

Zero-Emission Bus Evaluation Results: King County Metro Battery Electric Buses

FEBRUARY 2018

FTA Report No. 0118
Federal Transit Administration

PREPARED BY
Leslie Eudy
Matthew Jeffers
National Renewable Energy Laboratory



COVER PHOTO

Courtesy of King County Metro (Seattle) Proterra Catalyst fast-charge battery electric bus. Photo courtesy of National Renewable Energy Laboratory.

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m ³
yd³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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ABSTRACT

This report summarizes the experience and results from a battery electric bus (BEB) demonstration funded by the Federal Transit Administration (FTA) under the Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) program. In 2010, King County Metro transit agency in Seattle, Washington, received funding from a TIGGER award to add three zero-emission BEBs to its fleet. The BEBs in service at King County Metro are 40-foot fast-charge electric transit buses built by Proterra. FTA is collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to conduct in-service evaluations of advanced technology buses developed under its programs. This report presents evaluation results for the BEBs in comparison to a selection of baseline buses. The focus of the analysis is on one year of data from April 2016 through March 2017.

EXECUTIVE SUMMARY

The U.S. Department of Transportation's Federal Transit Administration (FTA) supports the research, development, and demonstration of low- and zero-emission technology for transit buses. FTA funds a number of research projects with a goal of facilitating commercialization of advanced technologies for transit buses that will increase efficiency and lower tailpipe emissions. FTA is collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to conduct in-service evaluations of advanced technology buses developed under its programs. NREL uses a standard evaluation protocol for evaluating the advanced technologies deployed under the FTA programs.

FTA seeks to provide results from new technologies being adopted by transit agencies. The eight evaluations selected to date include battery electric buses (BEBs) and fuel cell electric buses (FCEBs) from different manufacturers operating in fleets located in both cold and hot climates. NREL recently completed a yearlong evaluation of a fleet of BEBs in service at King County Metro (KC Metro) in Seattle, Washington. KC Metro's service area covers more than 2,000 square miles of King County, including the Seattle metro area. In February 2016, the agency began operating a fleet of three BEBs in its service area. The focus of the analysis is on one year of data from April 2016 through March 2017.

The BEBs in service at KC Metro are fast-charge, composite buses built by Proterra. KC Metro and NREL selected three conventional technologies for comparison to the BEBs: standard diesel buses from Gillig, diesel hybrid buses on New Flyer's Xcelsior platform, and electric trolley buses on New Flyer's Xcelsior platform. Buses in all four fleets are 40-foot, model year 2015 buses. The four bus fleets included in the evaluation are referred to in this analysis as the battery fleet, hybrid fleet, diesel fleet, and trolley fleet. In the introduction and summary sections of this report, the term "BEB" is used when referring to battery bus technology, transit bus evaluations, and NREL's analysis protocol. Table ES-1 provides a summary of the results for the battery fleet and baseline fleets.

The battery fleet accumulated 83,128 miles during the year, which is 27,709 miles per bus. The average monthly operating mileage per bus was 2,309 miles. The battery buses accumulated more miles than the diesel and trolley buses, but fewer miles than the hybrid buses. This is a function of planned use of the buses. The battery fleet is restricted to KC Metro routes 226 and 241, and the hybrid fleet is randomly dispatched on all routes, which include commuter routes. This results in a higher average speed for the hybrid buses and a faster mileage accumulation. The trolley buses are limited to the network of catenary lines in and around downtown Seattle, which results in lower speeds and fewer operating miles. The diesel buses are operated on one specific route on weekdays only.

Table ES-1
*Summary of Evaluation
 Results*

Data Item	Battery	Hybrid	Diesel	Trolley
Number of buses	3	10	3	10
Total mileage in data period	83,128	435,552	69,329	180,554
Average mileage per bus	27,709	43,555	23,110	18,055
Average monthly mileage per bus	2,309	3,630	1,926	1,505
Availability (85% is target)	80.6	90.5	86.4	84.9
Fuel economy (kWh/mile)	2.36	—	—	2.57
Fuel economy (miles/dge ^a)	15.9	6.3	5.3	14.7
Average speed, including stops (mph) ^b	14.8	15.2	14.6	9.0
Miles between roadcalls (MBRC) – bus ^c	2,771	7,641	17,332	1,641
MBRC – propulsion system only ^c	6,927	29,037	34,665	2,960
Total maintenance cost (\$/mile) ^d	0.26	0.32	0.46	0.46
Maintenance – propulsion system only (\$/mile)	0.05	0.12	0.13	0.17

^a Diesel gallon equivalent.

^b Based on scheduled revenue service.

^c MBRC data cumulative through March 2017.

^d Work order maintenance cost.

The overall average availability for the battery fleet was 80.6%. For the baseline buses, the overall average availability was 90.5% for the hybrid fleet, 86.4% for the diesel fleet, and 84.9% for the trolley fleet. Issues relating to general bus maintenance accounted for most of the downtime for all four fleets. The battery buses experienced several issues with the electric drive system.

The battery buses had an overall average efficiency of 2.36 kWh per mile, which equates to a fuel economy of 15.9 miles per diesel gallon equivalent (mpdge). The hybrid buses had an average fuel economy of 6.3 mpdge, and the diesel buses had a fuel economy of 5.3 mpdge. Monthly energy use data were not available for the trolley buses; however, a sample of total mileage and energy use for two of the trolley buses representing a 13-month period of operation was used to calculate an estimated average fuel economy of 14.7 mpdge for the trolley fleet.

During the data period, KC Metro paid an average of \$0.20/kWh for electricity for the battery buses and \$1.60/gal for diesel fuel. The fuel economy advantage of the hybrid fleet over the diesel fleet results in a slightly lower per-mile fuel cost for the hybrid fleet (\$0.25/mi) compared to the diesel fleet (\$0.30/mi). The per-mile fuel (electricity) cost for the battery fleet was \$0.57/mi. The electricity cost per mile calculation includes all electricity that KC Metro purchased from the utility. This represents the “grid-side” fuel cost per mile, not the “bus-side” fuel cost per mile. Despite having an average fuel economy that is 2.5 to 3 times higher than that of the baseline bus fleets in the evaluation, the battery fleet had higher per-mile fuel costs due to the large difference between diesel fuel and electricity prices.

KC Metro incurs demand charges when charging rates exceed 50 kW during the billing period. These demand charges made up a significant portion of the utility bills each month—between 34% and 54%. The monthly demand charges are inversely proportional to the monthly mileage of the battery fleet. Thus, the relative cost of demand charges decreases as the battery fleet mileage increases and the fast charger is more fully utilized. The charger utilization will increase as more battery buses are added to the route, or as the existing battery buses operate more frequently, or both.

The transit industry measures reliability as mean distance between failures, also documented as miles between roadcalls (MBRC). NREL tracks bus reliability categorized by total bus roadcalls, propulsion-related roadcalls, and energy storage system-related roadcalls. Propulsion-related roadcalls are a subset of total bus roadcalls for each bus fleet. Energy storage system-related roadcalls are a subset of the propulsion-related roadcalls, specific to the energy storage system of the battery buses. The diesel fleet had the highest bus MBRC at 17,332. The hybrid bus fleet achieved 7,641 MBRC. The battery fleet MBRC and trolley fleet MBRC are currently below 3,500.

The battery fleet propulsion-related MBRC was 6,927. Propulsion-related MBRC for the diesel and hybrid baseline fleets were similar to each other—34,665 and 29,037, respectively. The propulsion-related MBRC for the trolley buses was 2,960, which reflects the trolley fleet's low average mileage and early issues with the current collection system.

NREL also analyzed work order data to provide a comparison of maintenance costs between the battery fleet and the baseline fleets. After removing accident- and warranty-related items for all fleets, the average per-mile maintenance cost for the data period was \$0.26/mi for the battery buses, \$0.32/mi for the hybrid buses, \$0.46/mi for the diesel buses, and \$0.46/mi for the trolley buses. During the data period, the maintenance cost for the battery buses was 17.8% less than that of the hybrid buses; 44.1% less than that of the diesel buses; and 43.2% less than that of the trolley buses. These combined totals include scheduled and unscheduled maintenance.

NREL analyzed the maintenance data to determine costs by vehicle system. The systems with the highest percentage of maintenance costs for the battery buses and diesel buses were 1) cab, body, and accessories; 2) propulsion-related; and 3) preventive maintenance inspections. The systems with the highest percentage of maintenance costs for the hybrid buses were 1) propulsion-related; 2) cab, body, and accessories; and 3) preventive maintenance inspections. The systems with the highest percentage of maintenance costs for the trolley buses were 1) cab, body, and accessories; 2) propulsion-related; and 3) HVAC.

As with all new technology development, lessons learned during this project could aid other agencies considering BEB technology. KC Metro reports that it has had a positive experience with Proterra and that the manufacturer is very responsive. Proterra has expressed appreciation with KC Metro's feedback on the bus design and has used that input to make improvements. KC Metro reports the following successes:

- Implemented the agency's first BEB fleet
- Accumulated more than 100,000 miles on the battery buses in the first 15 months of revenue service
- Increased operation of the battery fleet since the end of the data collection period
- Initiated an order of eight more fast charge BEBs through a Low-No award.

Issues and lessons learned include the following:

- **Charger availability** – Availability of the on-route fast charger is critical for operation of a fast-charge BEB fleet. Downtime of the charger results in downtime for the fleet. KC Metro experienced this issue when the charger was damaged. While the issue was minor, the resulting downtime of the charger caused a major service interruption for the battery bus fleet during the two weeks it took to repair the charger.
- **Operator training** – Driver training is an ongoing challenge because the BEBs operate differently from the conventional buses in the agency's fleet. The primary training differences are learning the charger docking procedure and ensuring the BEBs are fully charged before returning to the base at the end of a shift. Once KC Metro installs a fast charger at the base, the need to fully charge the BEBs at the end of the day will no longer be necessary. Any new operators for the routes serviced by the BEBs need to be trained on the operational differences. Transit agencies deploying electric buses should consider this when planning training programs.
- **Operations planning** – The scheduling department needs to understand the operational differences for fast charged BEBs. The short range of these buses requires them to operate on a selection of routes that return to the charging station regularly. Schedulers need to limit service to the selected routes until the agency adds chargers to other locations. The agency also has layovers planned in its route schedules. With conventional buses, an operator can shorten the layover to make up lost time and keep buses on schedule. For electric buses, however, that planned layover includes time for charging. Shortening the layover to make up schedule slip could result in the bus not getting a full charge.
- **Parts list for inventory** – Parts availability is a common issue with agencies deploying advanced technology buses. KC Metro reports that Proterra has delivered parts quickly, but the agency needs to keep some parts on hand to

speed up the process. The agency is working with Proterra to develop a list of parts for on-site inventory.

KC Metro is committed to an environmentally-friendly fleet and plans to purchase 120 BEBs by 2020. In 2017, the agency entered into a contract with Proterra to purchase up to 73 BEBs.

Introduction

The U.S. Department of Transportation's (DOT's) Federal Transit Administration (FTA) supports the research, development, and demonstration of low- and zero-emission technology for transit buses. FTA funds a number of research projects with a goal of facilitating commercialization of advanced technologies for transit buses that will increase efficiency and lower tailpipe emissions. These programs include the following:

- **National Fuel Cell Bus Program (NFCBP)** – a \$180 million, multi-year, cost-share research program for developing and demonstrating commercially viable fuel cell technology for transit buses.
- **Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER)** – \$225 million for capital investments that would reduce greenhouse gas emissions and/or lower the energy use of public transportation systems.
- **Low or No Emission Vehicle Deployment Program (Low-No)** – \$186.9 million in funding (FY13–FY17) to transit agencies for capital purchases of zero-emission and low-emission transit buses that have been largely proven in testing and demonstration efforts but are not yet widely deployed.

FTA understands the need to share early experience of advanced technologies with the transit industry. FTA is funding evaluations of a selection of these projects to provide comprehensive, unbiased performance results from advanced technology bus development, operations, and implementation. These evaluations have proved useful for a variety of groups including transit operators considering the technology for future procurements, manufacturers needing to understand the status of the technology for transit applications, and government agencies making policy decisions or determining future research needs. The evaluations include economic, performance, and safety factors. Data are collected on the operation, maintenance, and performance of each advanced technology fleet and a comparable baseline fleet operating at the same site (if available).

The purpose of this report is to outline the evaluation plan and analysis protocol and present the results from a one-year evaluation of three battery electric buses (BEBs) at King County Metro in Seattle, Washington.

SECTION 2

Zero-Emission Bus Evaluations Planned

FTA is collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to conduct in-service evaluations of advanced technology buses. For more than a decade, NREL has been evaluating advanced technology transit buses using a standard data collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations. Funding for these evaluations has come from several agencies including FTA, DOE, and the California Air Resources Board. NREL has evaluated fuel cell electric buses (FCEBs) as well as BEBs following this standard protocol. DOT's Research, Development, and Technology Office (OST-R) also has an interest in zero-emission bus (ZEB) technology deployment and commercialization. OST-R is coordinating and collaborating with FTA on the evaluation process and results by providing funding to cover additional evaluations. This section provides the list of evaluations selected to date and outlines the protocol used for collecting and analyzing the data.

Selected Projects

NREL uses a set of criteria to prioritize the available projects for selection that include number of buses deployed, record-keeping practices of the transit agency, commitment level of the bus original equipment manufacturer (OEM), and the availability of appropriate baseline buses for comparison. The criteria are not intended to be rigid; however, the determination of priority is based on how many criteria are met. In consultation with FTA, NREL has selected several projects that are in the highest priority category. Other projects will be chosen as more information becomes available. Table 2-1 lists the projects selected for evaluation as of the publication date of this report.

