, the EB charges to 95% SoC at the FC.

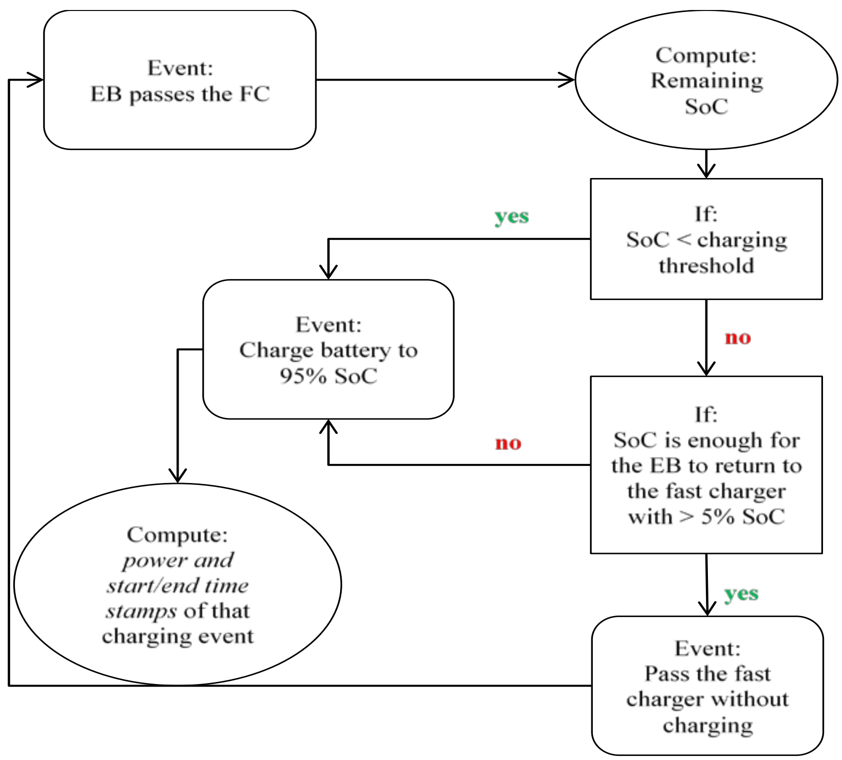

Figure 11. Schematic representation of the charging model

The model calculated the start and end time of each charging event. The electric power on a second to second basis of that charging event is determined from a charging power curve, provided by Proterra. The power demand is averaged over every 30-minute period which can be calculated from the power and times of the charging events.

The optimal CT was determined by performing an exhaustive enumeration covering the full range CT of 0–95%, as shown in Figure 12. The optimal peak demand of 124 kW is achieved with CT of 60–64%, while the highest peak demand of 213 kW resulted from CT of 0–28%. Since the demand charge is proportional to the peak demand, the minimum and maximum demand charges per month are calculated to be $1590 and $2700, respectively. These are also shown in Figure 12.