Table 2-1 *Selected Evaluation Projects*

Site #	Transit Agency and Location	Project Description	Evaluation Status
1	King County Metro, Seattle, WA	3 Proterra 40-ft Catalyst buses and 1 fast-charge station	Completed
2	Long Beach Transit, Long Beach, CA	10 BYD 40-ft BEBs, overnight charging with 1 inductive charger on route	Initiated April 2017
3	Central Contra Costa Transit Authority, Concord, CA	4 Gillig/BAE Systems 29-ft BEBs, overnight charging with 1 inductive charger on route	Initiated April 2017
4	Orange County Transportation Authority, Santa Ana, CA	1 American Fuel Cell Bus (AFCB): BAE Systems, Ballard Power Systems, and ENC	Initiated June 2016
5	Stark Area Regional Transit Authority, Camden, OH	7 AFCBs	Initiated August 2017
6	Massachusetts Bay Transportation Authority, Boston, MA	1 AFCB with Nuvera PowerTap system fueling infrastructure	Initiated January 2017
7	Southeastern Pennsylvania Transportation Authority, Philadelphia, PA	25 Proterra 40-ft Catalyst E2 BEBs	Planned 2018
8	Duluth Transit, Duluth, MN	6 Proterra 40-ft Catalyst E2 BEBs	Planned 2018

Evaluation Protocol

In 2012, DOE and FTA established performance and cost targets for FCEBs.¹ Interim targets were set for 2016 along with ultimate targets that FCEBs would need to meet to compete with current commercial-technology buses. DOE and FTA have not established performance targets specific to BEBs, but the performance targets established for FCEBs were based on typical conventional buses and the targets could be considered appropriate for any advanced technology. Table 2-2 shows a selection of these technical targets for FCEBs.

Table 2-2 *DOE/FTA Performance, Cost, and Durability Targets for FCEBs^a*

	Units	2016 Target	Ultimate Target
Bus lifetime	years/miles	12/500,000	12/500,000
Power plant lifetime ^b	hours	18,000	25,000
Bus availability	%	85	90
Fuel fills	per day	1 (<10 min)	1 (<10 min)
Bus cost ^c	\$	1,000,000	600,000
Roadcall frequency (bus/fuel cell system)	miles between roadcalls MBRC)	3,500/15,000	4,000/20,000
Operation time	hours per day/		
days per week	20/7	20/7	
Scheduled and unscheduled maintenance cost ^d	\$/mile	0.75	0.40
Range	miles	300	300
Fuel economy	miles per diesel gallon equivalent	8	8

^a Cost targets for subsystems (power plant and hydrogen storage) not included.

^b Power plant defined as fuel cell system and battery system.

^c Cost projected to production volume of 400 systems per year; assumed for analysis purposes only, does not represent anticipated level of sales.

^d Excludes mid-life overhaul of power plant.

¹ Fuel Cell Technologies Program Record #12012, September 12, 2012.

NREL uses a standard evaluation protocol for evaluating the advanced technologies deployed under the FTA programs. Data parameters include the following:

- Bus system descriptions
- Operations duty-cycle description
- Bus use and availability
- Energy/fuel consumption and cost
- Maintenance cost
- Roadcalls
- Infrastructure and facility modification descriptions
- Capital costs
- Implementation experience

For each selected fleet, NREL collects all fueling/charging, cost, and maintenance data for a period of 12 to 18 months to provide a full year of operation data for the analysis. For each site, NREL collects data on conventional technology baseline buses for comparison. For most fleets, the baseline buses are diesel buses. For fleets that do not operate diesel buses, the baseline buses are usually compressed natural gas (CNG) buses. Other technologies, such as diesel hybrid buses, will be included in the evaluation if they are available. The best comparisons are made between buses of the same make, model, production year, size, and route deployment. In that case, the only difference is the propulsion system. This is not always possible. NREL works with the transit agency to determine which vehicles the agency has in operation and selects the best possible baseline match for each evaluation based on what is available. The following sections outline the analysis approach for each parameter.

Bus System Descriptions

This category of data includes general descriptions of the buses and systems. NREL provides a form that the agency fills out for both the ZEBs and baseline vehicles. The form asks for specifications of the vehicle propulsion system and subsystems as well as accessory equipment. This information documents that the baseline vehicles are similar in equipment to the advanced technology buses. NREL collects these data at the beginning of the project; however, changes may be required if major systems are altered.

Operations Duty-Cycle Description

NREL collects duty-cycle descriptions from the transit agency to understand how the ZEBs are used compared to the baseline buses. Data collected include descriptions of the expected routes, operating hours during a typical work day,

number of days per week that the vehicle is operated, the amount of fuel and range (in miles) that are expected during a given work day and between fueling/charging, and other information on how the vehicles are used. Transit agencies typically provide these data in text format. NREL uses the data to determine an average operating speed. Occasionally, bus OEMs provide detailed Global Positioning System (GPS) data from the on-board data collection systems. In those cases, NREL will develop specific route maps showing the planned use of the ZEBs.

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage may indicate downtime for maintenance or purposeful reduction of planned work for the buses. NREL expresses bus use as average miles accumulated per month. NREL uses a general target of 3,000 miles per month for this metric; however, the monthly miles for each agency will vary depending on the planned use of the buses. If a ZEB fleet does not meet this target, it does not indicate a specific limitation for the technology. NREL collects the mileage data for the ZEBs and baseline buses and calculates average monthly miles accumulated per bus.

Availability is the number of days the buses are actually available compared to the days that the buses are planned for operation, expressed as percent availability. The analysis calculates availability for morning pull-out and doesn't necessarily reflect all-day availability. Transit agencies typically have a target of 85% availability for their fleets to allow time to handle scheduled and unscheduled maintenance. The sources for availability data vary from fleet to fleet. NREL works with each agency to determine the best source for the data. In addition to tracking the overall availability, NREL collects the reasons for unavailability. Categories for unavailability include issues related to general bus systems, preventive maintenance, electric drive, battery system, and fuel cell system. These data help indicate whether the issues are due to the advanced technology components or are problems with conventional bus systems.

Energy/Fuel Consumption

Data needed for this category include records of each fueling or charging event. For liquid- and gas-fueled buses, NREL collects individual fueling records (amount of fuel, odometer reading, hour reading, date, and fueling time) and fuel prices (each fuel, each time the fuel price changes—price and date). For the BEBs, NREL collects daily energy use (total kWh, number of charges, miles traveled) and utility bills for each charging location (in-depot or on-route fast charger). NREL analyzes these data to calculate monthly fuel economy and fuel/energy cost per mile. For the BEBs, NREL uses the bus energy use and utility energy data to calculate the charging losses.

To compare the electrical energy used by the BEBs to the diesel fuel energy used by the baseline hybrid and diesel buses, the electrical energy is converted to diesel gallon equivalent (dge). The energy content of each fuel² is used to create the conversion factor shown below:

- Lower heating value for diesel fuel = 128,488 Btu/gal
- U.S. average energy content of electricity = 3,414 Btu/kWh
- Conversion factor = 128,488 Btu/gal / 3,414 Btu/kWh = 37.64 kWh/gal

Maintenance Cost

Maintenance data include each repair action—such as preventive (scheduled) maintenance, unscheduled maintenance, and roadcalls—and date of repair, labor hours, number of days out of service, odometer reading, parts replaced, parts cost, and descriptions of problem reported and actual repair performed. NREL also collects data and cost for any fluid addition (oil, transmission fluid, deionized water). Engine oil changes are included as part of preventive maintenance. The maintenance data are used to estimate operating costs (along with fuel and engine oil consumption costs). Because accident-related repairs are extremely variable from bus to bus, NREL eliminates those costs from the analysis for both ZEB and baseline bus fleets.

NREL also eliminates warranty cost data from the operating cost calculation because those costs are covered in the purchase price of the buses. Labor costs may be included in this analysis depending on the mechanic who performed the work (operator or manufacturer) and whether those hours were reimbursed under the warranty agreement. For consistency, NREL uses a labor cost of \$50/hour. Cost per mile is calculated as follows:

$$\text{Cost per mile} = [(\text{labor hours} * \$50/\text{hr}) + \text{parts cost}] / \text{mileage}$$

NREL calculates total cost per mile as well as scheduled and unscheduled cost per mile. To understand the differences between conventional and ZEB technology, NREL presents the cost per mile by vehicle system. The work orders are coded using vehicle maintenance reporting standards (VMRS) developed by the American Trucking Association to aid the industry in tracking equipment and maintenance using a common standard. The propulsion-related systems were chosen to include only those systems of the vehicles that could be affected directly by the selection of a fuel or advanced technology. NREL bases the VMRS coding on parts that were replaced. If there was no part replaced in a given repair, then NREL selects the code by the system being worked on. System categories include the following:

² Alternative Fuels Data Center, fuel properties database, http://www.afdc.energy.gov/fuels/fuel_properties.php.

- Cab, body, and accessories – includes body, glass, cab and sheet metal, seats and doors, and accessory repairs such as hubodometers and radios
- Propulsion-related systems (subsystems included):
 - Engine/power plant (includes fuel cell for FCEBs)
 - Electric propulsion system
 - Fuel system
 - Exhaust
 - Non-lighting electrical system—general electrical, charging, cranking, ignition
 - Air intake
 - Cooling
 - Transmission
 - Hydraulic
- Preventive maintenance inspection (PMI) – labor for inspections during preventive maintenance
- Brakes – includes brake pads, disks, calipers, anti-lock braking system, and brake chambers
- Frame, steering, and suspension
- HVAC
- Lighting
- Air system (general)
- Axles, wheels, and drive shaft
- Tires

Roadcalls

All roadcalls are marked in the maintenance data collected. A roadcall, or revenue vehicle system failure, is defined as a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a roadcall. The analysis described here includes only roadcalls that were caused by “chargeable” failures. Chargeable roadcalls include systems that can physically disable the bus from operating on route, such as interlocks (doors, air system), engine, or things that are deemed to be safety issues if operation of the bus continues. They do not include roadcalls for issues with components such as radios, fareboxes, or destination signs.

The transit industry measures reliability as mean distance between failures, also documented as miles between roadcalls (MBRC). MBRC is calculated by dividing the number of miles traveled by the number of roadcalls. NREL uses the roadcall

data to calculate cumulative MBRC over time. MBRC results in the report are categorized as follows:

- *Bus MBRC* – includes all chargeable roadcalls. This category includes propulsion-related issues as well as problems with bus-related systems such as brakes, suspension, steering, windows, doors, and tires.
- *Propulsion-related MBRC* – includes roadcalls that are attributed to the propulsion system and is a subset of the bus MBRC. Propulsion-related roadcalls can be caused by issues with the engine, transmission, batteries, fuel cell system, or electric drive.
- *Energy storage system (ESS)-related MBRC* – includes roadcalls attributed to the ESS only (specific to BEBs).
- *Fuel cell system-related MBRC* – includes roadcalls attributed to the fuel cell and balance of plant only (specific to FCEBs).

Transit agencies are required to report costs and specific performance data to FTA through the National Transit Database (NTD). After Congress required data reporting in 1974, FTA developed the NTD as a repository of financial, operating, and asset condition data for American transit agencies. These data are published on the NTD website.³ The vehicle maintenance reliability metrics used by the NTD are as follows:

- *Major mechanical system failure* – a failure of some mechanical element of the revenue vehicle that prevents the vehicle from completing a scheduled revenue trip or from starting the next scheduled revenue trip because actual movement is limited or because of safety concerns.
- *Other mechanical system failure* – a failure of some other mechanical element of the revenue vehicle that, because of local agency policy, prevents the revenue vehicle from completing a scheduled revenue trip or from starting the next scheduled revenue trip even though the vehicle is physically able to continue in revenue service. Examples include a malfunction in the farebox or the air conditioner.

Total revenue system failures would be a sum of the two categories. The NTD categories do not exactly match the roadcall definitions used in the standard NREL protocol. The primary difference is that NTD's other mechanical system failures category includes failures of items such as fareboxes and destination signs. This results in the NTD total failures being higher than that of the NREL analysis. Removing these failures from the NTD data would result in higher overall industry average MBRC. In addition, the NTD major mechanical system failure category includes some roadcalls that are not for the propulsion system. The NTD has no category for power plant failures; therefore, there is no direct comparison for fuel cell system-related or ESS-related MBRC.

³ NTD website, <https://www.transit.dot.gov/ntd>.

Infrastructure and Facility Modification Descriptions

At the beginning of the data collection period, NREL collects details on the fleet's operations including a description of facilities and services, maintenance and fueling practices, and any other information needed to get a complete understanding of the fleet's experience with the ZEBs. Descriptions of facilities include fueling, charging, maintenance, and vehicle storage facilities that may be associated with the ZEBs.

Capital Costs

Data on capital costs include costs for any facility modifications that are required for operation of ZEBs. The vehicle capital costs include the costs for new vehicles and propulsion systems.

Implementation Experience

The experiences of a transit agency in implementing any new technology are an important part of fully understanding the current status of that technology. NREL collects data on the fleet implementation experience to document the background work needed for successful implementation of ZEBs, as well as some of the potential pitfalls and lessons learned. The types of information collected in support of this activity include:

- Documentation of the history that led to the agency's decision to purchase ZEBs, its previous experience with alternative fuels, etc.
- Roles of important supporting organizations such as vehicle manufacturer and supplier, fuel suppliers, and federal, state, or local government agencies.
- Specific incentives for advanced technology vehicles, and regulations or disincentives for the other options that helped form the agency's decision to purchase ZEBs.
- Driver, fleet personnel, and customer perceptions of the new technology vehicles.
- Special fleet needs such as mechanic, driver, or technician training requirements, special equipment, and safety issues.
- Description of the training implementation strategy including employee orientation, operations and maintenance personnel, and the costs of this training.
- What it took to bring these vehicles into revenue service, and what technical/non-technical hurdles were overcome.

SECTION 3

KC Metro BEB Evaluation Results

In February 2016, King County Metro (KC Metro) began operating a fleet of three battery electric buses in its service area. This section summarizes the evaluation results for the battery buses in comparison to a selection of baseline buses. The focus of the analysis is on one year of data from April 2016 through March 2017.