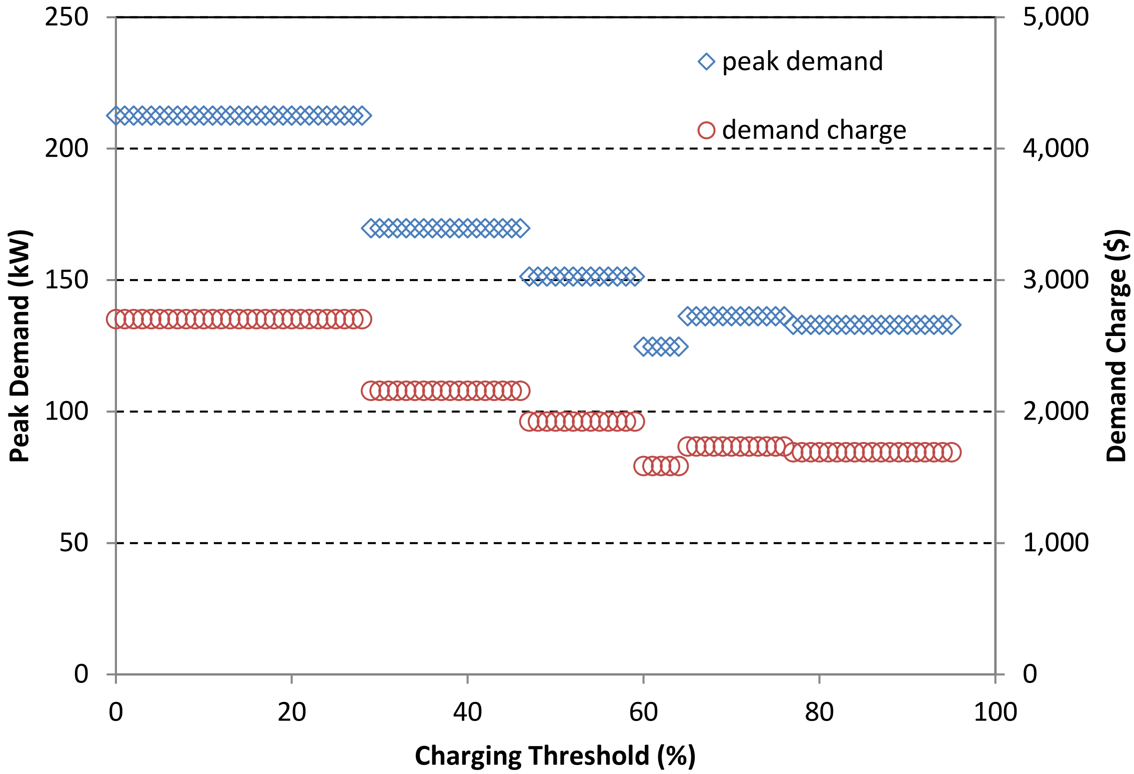

Figure 12. Peak demand and demand charge at different charging thresholds for 5 EBs

Assuming a typical 12-year transit bus service life, the optimal demand charge could save $160,000 compared to non-optimal demand charging scenarios. The optimal demand charge represents 43% of the total electricity cost and is significantly lower than the 78% mentioned in Section 3.4. The impact of CT on the daily demand profile is revealed in Figure 13, in which CT of 20%, 40%, 60%, and 80% curves represent CT of 0–28%, 29–46%, 60–64%, and 77–95% scenarios, respectively. Each point on the curve represents a power reading for a demand period. The 20% and 40% profiles exhibit alternating deep valleys and high peaks. In contrast, the 60% and 80% curves show smoother profiles which means that the total energy drawn from the grid is more evenly distributed in all the half hour windows. As a result, lower peaks can be achieved.

Figure 14 reveals the impact of CT on individual charging events. Each colored bar represents one charging event and each color represent one EB. The left and right borders of a bar represent the start and end time stamps of a charging event, and the width of the bar represents the charging duration. In general, the higher CT results in larger number of charging events and shorter charging durations. The charging events in the 40% and 20% CT scenarios form clusters, which contributes to the big peaks and valleys in their demand profiles in Figure 13. In contrast, the charging events in the 80% and 60% CT scenarios are evenly distributed, which result in smoother demand profiles. The model also accounts for overlapping events, as shown in the 80% and 20% scenarios (the magnified regions). When overlap happens, the model allows the EB with a later start time to wait until the event with an earlier start time is finished. In the optimal charging scenario (60% CT), there are no overlapping events, and the minimum gap between two consecutive charging events is 14 minutes. Thus this charging strategy can be easily implemented in the real world operation.