Fleet Profile—KC Metro

KC Metro provides public transit service to King County, Washington. Its service area covers more than 2,000 square miles, including the Seattle metro area, and contains more than 2 million residents. Figure 3-1 is a map showing part of KC Metro's service area (the shaded Bellevue region can be seen in greater detail in Figure 3-7). KC Metro's bus fleet operates on 215 routes and serves

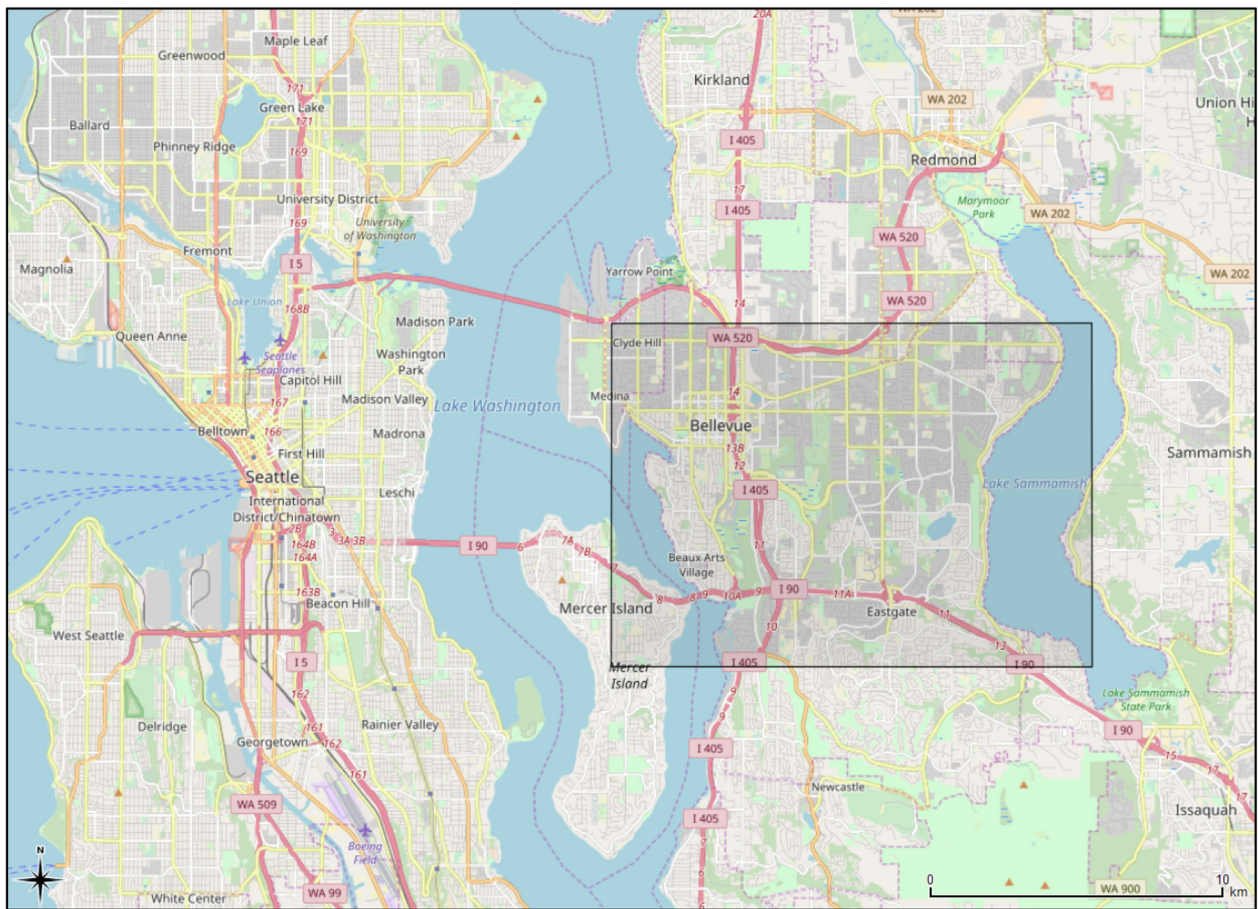


Figure 3-1 KC Metro Service Area Map with Shaded Bellevue Region

approximately 395,000 passengers each weekday, on average. Its fleet of 1,500+ vehicles contains buses of several different propulsion types, including standard and hybrid diesel buses, battery electric buses and electric trolley buses.

In 2010, KC Metro received funding from a TIGGER award to add three zero-emission BEBs to its fleet. The agency selected Proterra's 40-foot Catalyst BEB for the project. Proterra was founded in 2004 with the mission to develop and manufacture advanced technology all-electric heavy-duty vehicles. The Catalyst BEB features a lightweight composite body and is capable of fast charging at stops along its route.

Bus Technology Descriptions

The BEBs in service at KC Metro are fast-charge, composite buses built by Proterra. Based on the in-service buses that KC Metro had available, NREL selected three technologies for comparison to the BEBs including standard diesel buses from Gillig as well as diesel hybrid and electric trolley buses on New Flyer's Xcelsior platform. Buses in all four fleets are 40-foot, model year 2015 buses. The four bus fleets included in the evaluation are referred to in this analysis as the battery fleet, hybrid fleet, diesel fleet and trolley fleet. Table 3-1 provides selected specifications for each bus type. Figure 3-2 is a photo of one of the battery buses. The baseline buses are pictured in Figure 3-3, Figure 3-4, and Figure 3-5.

Table 3-1 *System Descriptions for the Battery Electric, Hybrid, Diesel, and Trolley Buses*

Vehicle System	Battery	Hybrid	Diesel	Trolley
Number of buses in evaluation	3	10	3	10
Bus manufacturer	Proterra	New Flyer	Gillig	New Flyer
Bus year and model	2015 Catalyst	2015 Xcelsior hybrid	2015 G27D102N4	2015 Xcelsior trolley
Length (ft)	42.5	41	40	41
Motor or engine	Permanent magnet, UQM, PP220	Diesel engine, Cummins ISB-280, 6.7L	Diesel engine, Cummins ISL	Traction motor, 3 phase asynchronous AC
Rated power	220 kW peak (295 hp)	280 hp @ 2,700 rpm	280 hp @ 2,200 rpm	240 kW
Energy storage	Lithium-titanate batteries, TerraVolt 331 volts, 105 kWh total energy	Lithium-ion/FePO4 batteries, 630 volts, 11.6 kWh total energy	None	Lithium-ion/FePO4 batteries, 436 volts, 21 kWh total energy
Accessories	Electric	Electric	Mechanical	Electric
Bus purchase cost	\$797,882	\$584,591	\$497,103	\$892,960

Figure 3-2

KC Metro Proterra
Catalyst Battery
Electric Bus



Figure 3-3

KC Metro New Flyer
Diesel Hybrid Bus



Figure 3-4

Gillig Diesel Bus
Operated by KC
Metro for Sound
Transit (photo
courtesy of KC Metro)



Figure 3-5
*KC Metro New Flyer
 Electric Trolley Bus*



Charging and Maintenance Facilities

The battery buses and hybrid buses operate out of KC Metro's Bellevue Base. The diesel buses are part of Sound Transit's fleet but are operated by KC Metro out of the agency's East Base, which is across the street from the Bellevue Base. The trolley buses operate in downtown Seattle and are housed and maintained at KC Metro's Atlantic Base. KC Metro staff maintains all the baseline buses including performing most warranty work. The agency invoices the individual OEMs for reimbursement of any work covered under warranty. Proterra has an on-site technician that handles all warranty work on the battery buses. Operators are expected to charge the buses at the fast-charge station prior to returning to the base at the end of each day. KC Metro uses a slow charger at the base for times when a bus needs additional charging. The installation of this slow charger was the only modification needed to allow maintenance of the battery buses inside the facility. Once KC Metro installs a fast charger at the base, the need to fully charge the BEBs at the end of the day will no longer be necessary.

KC Metro installed a fast charger at its Eastgate Park and Ride to charge the buses. Figure 3-6 shows the fast-charge station.

Figure 3-6
Fast-Charge Station at
KC Metro Park-and-
Ride



In-Service Operations Evaluation Results

This section focuses on the results of a full year of operation from April 2016 through March 2017 (the evaluation period). KC Metro put the battery buses into service in February 2016. The diesel and trolley buses were placed into service at about the same time as the battery buses. The diesel hybrid buses were placed into service in 2015. The average odometer reading for each fleet at the start of the evaluation was 2,274 miles for the battery buses, 25,351 miles for the hybrid buses, 1,046 miles for the diesel buses, and 901 miles for the trolleys.

Route Assignments

KC Metro primarily operates the battery buses on routes 226 and 241, which each connect the Bellevue Transit Center to the Eastgate Park-and-Ride and together form a loop around the Bellevue/East Bellevue area. Figure 3-7 shows the two routes on which the battery buses operate. These routes existed prior to the deployment of the battery buses.

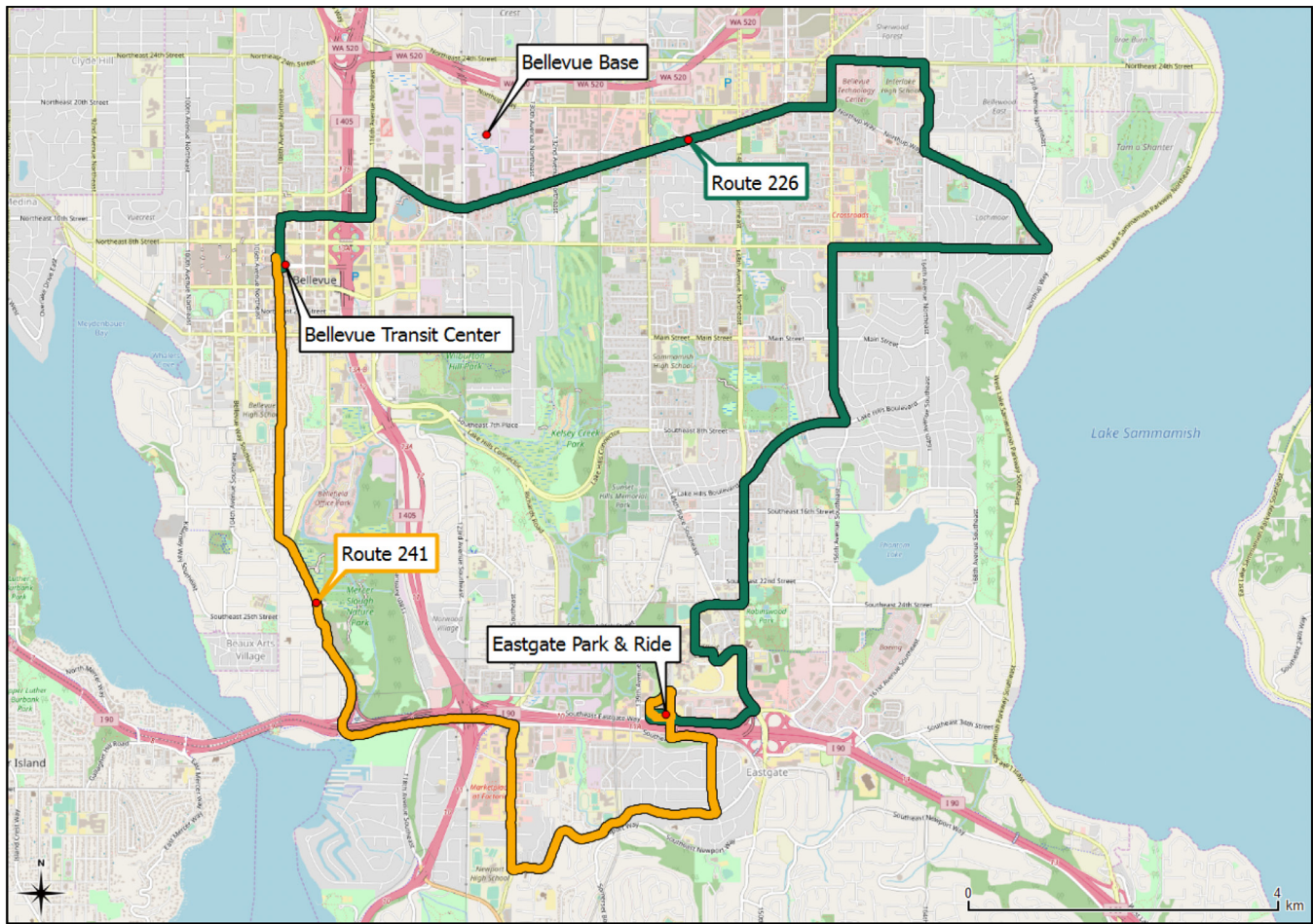


Figure 3-7 Route Map for KC Metro Routes 226 and 241

The battery buses charge at the fast-charge station during every pass through the Eastgate Park and Ride. Figure 3-8 displays the power and state of charge (SOC) of the ESS for one example charge/drive cycle along this route. After a fast charge returns the ESS to a high SOC, the SOC slowly decreases as the bus drives along the route. Some of the discharge power required to accelerate the bus is returned to the ESS through regenerative braking when the bus slows down. The next stop at the Eastgate fast charger boosts the SOC from 25% to nearly 100% in approximately 10 minutes.

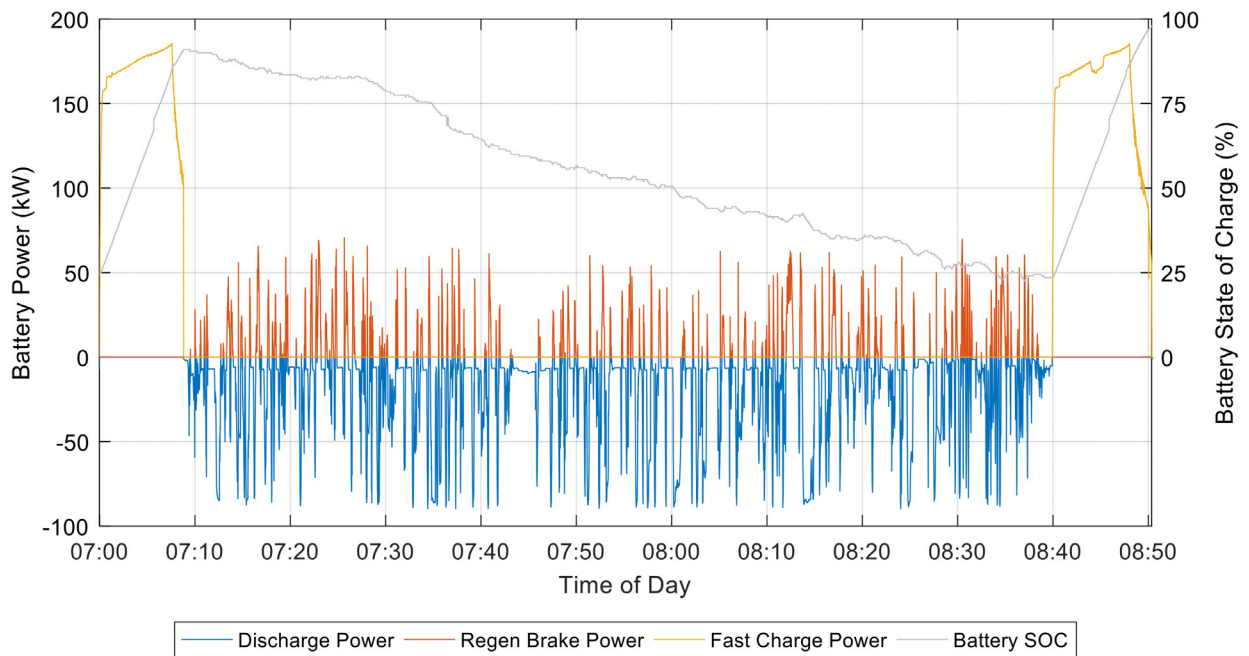


Figure 3-8 Battery Charge and Discharge Power and State of Charge for One Example Charge Cycle

Based on scheduled revenue service, the battery buses have an average speed of 14.8 mph. The hybrid buses are randomly dispatched from the Bellevue base and cover all routes, including some commuter service. This results in a slightly faster average speed, at 15.2 mph. The diesel buses operate on a specific route for Sound Transit with an average speed of 14.6 mph. The trolley buses operate out of the Atlantic base and are limited to the network of catenary lines in and around downtown Seattle. The trolley buses have on-board energy storage that allows off-wire capability for a short range to change from wire to wire or avoid temporary blockage of the street. Because they operate in the heavily congested downtown area, the average speed for the trolley buses is much lower than that of the other fleets, at 9.0 mph. These average speeds are calculated using revenue service schedules and do not include deadhead or out of service miles.