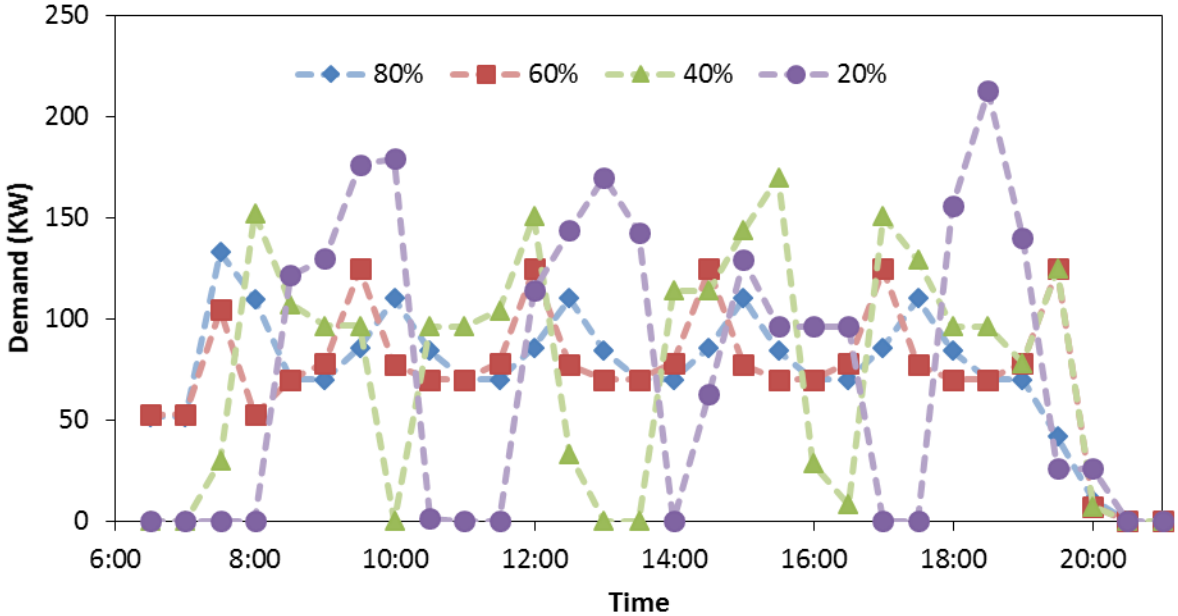

Figure 13. Daily demand profiles using different charging thresholds

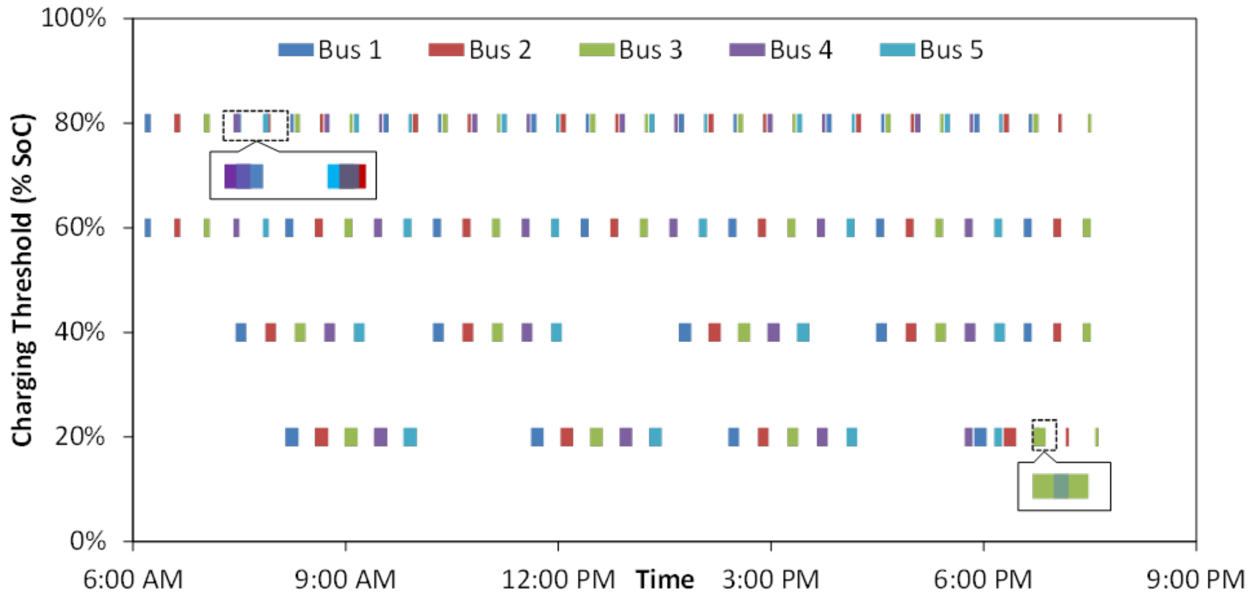

Figure 14. Charging events under different charging thresholds

In conclusion, this work demonstrated that by adopting an appropriate charging strategy, significant savings in demand charges can be achieved, without incurring additional infrastructure cost (e.g. batteries) or the need for a special electricity rate structure. In cities where a higher demand charge rate or a shorter-duration demand period (e.g. 15 min) is used, the savings could be even more significant.

5.0 Impacts/Benefits

The case study of Tallahassee electric bus fleet provides planners interested in adopting electric bus fleets a holistic view of the benefits and challenges associated with electric transit bus adoption. It also provides a technical background for making future policies and incentives to encourage alternative vehicle transit adoption. The charging strategy developed significantly lowers the demand charge without the requirement for any additional hardware cost or policy changes, and can be adopted at no cost to the transit agencies.

The EB energy consumption model and the charging strategy model developed by this work can be used to study the scheduling and demand charges of electric transit bus systems with different driving cycles and routes. In addition, it can be used to explore methods such as battery energy storage systems to reduce demand charges, as well as conduct comparative studies of EB with different battery technologies.

6.0 References

1. Neff, J.; Dickens, M. 2014 public transportation fact book, Appendix A: historical tables; *American Public Transportation Association*: Washington, DC 20006, **2014**.
2. *M.J. Bradley & Associates LLC,* Comparison of modern CNG, diesel and diesel hybrid-electric transit buses: efficiency and environmental performance, Concord, MA.
3. U.S. Energy Information Adminstration. http://www.eia.gov/petroleum/gasdiesel/.
4. StarMetro electric bus television commercials, https://www.youtube.com/watch?v=2i7LnHzRMuA; https://www.youtube.com/watch?v=PwndHLtfzP8; and https://www.youtube.com/watch?v=8JUUFulMoHs.
5. U.S. Energy Information Adminstration. https://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states.
6. Qin, N.; Gusrialdi, A.; Brooker, R.; Raissi, A.; Numerical Analysis of Electric Bus Fast Charging Strategies for Demand Charge Reduction, *Transportation Research Part A: Policy and Practice*, (**2016**), 94, 386-396.