Bus Use

Figure 3-9 tracks the accumulated mileage and operating hours of the battery buses since they were placed into service. KC Metro has been operating the battery buses continuously since February 2016, accumulating almost 100,000 total fleet miles by the end of March 2017.

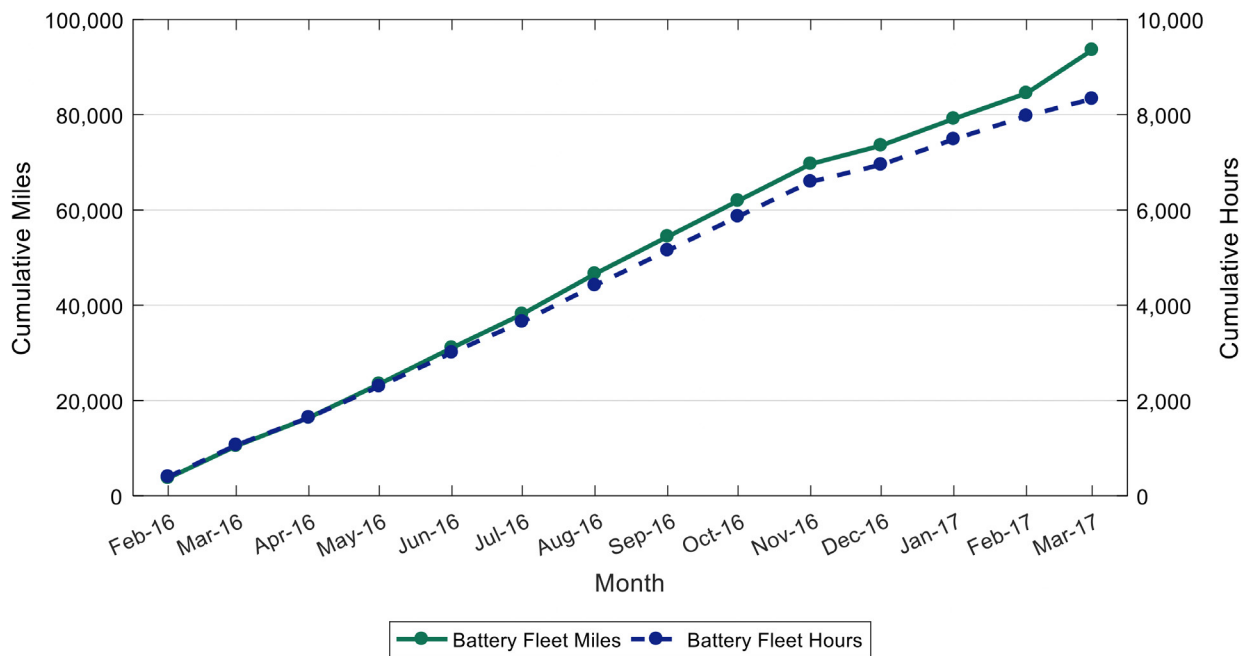


Figure 3-9 Cumulative Miles and Hours for Battery Bus Fleet

Table 3-2 provides the evaluation period mileage for each bus and the average monthly mileage by bus type, which is also displayed in Figure 3-10. The battery buses each averaged between 1,200 and 3,100 miles per month, with an overall fleet average of 2,309 monthly miles per bus. This is lower than the baseline hybrid bus fleet average of 3,659 monthly miles per bus but higher than the diesel and trolley bus fleet averages of 1,952 and 1,486 monthly miles per bus, respectively. These differences are a result of the planned operation of these fleets. The battery fleet is restricted to lines 226 and 241 and the hybrid fleet is randomly dispatched on all routes, including commuter routes with higher speeds which allows faster mileage accumulation.

Proterra was the primary source of data for the battery fleet mileage, charges, and energy use during this evaluation. Proterra's data collection system malfunctioned during March 2017, resulting in a partial loss of data. To fill in the gap in the Proterra data set, NREL obtained daily mileage totals from KC Metro. The information presented in this report is a hybrid of mileage data from Proterra and KC Metro to properly capture all the fleet mileage. Prior to creating the hybrid data set, NREL verified that the records matched closely by comparing the Proterra and KC Metro data sets during months for which there were no data losses.

Table 3-2
Average Monthly
Mileage (Evaluation
Period)

Bus #	Total Mileage	Months	Average Monthly Mileage	Bus #	Total Mileage	Months	Average Monthly Mileage
4601	27,769	12	2,314	9124	22,231	12	1,853
4602	29,875	12	2,490	9125	24,091	12	2,008
4603	25,484	12	2,124	9126	23,007	12	1,917
Battery fleet	83,128	36	2,309	Diesel fleet	69,329	36	1,926
7239	50,912	12	4,243	4364	17,969	12	1,497
7241	46,888	12	3,907	4371	19,195	12	1,600
7245	49,780	12	4,148	4373	16,941	12	1,412
7246	45,338	12	3,778	4374	18,276	12	1,523
7247	46,376	12	3,865	4375	17,837	12	1,486
7249	47,034	12	3,920	4376	17,139	12	1,428
7250	40,185	12	3,349	4377	16,781	12	1,398
7252	36,305	12	3,025	4380	19,289	12	1,607
7253	34,532	12	2,878	4383	18,989	12	1,582
7254	38,202	12	3,184	4384	18,138	12	1,512
Hybrid fleet	435,552	120	3,630	Trolley fleet	180,554	120	1,505

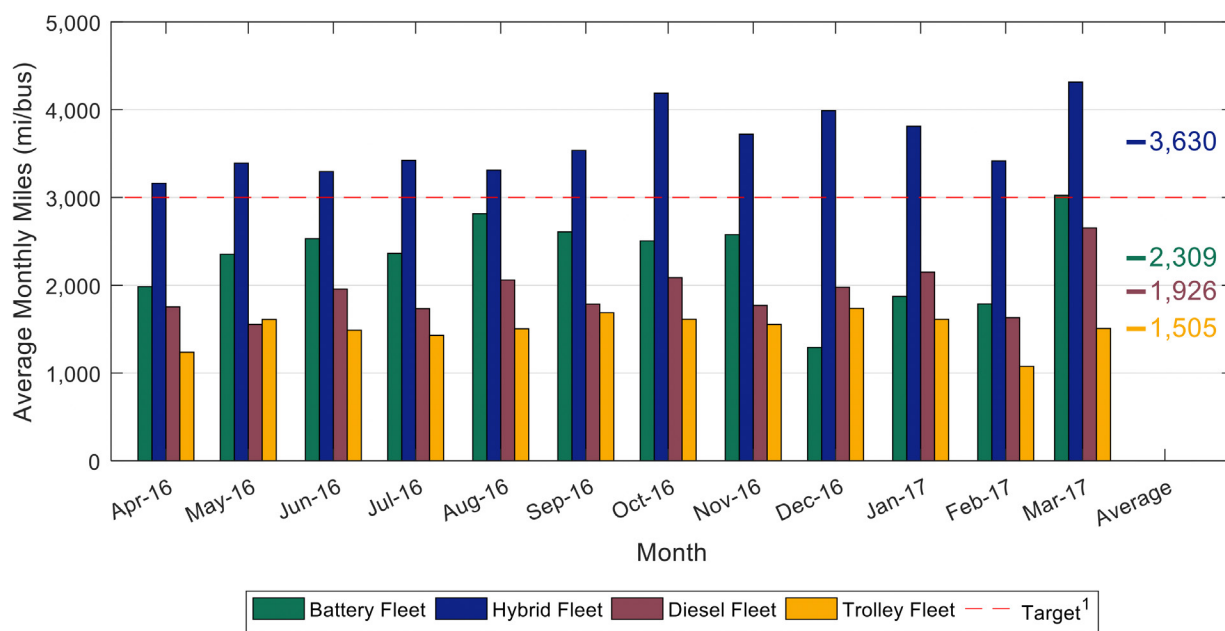


Figure 3-10 Average Monthly Miles for All Four Bus Fleets

Availability

The availability analysis covers 12 months of data collection and evaluation, August 2016 through July 2017. The date range for the availability analysis does not exactly match the evaluation period date range discussed in other sections of this report—April 2016 through March 2017—due to a delay in the collection of availability data at the beginning of the evaluation. KC Metro provided daily status reports to determine bus availability. The reports summarized open work orders at 8:00AM every morning. If one of the evaluation buses was included in the list, it was deemed unavailable for service at morning pull-out (8:00AM for this analysis). NREL further analyzed the open work order reports to determine the primary reason each bus was held out of service. These maintenance reasons were grouped into the unavailability categories shown in the availability charts. The bus maintenance category applies to all general maintenance issues not specific to a powertrain. Other categories include preventive maintenance (PM), electric drive system, ESS, charging issues, current collection, hybrid system, transmission, and engine. Some of the categories are not applicable to all of the bus fleets.

KC Metro's planned operation varies by bus fleet. The baseline hybrid and trolley bus fleets are in service every day, including weekends. The standard diesel buses in the evaluation operate on weekdays only. The battery fleet operates on weekdays, with one battery bus also operating on Saturdays. During the evaluation period, KC Metro did not plan to operate the battery buses on Sundays. Thus, NREL based the availability analysis on a seven-day week for the hybrid and trolley fleets and a five-day week (weekdays only) for the battery and diesel fleets. The data presented are based on availability at morning pull-out, as described above, and do not necessarily reflect all-day operation. There are some instances when a bus was removed from service after being available at morning pull-out, as well as instances when a bus that was unavailable at 8:00 AM became available for service later the same day. The frequency of these two scenarios was not tracked or included in the analysis. Their impacts on the fleet availability are largely expected to offset each other.

One of the battery buses was out of service for much of December and January after being damaged by improper towing. NREL regards the matter as an accident and not relevant to measuring bus technology performance. Therefore, the downtime was removed from the analysis. The damage is considered to have resulted from a lapse in training rather than a problem with the technology. While other buses were involved in minor accidents during the data period, none of the incidents resulted in significant downtime.

Table 3-3 summarizes the availability for the four fleets during the data period. The overall average availability for the battery fleet was 80.6%. For the baseline buses, the overall average availability was 90.5% for the hybrid fleet, 86.2% for the diesel fleet, and 84.9% for the trolley fleet.

Table 3-3 Summary of Availability by Bus for All Four Fleets

Bus #	Planned Days	Available Days	Percent Availability	Bus #	Planned Days	Available Days	Percent Availability
4601	235	193	82.1%	9124	259	223	86.1%
4602	259	202	78.0%	9125	259	222	85.7%
4603	259	212	81.9%	9126	259	226	87.3%
Battery fleet	753	607	80.6%	Diesel fleet	777	671	86.4%
7239	363	331	91.2%	4364	363	324	89.3%
7241	363	293	80.7%	4371	363	338	93.1%
7245	363	329	90.6%	4373	363	326	89.8%
7246	363	335	92.3%	4374	363	284	78.2%
7247	363	325	89.5%	4375	363	324	89.3%
7249	363	326	89.8%	4376	363	290	79.9%
7250	363	347	95.6%	4377	363	311	85.7%
7252	363	341	93.9%	4380	363	333	91.7%
7253	363	324	89.3%	4383	363	326	89.8%
7254	363	335	92.3%	4384	363	225	62.0%
Hybrid fleet	3630	3286	90.5%	Trolley fleet	3630	3081	84.9%

Figure 3-II tracks the monthly average availability for the battery bus fleet and the baseline bus fleets as line series along the top of the chart. The three baseline fleets generally maintained availability above 80% during the data period. After a few months of initially high availability, the battery bus fleet experienced a significant drop in availability in December 2016. Much of this unavailability was downtime from only one of the battery buses, which developed problems with the HVAC system and roof of the bus body.

The stacked columns in Figure 3-II show the number of days that the battery buses were unavailable, organized into five categories. For most months, the primary reason for battery bus downtime was general bus maintenance issues that are not related to the energy storage or electric drive systems. A chart showing the monthly availability trends for the individual battery buses is included in the Appendix.

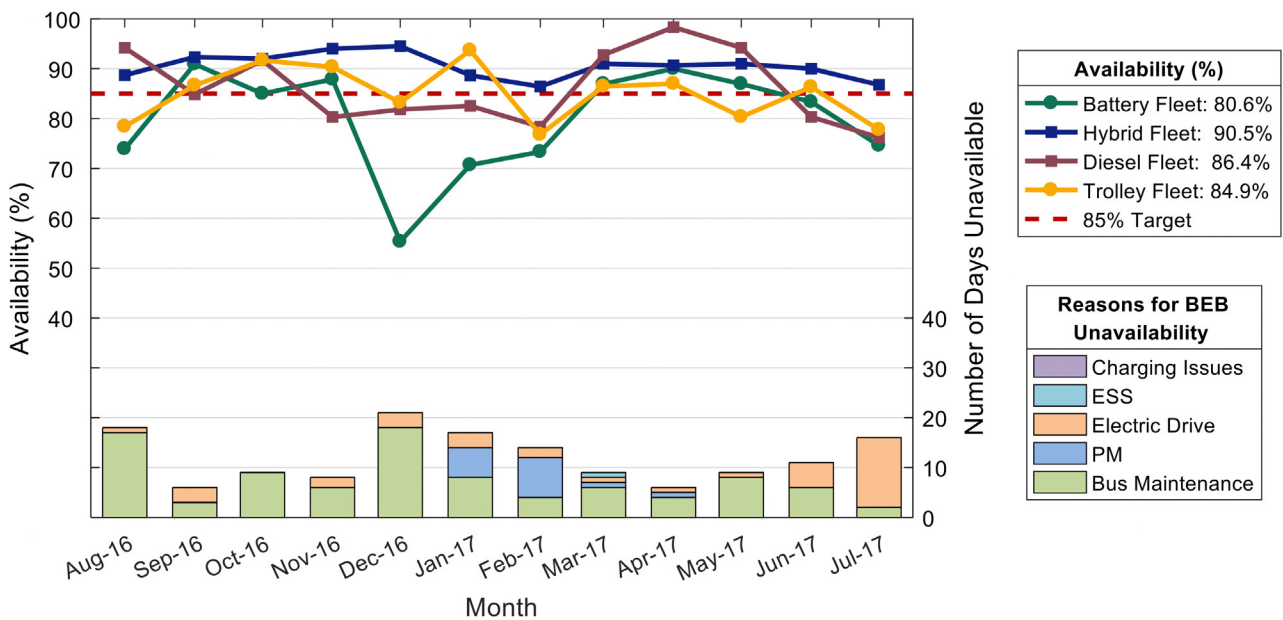


Figure 3-11 Monthly Availability for All Four Bus Fleets and Reasons for Unavailability for Battery Fleet

Figure 3-12 shows the percentage of days that each bus fleet was available for service and the reasons for unavailability for the percentage of days the buses were out of service. This chart represents the availability data period of August 2016 through July 2017. Issues relating to general bus maintenance accounted for most of the downtime for all four fleets, ranging from 6.2% to 12.1% of the total planned service time for each fleet. Electric drive system issues accounted for 4.8% of the total battery fleet time. Some of these issues are discussed in more detail in the Summary of Achievements and Challenges section. The trolley bus fleet experienced several issues with the current collection system (including the shoes, poles, etc.) that connects to the catenary wire system to transfer electric power to the bus. This downtime accounted for 3.7% of the trolley fleet's planned service time. The hybrid and diesel buses in this evaluation experienced few problems that caused downtime other than general bus maintenance. Table 3-4 corresponds to Figure 3-12 and provides a fleet-level breakdown of the availability percentages for each category.

Figure 3-12
Overall Availability
for All Four Bus Fleets
during Evaluation
Period

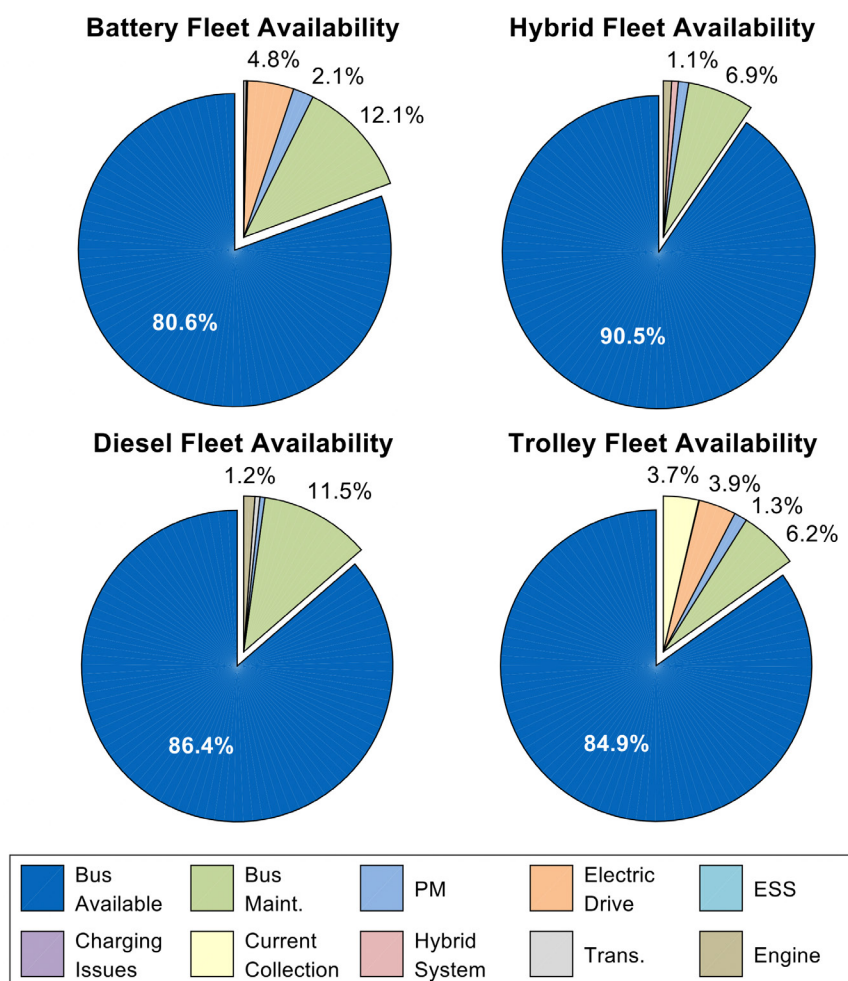


Table 3-4 Summary of Availability and Unavailability by Category for All Four Fleets

Category	Battery # Days	Battery %	Hybrid # Days	Hybrid %	Diesel # Days	Diesel %	Trolley # Days	Trolley %
Planned days	753	-	3,630	-	777	-	3,630	-
Days available	607	80.6%	3,286	90.5%	671	86.4%	3,081	84.9%
Unavailable	146	19.4%	344	9.5%	106	13.6%	549	15.1%
Bus	83	11.0%	249	6.9%	89	11.5%	224	6.2%
PM	15	2.0%	39	1.1%	4	0.5%	49	1.3%
Electric drive	45	6.0%	-	-	-	-	141	3.9%
ESS	1	0.1%	-	-	-	-	2	0.1%
Charging issues	0	0.0%	-	-	-	-	-	-
Current collection	-	-	-	-	-	-	133	3.7%
Hybrid system	-	-	25	0.7%	-	-	-	-
Transmission	2	0.3%	0	0.0%	4	0.5%	-	-
Engine	-	-	31	0.9%	9	1.2%	-	-

Energy Use, Fuel Economy, and Cost

Operating primarily on routes 226 and 241, the battery buses stop to charge at each pass through the Eastgate Park and Ride. Because the battery buses are on a fixed route and consistent schedule, the number of battery fleet charges per month is largely dictated by the availability of the battery buses—that is, how often all three battery buses operated each month—and thus, the number of charges corresponds directly to the miles traveled by the battery fleet each month. The monthly energy consumption of the battery fleet generally corresponds to the number of monthly charges but it also varies from month to month based on factors that affect bus fuel efficiency, such as ridership, operator driving habits, traffic, and weather conditions. This monthly energy consumption (bus-side) is measured from the ESS of the battery buses; the total energy purchased from the utility (grid-side) is discussed below.

Figure 3-13 shows the monthly total energy consumption and number of charges for the battery buses. Throughout most of the evaluation period, the battery fleet charged between 400 and 500 times per month. The number of charges dropped in December, January, and February; this is consistent with the lower accumulated mileage due to the reduced service of the battery buses in these months. The battery fleet averaged 16.3 miles per charge during the data period. The monthly energy consumption for the battery fleet varied between 10,000 kWh and 19,000 kWh, with most months exceeding 15,000 kWh. The battery buses received 38.5 kWh per charge, on average. The monthly average energy per charge varied throughout the year as the fuel economy/efficiency changes, from a low of 34.3 kWh/charge to a high of 45.9 kWh/charge.

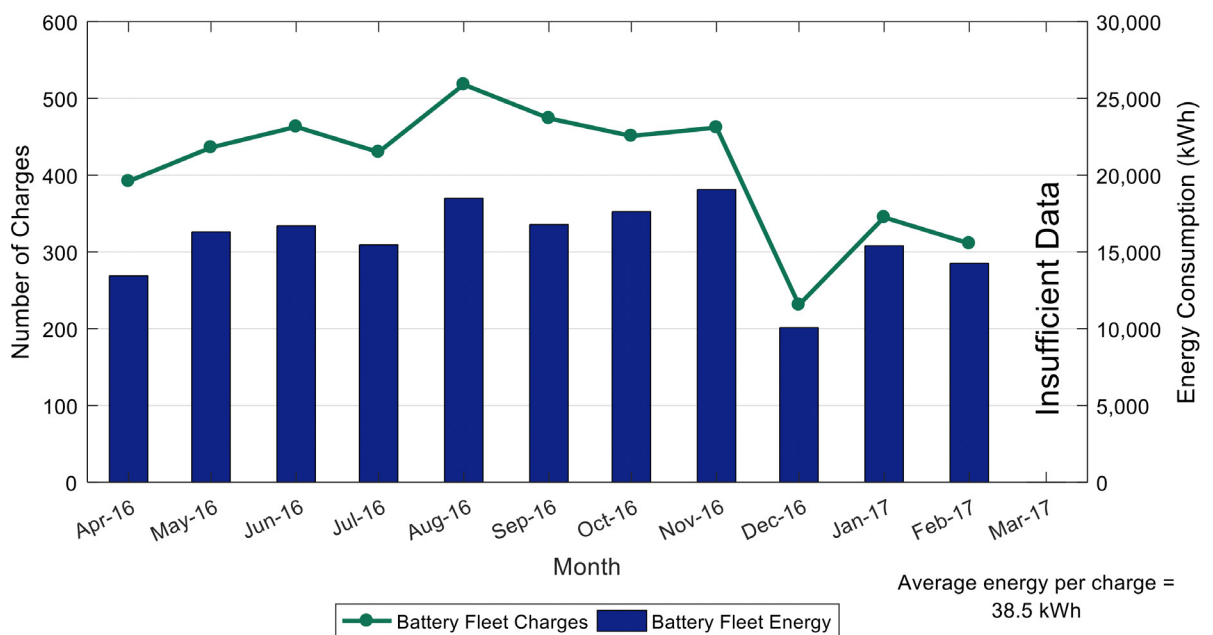


Figure 3-13 Monthly Charges and Monthly Energy Consumption for Battery Fleet

Figure 3-14 shows the monthly average fuel economy in miles per diesel gallon equivalent (mpdge) for the battery, hybrid, and diesel bus fleets. Monthly energy consumption data were not available for all the trolley buses during the evaluation period so the fleet average fuel economy trend could not be included. However, a sample of total mileage and energy consumption for two of the trolley buses representing approximately 13 months of operation (October 2016 through November 2017) was used to calculate an estimated average fuel economy for comparison. This data sample was provided by KC Metro. It should be noted that regenerative braking on the trolley buses was disabled for a portion of this data period, which reduces the calculated fuel economy. The electrical energy used by the battery buses and the trolley buses was converted to dge using a conversion factor of 37.64 kWh/dge. This energy conversion is detailed in Section 2. Also plotted in Figure 3-14 is the average daily high temperature recorded at Renton Municipal Airport in King County. The average fuel economy of the battery buses corresponds well to the seasonal variation in ambient air temperature. Battery fleet fuel economy varied from a high of 17.6 mpdge in September 2016 to a low of 13.3 mpdge in December 2016. The overall average fuel economy for the data period was 15.9 mpdge. The estimated average fuel economy for the trolley buses was slightly lower at 14.7 mpdge. The fuel economy for the hybrid and diesel bus fleets did not vary much throughout the year; their overall averages were 6.3 mpdge and 5.3 mpdge, respectively. Table 3-5 lists the per-bus mileage, fuel use, and fuel economy along with the fleet averages.

The bus fuel economy is sensitive to the average speed (and stops per mile) of the bus, which is determined by the routes on which it is scheduled to run.

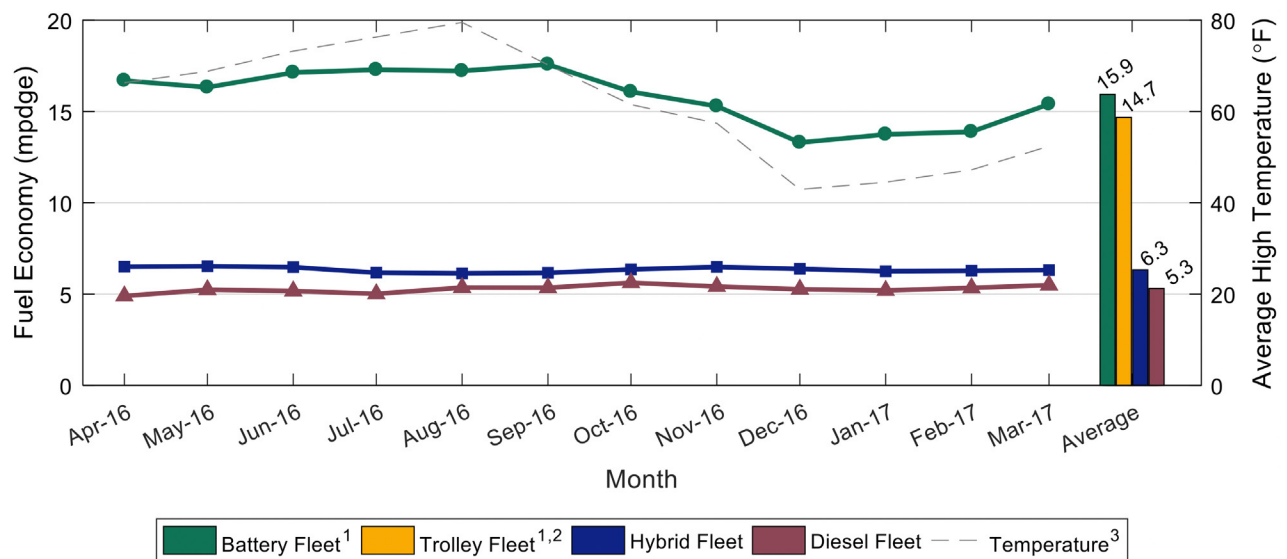


Figure 3-14 Monthly Fuel Economy for Battery, Hybrid, and Diesel Bus Fleets

Table 3-5
Mileage, Fuel Use,
and Fuel Economy

Bus	Mileage (fuel base)	Fuel Consumption (kWh)	Fuel Consumption (dge)	Fuel Economy (kWh/mi)	Fuel Economy (mpdge)
4601	25,163	58,851	1,564	2.34	16.09
4602	28,542	67,545	1,795	2.37	15.91
4603	23,858	56,859	1,511	2.38	15.79
Battery fleet	77,563	183,255	4,869	2.36	15.93
7239	49,768	-	7,853	-	6.34
7241	45,544	-	7,236	-	6.29
7245	49,226	-	7,649	-	6.44
7246	44,684	-	7,153	-	6.25
7247	45,742	-	7,462	-	6.13
7249	46,515	-	7,580	-	6.14
7250	39,799	-	6,335	-	6.28
7252	36,563	-	5,563	-	6.57
7253	33,958	-	5,348	-	6.35
7254	38,037	-	5,697	-	6.68
Hybrid fleet	429,836	-	67,874	-	6.33
9124	22,231	-	4,238	-	5.25
9125	23,662	-	4,463	-	5.30
9126	22,319	-	4,207	-	5.31
Diesel fleet	68,212	-	12,909	-	5.28
4371	29,253	73,951	1,965	2.53	14.89
4375	32,527	84,533	2,246	2.60	14.48
Trolley fleet ^a	61,780	158,484	4,211	2.57	14.67

^a Trolley fleet fuel economy estimated based on data from two trolley buses during 13 months of operation.

Figure 3-15 compares the average cost per mile for each fleet's transportation fuel—electricity for the battery fleet and diesel fuel for the baseline hybrid and diesel fleets. The per-mile fuel cost is a function of the unit price of the fuel and the fuel efficiency of the buses. The per-mile fuel costs for the diesel and hybrid buses varied only slightly throughout the evaluation period because these two factors (diesel price and bus fuel economy) both remained relatively constant. The fuel economy advantage of the hybrid fleet over the diesel fleet results in a slightly lower per-mile fuel cost for the hybrid fleet (\$0.25/mi) compared to the diesel fleet (\$0.30/mi). The battery fleet experienced higher per-mile fuel costs (\$0.57/mi) than the baseline fleets, especially during the winter months. This trend is a result of the battery fleet's lower fuel economy during the winter and higher electricity rates during the winter. The higher electricity rates were compounded by the fact that the battery fleet traveled fewer miles in December, January, and February, which resulted in higher costs from demand charges on a per-mile basis. The electricity cost per mile calculation includes all electricity that KC Metro purchased from the utility. It does not exclude any charging

losses from transferring the electricity to the battery buses. In other words, this represents the “grid-side” cost per mile, not the “bus-side” cost per mile that would be calculated from the average bus fuel economy and the unit price of fuel.

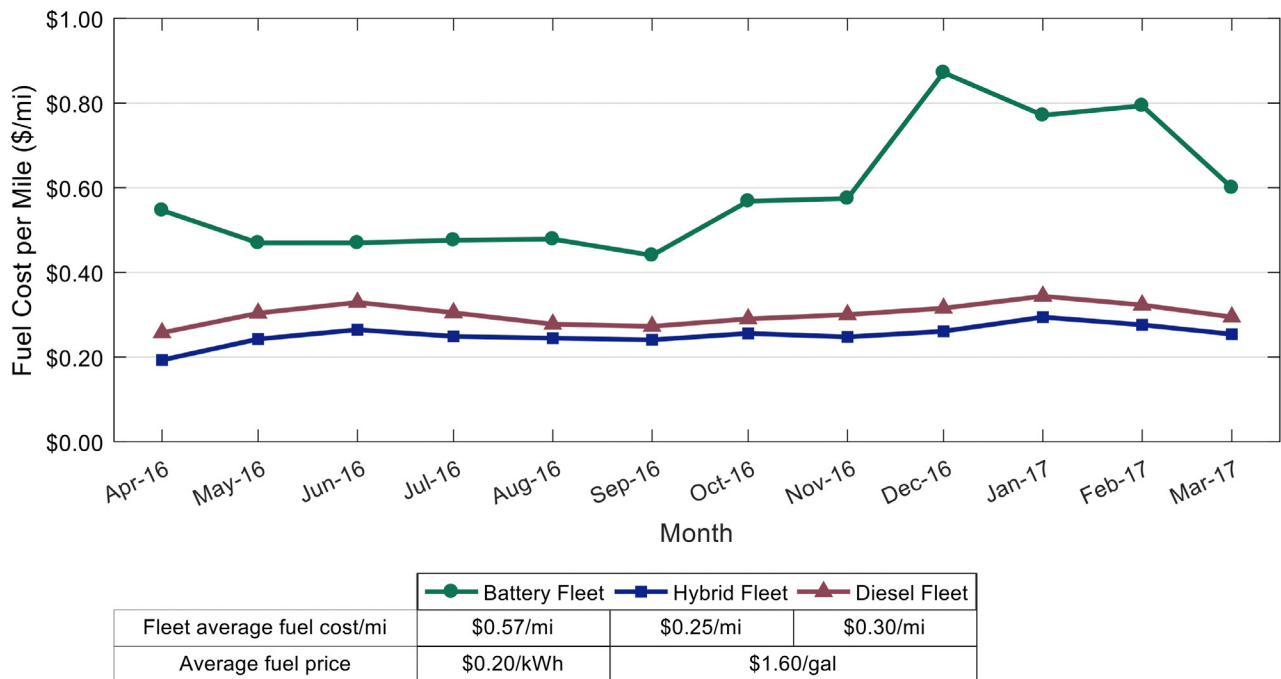


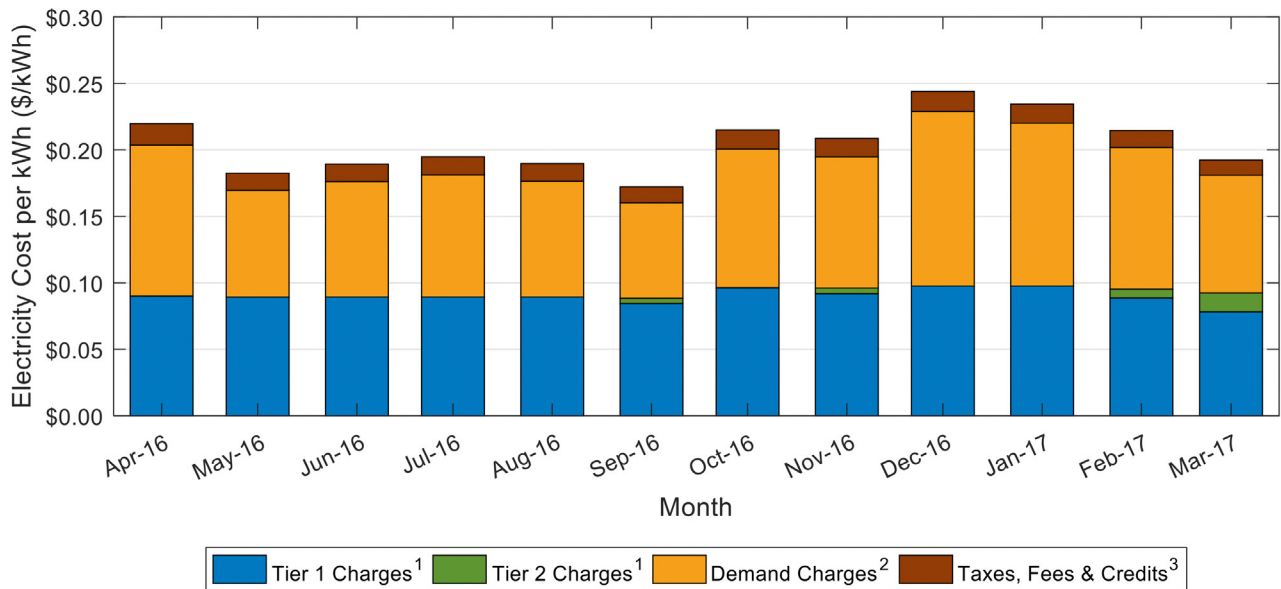
Figure 3-15 Monthly Fuel Cost per Mile for Battery, Hybrid, and Diesel Bus Fleets

Despite having an average fuel economy that is 2.5 to 3 times higher than that of the baseline bus fleets in the evaluation, the battery fleet had higher per-mile fuel costs due to the large difference between diesel fuel prices and electricity prices. The average price that KC Metro paid for diesel fuel was \$1.60/dge and the average price paid for electricity was \$0.20/kWh, or \$7.66/dge. The equivalent electricity price is 4.8 times higher than the diesel price. A comparison of the monthly average fuel prices is provided in the Appendix.

KC Metro provided the diesel fuel prices used in this evaluation in the monthly fueling records. The electricity rates were derived from the monthly bills from KC Metro’s electric utility provider, Puget Sound Energy, which were also provided by KC Metro. The utility bills are specifically for the Proterra fast charger installed at the Eastgate Park and Ride. This analysis of electricity costs does not include electricity from slow charges at the Bellevue base; these charges were infrequent and would account for a very small fraction of the total energy consumption of the battery fleet.

A breakdown of the component costs that make up each month’s electricity bill is shown in Figure 3-16, in units of \$/kWh. Under Puget Sound Energy’s

Commercial 25 rate structure, Tier 1 electricity rates are charged for the first 20,000 kWh consumed each monthly billing period. All additional energy consumed in a billing period is charged at the Tier 2 rate, which is lower than the Tier 1 rate. Demand charges are incurred when charging rates exceed 50 kW during the billing period. All remaining utility bill charges—including infrastructure cost recovery, administrative fees, city and state utility taxes, and renewable energy credits (deductions)—are combined to form the Taxes, Fees & Credits category.



1. Tier 1 electric rate is applied to the first 20,000kWh used per month; Tier 2 rate is applied to all additional energy

2. Demand Charges are incurred for charging rates > 50kW

3. "Taxes, Fees & Credits" includes all remaining utility bill items (positive & negative charges)

Figure 3-16 Breakdown of Monthly Electric Utility Costs

The Tier 1 base rate for electricity changes between the summer and winter seasons. The Tier 1 winter base rate was \$0.0976/kWh and the Tier 1 summer base rate was 8.4% lower at \$0.0893/kWh during the evaluation period. KC Metro was only charged the Tier 2 rate in four months of the evaluation period, when the monthly energy consumption exceeded 20,000 kWh. Combined charges for Taxes, Fees & Credits cost between \$0.008/kWh and \$0.016/kWh, which was consistently 6%–7% of the utility bills. Demand charges were incurred every month and made up a significant portion of the utility bills—between 34% and 54%. Demand charges were higher than the combined Tier 1 and Tier 2 energy consumption charges in 6 of the 12 months. Because the Tier 1 charges and the Taxes, Fees & Credits are relatively consistent throughout the year, the effective monthly utility rate (\$/kWh) is driven by the monthly demand charges.

The monthly demand charges (\$/kWh) are inversely proportional to the monthly mileage of the battery fleet. Thus, the relative cost of demand charges decreases as the battery fleet mileage increases and the fast charger is more fully utilized. The charger utilization will increase as more battery buses are added to the route, or as the existing battery buses operate more frequently, or both. As a hypothetical example to illustrate this point, if the annual mileage and energy consumption of the battery fleet doubled, the utility bills would increase by 40%–50% due to the increased energy consumption (Tier 1 charges, Tier 2 charges, and Taxes, Fees and Credits are based on energy consumption). The combined costs for Tier 1 charges, Tier 2 charges, and Taxes, Fees and Credits would account for 65%–70% of the total utility bill (up from approximately 50%), and the demand charges would account for the remaining 30%–35% of the total (down from approximately 50%). While the total utility bill would increase by 40%–50%, the overall cost per mile for electricity would decrease because the mileage increased by 100%.

Table 3-6 shows the average electric utility rates (\$/kWh) during the evaluation period. The overall effective rate is the total cost of the utility bills divided by the total energy consumption. The first four rows of the table show the effective rates of the four major categories that constitute the total utility bill. Demand charges were the largest, accounting for 47.9% of the utility costs. Tier 1 charges were close to demand charges, at 44.1% of the total. Taxes, Fees & Credits and Tier 2 categories only accounted for 6.6% and 1.4%, respectively. The last four rows of the table show the average effective rates that KC Metro paid during the summer and winter months, and it provides the base rates for Tier 1 charges in summer and winter for comparison.

Table 3-6
Utility Electricity Rates

	Electric Rate (\$/kWh)	Percent of Total
Overall effective rate for Tier 1 charges	0.0897	44.1
Overall effective rate for Tier 2 charges	0.0029	1.4
Overall effective rate for Demand charges	0.0975	47.9
Overall effective rate for Taxes, Fees, & Credits	0.0134	6.6
Overall effective rate	0.2035	100.0
Average effective rate for summer months (Apr–Sep)	0.1898	—
Average effective rate for winter months (Oct–Mar)	0.2158	—
Tier 1 base rate for summer months (Apr–Sep)	0.0893	—
Tier 1 base rate for winter months (Oct–Mar)	0.0976	—

Roadcall Analysis

Figure 3-17 provides a summary of propulsion-related roadcalls for the four bus fleets in the evaluation, separated by propulsion subsystem and normalized by the number of buses in each fleet for comparison. The battery fleet experienced 4.0 propulsion-related roadcalls per bus, primarily due to the electric drive system. The hybrid and diesel bus fleets experienced some issues with the cooling system and electrical system, resulting in only 1.5 and 0.7 roadcalls per bus, respectively. The trolley fleet had an average of 6.1 propulsion system roadcalls per bus, dominated by problems with the current collection system.

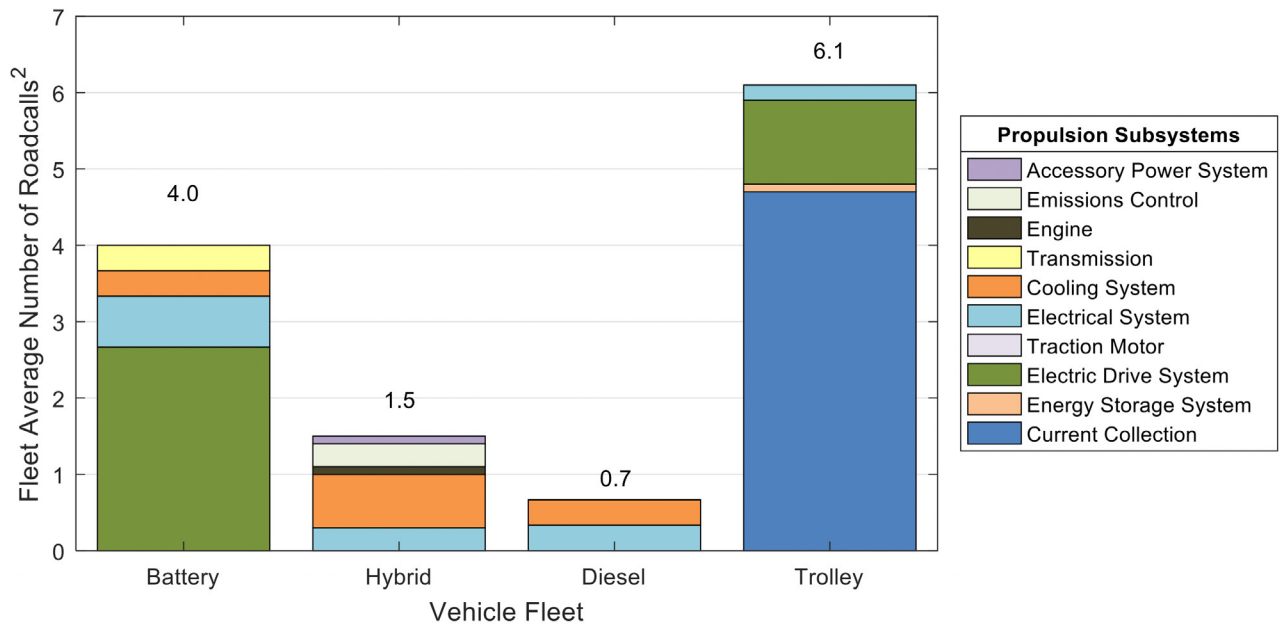


Figure 3-17 Summary of Propulsion-Related Roadcalls for All Four Bus Fleets, Organized by Subsystem

Figure 3-18 provides the cumulative MBRC for the battery buses and baseline buses categorized by total bus roadcalls, propulsion-related roadcalls, and ESS-related roadcalls. Propulsion-related roadcalls are a subset of bus roadcalls for all bus fleets. ESS-related roadcalls are a subset of the propulsion-related roadcalls, specific to the ESS of the battery buses. The DOE/FTA target of 4,000 MBRC is included in the graph as a red dashed line. The ESS-related MBRC is not included in the chart because there were zero ESS-related roadcalls during the evaluation period. The diesel fleet had the highest bus MBRC at 17,332. The hybrid bus fleet achieved 7,641 MBRC. The battery fleet MBRC and trolley fleet MBRC are currently below the ultimate target.

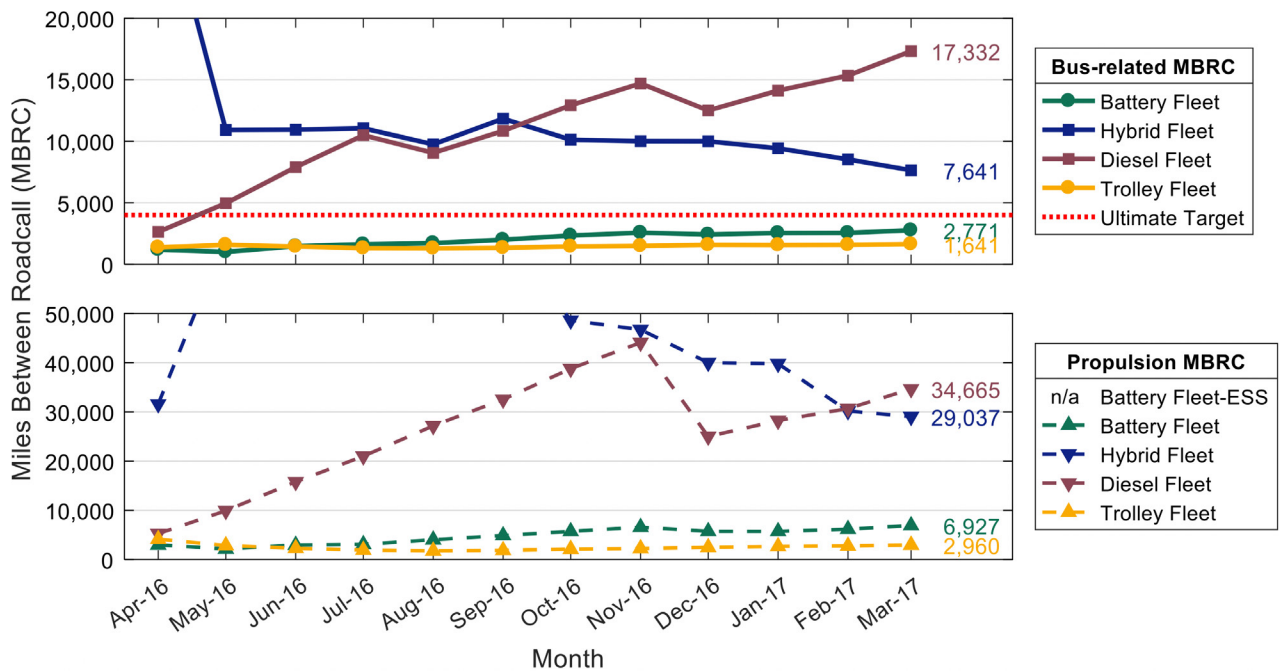


Figure 3-18 Cumulative Bus MBRC and Propulsion-Related MBRC for All Four Bus Fleets

The battery fleet propulsion-related MBRC was 6,927. Propulsion-related MBRC for the diesel and hybrid baseline fleets were similar to each other—34,665 and 29,037, respectively. The propulsion-related MBRC for the trolley buses was 2,960, which reflects the low average mileage and early issues with the current collection system. The new trolleys have shorter poles that are mounted closer to the front of the bus than they were on KC Metro’s earlier-design trolleys. KC Metro has experienced several issues with the system including wearing of the wires and the poles coming off the wires unexpectedly. Downtown road conditions in the city compound the situation. There are many areas where the road surface crowns and causes the system to flex with the bus movement, resulting in the poles coming off the wires. In addition, the wire tends to sag in the summer during hot days creating a worst-case scenario. KC Metro is working closely with the manufacturer to find a solution to the problem and expects the incidents to decrease.

Maintenance Analysis

This section first covers total maintenance costs and then maintenance costs by bus system. As mentioned in Section 2, NREL excludes warranty repairs from the calculations. The battery buses were under warranty for the entire data period. A Proterra technician stationed at the base handles most of the repair work on the advanced technology components. KC Metro mechanics handle much of the general bus repair and assist the Proterra technician as needed. The

warranty for the hybrid and diesel buses ended early in the data period. The trolley buses were under warranty for the majority of the data period. KC Metro typically handles all warranty work for its buses and submits claims to the OEM for reimbursement. As a result, the work orders submitted for analysis include costs that should be covered under warranty. NREL worked with the agency to collect the warranty claims and remove those costs from the data set.

Total Work Order Maintenance Costs

Table 3-7 shows maintenance costs per mile for the four bus fleets and includes total cost, scheduled cost, and unscheduled cost. Scheduled costs include PM based on the OEMs' recommendations. All other maintenance is included in unscheduled costs. During the data period, the maintenance cost for the battery buses was 17.8% less than that of the hybrid buses; 44.1% less than that of the diesel buses; and 43.2% less than that of the trolley buses.

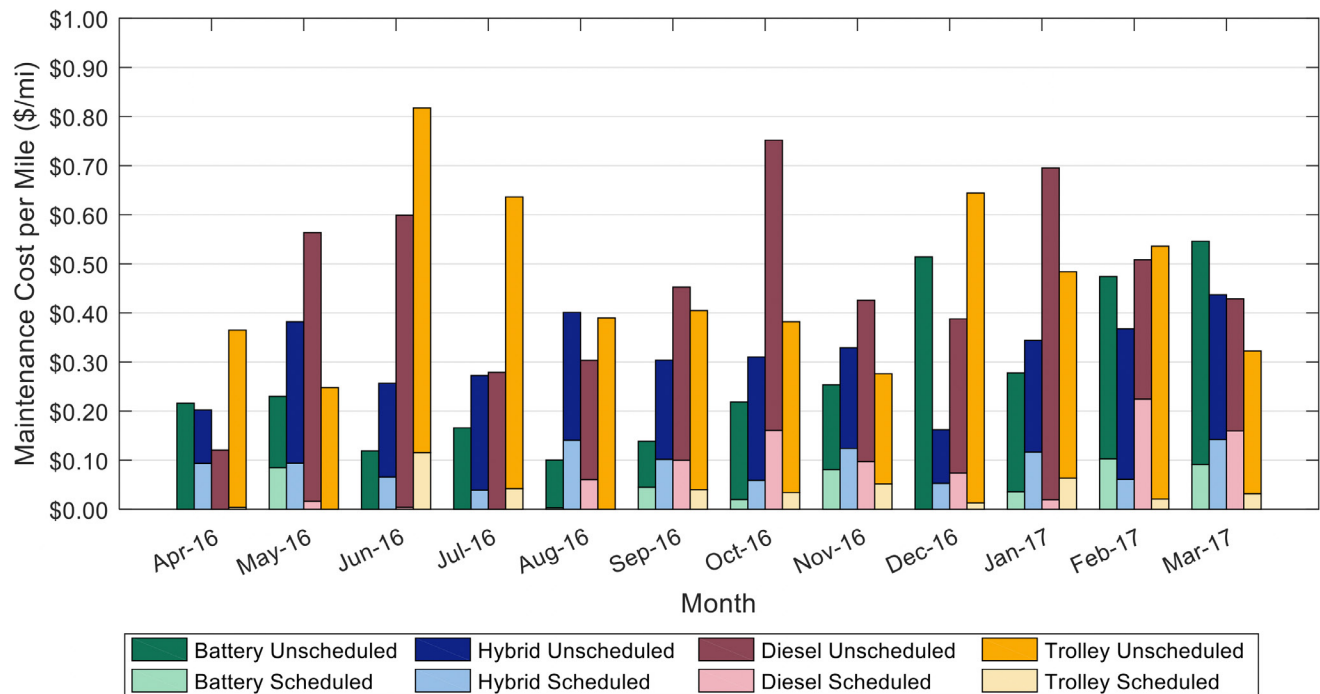
Table 3-7
Total Work Order
Maintenance Costs

Bus Fleet	Mileage	Parts (\$)	Labor Hours	Scheduled Cost per Mile (\$)	Unscheduled Cost per Mile (\$)	Total Cost per Mile (\$)
4601	27,769	693.79	108.5	0.04	0.18	0.22
4602	29,875	962.95	120.5	0.02	0.21	0.23
4603	25,484	317.94	162.8	0.06	0.27	0.33
Total Battery	83,127	1,974.69	391.8	0.04	0.22	0.26
7239	47,898	4,183.35	190.7	0.12	0.17	0.29
7241	46,888	4,404.99	225.1	0.08	0.25	0.33
7245	49,780	1,565.69	206.8	0.09	0.15	0.24
7246	45,338	3,669.04	291.1	0.09	0.31	0.40
7247	46,376	2,604.87	224.1	0.09	0.21	0.30
7249	47,034	4,117.16	253.4	0.09	0.27	0.36
7250	40,185	1,755.08	197.1	0.10	0.19	0.29
7252	36,305	1,835.44	161.1	0.08	0.19	0.27
7253	34,532	2,432.33	227.2	0.07	0.33	0.40
7254	38,202	2,943.51	180.8	0.10	0.22	0.31
Total Hybrid	432,538	29,511.45	2,157.1	0.09	0.23	0.32
9124	22,231	1,705.01	190.3	0.08	0.43	0.50
9125	24,091	3,207.66	180.6	0.08	0.43	0.51
9126	23,007	1,024.52	153.5	0.08	0.30	0.38
Total Diesel	69,329	5,937.19	524.3	0.08	0.39	0.46
4364	17,969	964.54	163.3	0.03	0.48	0.51
4371	19,195	587.38	138.0	0.02	0.37	0.39
4373	16,941	884.20	168.5	0.03	0.52	0.55
4374	18,276	785.54	128.9	0.02	0.38	0.40
4375	17,837	750.56	147.4	0.03	0.42	0.46

**Table 3-7
cont'd***Total Work Order
Maintenance Costs*

Bus Fleet	Mileage	Parts (\$)	Labor Hours	Scheduled Cost per Mile (\$)	Unscheduled Cost per Mile (\$)	Total Cost per Mile (\$)
4376	17,139	4,021.67	143.2	0.05	0.60	0.65
4377	16,781	847.99	144.6	0.05	0.43	0.48
4380	19,289	1,159.07	121.9	0.05	0.33	0.38
4383	18,989	1,080.04	143.1	0.03	0.40	0.43
4384	18,138	383.67	122.4	0.03	0.32	0.36
Total Trolley	180,554	11,464.65	1,421.0	0.04	0.42	0.46

The monthly scheduled and unscheduled maintenance cost per mile for the four fleets of buses are shown as stacked columns in Figure 3-19.

**Figure 3-19** *Monthly Scheduled and Unscheduled Maintenance Cost per Mile for All Four Bus Fleets*

Work Order Maintenance Costs Categorized by System

Table 3-8 shows maintenance costs per mile by vehicle system and bus fleet (without warranty costs). The color shading denotes the systems with the highest percentage of maintenance costs: orange for the highest, green for the second highest, and purple for the third highest. The vehicle systems shown in the table are as follows:

- Cab, body, and accessories – includes body, glass, cab and sheet metal, seats and doors, and accessory repairs such as hubodometers and radios
- Propulsion-related systems – repairs for exhaust, fuel, engine, electric motors, battery modules, propulsion control, non-lighting electrical (charging, cranking and ignition), air intake, cooling, and transmission
- PMI – labor for inspections during preventive maintenance
- Brakes – includes brake pads, disks, calipers, anti-lock braking system, and brake chambers
- Frame, steering, and suspension
- HVAC
- Lighting
- Air system (general)
- Axles, wheels, and drive shaft
- Tires

Table 3-8 *Work Order Maintenance Cost per Mile by System^a*

System	Battery Cost per Mile (\$)	Battery Percent of Total (%)	Hybrid Cost per Mile (\$)	Hybrid Percent of Total (%)	Diesel Cost per Mile (\$)	Diesel Percent of Total (%)	Trolley Cost per Mile (\$)	Trolley Percent of Total (%)
Propulsion-related	0.05	18.6	0.12	38.0	0.13	27.8	0.17	37.5
Cab, body, and accessories	0.13	49.7	0.12	36.7	0.24	50.7	0.19	40.6
PMI	0.03	10.8	0.04	12.0	0.04	8.4	0.03	5.7
Brakes	0.01	4.5	0.01	2.2	0.03	5.9	0.01	1.9
Frame, steering, and suspension	0.00	1.0	0.01	2.2	0.00	0.4	0.01	1.4
HVAC	0.01	4.4	0.01	2.9	0.02	5.0	0.05	9.9
Lighting	0.01	2.7	0.01	1.7	0.00	0.3	0.00	1.0
General air system repairs	0.01	4.1	0.01	3.2	0.00	1.1	0.01	1.7
Axles, wheels, and drive shaft	0.00	0.0	0.00	0.3	0.00	0.2	0.00	0.2
Tires	0.01	4.1	0.00	0.7	0.00	0.2	0.00	0.1
Total	0.26	100	0.32	100	0.46	100	0.46	100

^a The top three categories for maintenance for each fleet are color coded as follows: orange—highest, green—second highest, and purple—third highest.

The systems with the highest percentage of maintenance costs for the battery buses and diesel buses were 1) cab, body, and accessories; 2) propulsion-related; and 3) PMI. The systems with the highest percentage of maintenance costs for the hybrid buses were 1) propulsion-related; 2) cab, body, and accessories; and 3) PMI. The systems with the highest percentage of maintenance costs for the trolley buses were 1) cab, body, and accessories; 2) propulsion-related; and 3) HVAC. Figure 3-20 shows the monthly cost per mile by system for the battery

fleet. The maintenance costs for the battery buses increased toward the end of the data period, primarily driven by cab, body, and accessories costs as well as some propulsion-related costs.

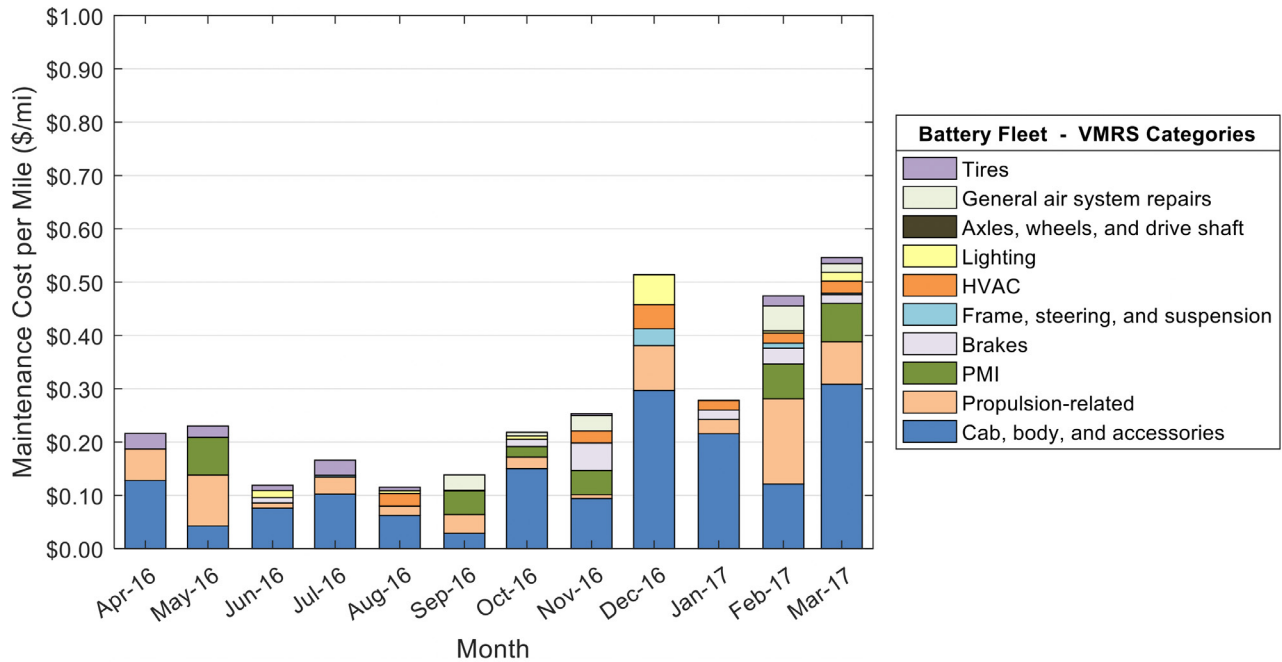


Figure 3-20 Monthly Maintenance Cost per Mile by System for Battery Bus Fleet

Figure 3-21 shows the monthly cost per mile by system for the hybrid fleet. The overall cost per mile for the hybrid buses was consistent during most of the data period. Cab, body, and accessories issues that resulted in higher maintenance costs included problems with water leaks, a broken windshield, and a farebox replacement. Propulsion system issues included cooling leaks, a tune-up, traction motor replacement, and a failed nitrogen oxides (NOx) sensor.

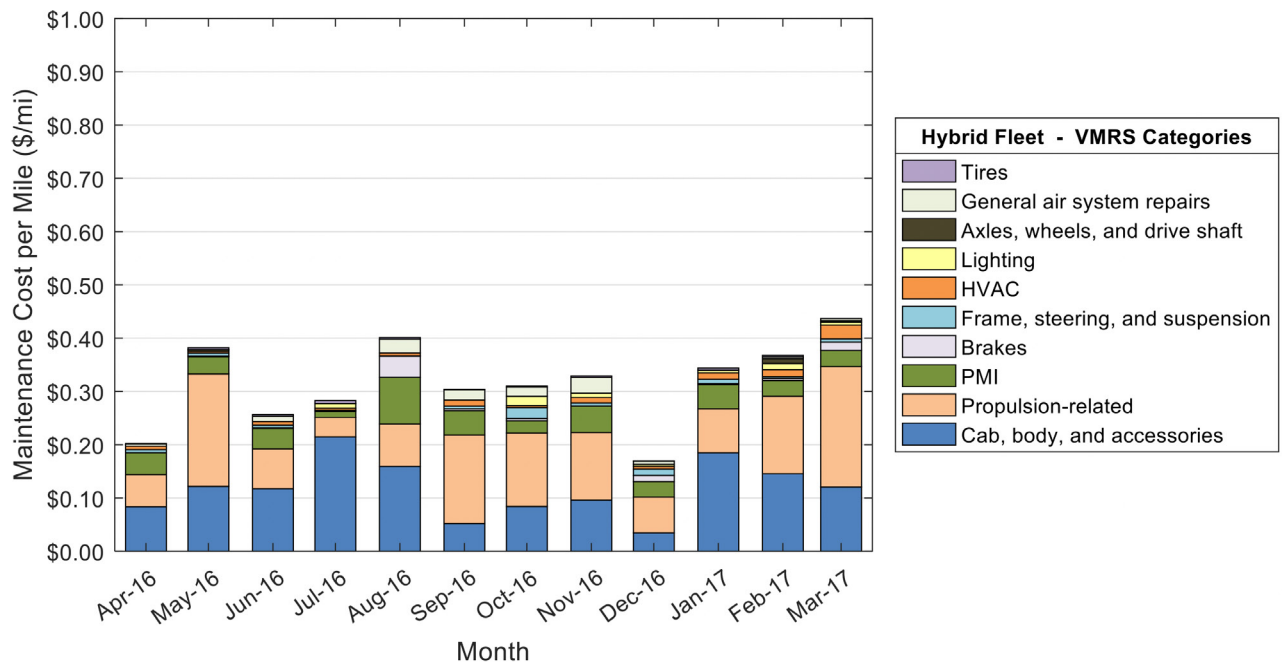


Figure 3-21 *Monthly Maintenance Cost per Mile by System for Hybrid Bus Fleet*

Figure 3-22 shows the monthly cost per mile by system for the diesel fleet. The majority of issues with the diesel buses were in the cab, body, and accessories category. Issues include problems with a destination sign, windshield wipers, and a radio. Propulsion category issues included problems with the electrical system and low-voltage batteries.

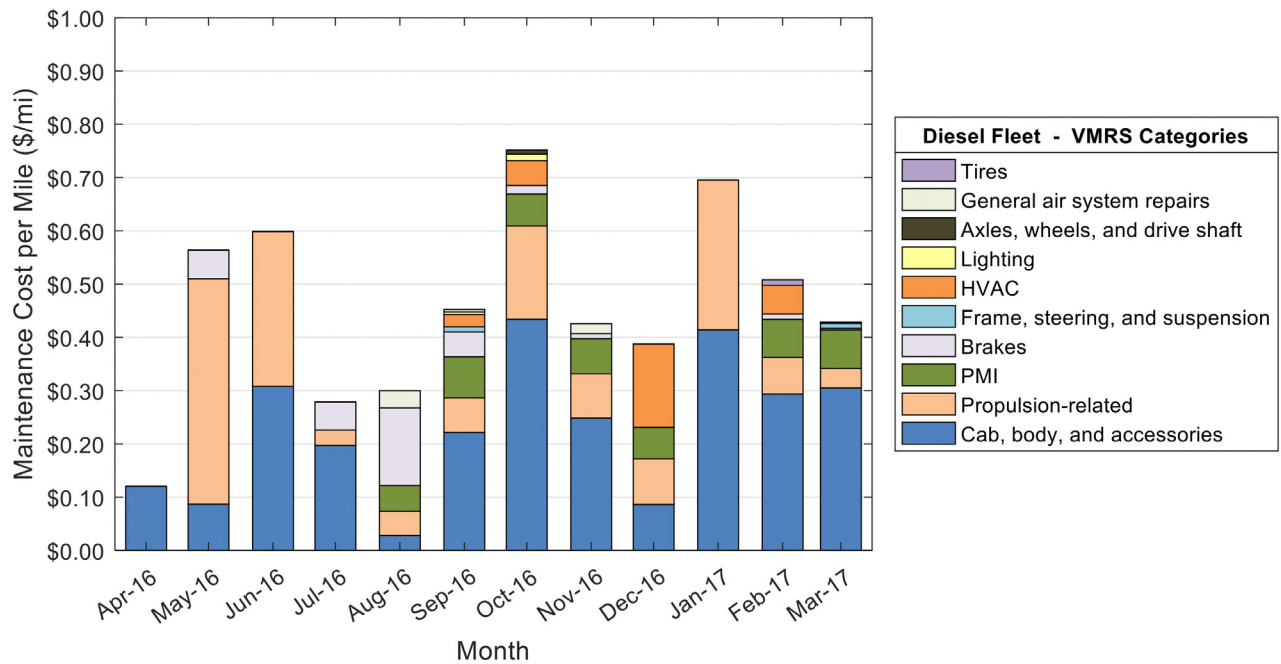


Figure 3-22 *Monthly Maintenance Cost per Mile by System for Diesel Bus Fleet*

Figure 3-23 shows the monthly cost per mile by system for the trolley fleet. Issues experienced in the cab, body, and accessories category included repairs for radios and fareboxes. Propulsion-related repairs included issues with the electric drive and current collection systems. Issues with the HVAC system increased costs during several months in the evaluation period.

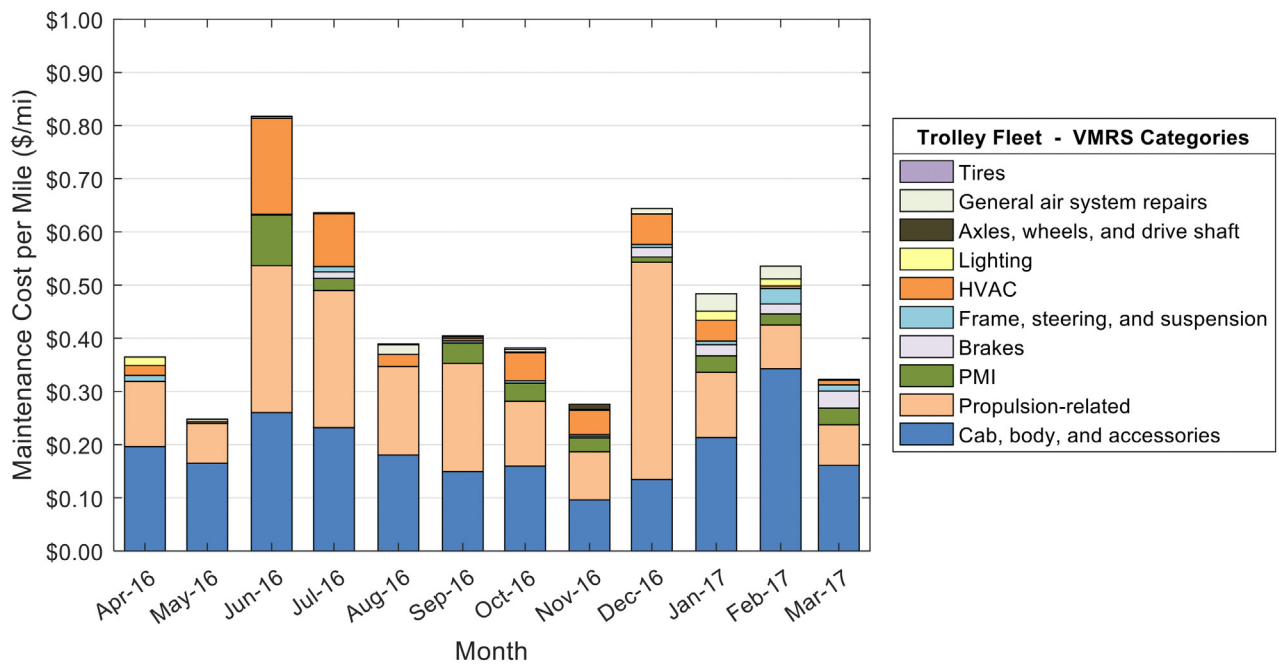


Figure 3-23 Monthly Maintenance Cost per Mile by System for Trolley Bus Fleet

Propulsion-Related Work Order Maintenance Costs

Propulsion-related vehicle systems include the exhaust, fuel, engine, battery modules, electric propulsion, air intake, cooling, non-lighting electrical, transmission, and hydraulic systems. These vehicle subsystems have been separated to highlight how maintenance costs for the propulsion system are affected by the change from conventional technology (diesel) to advanced technology (batteries). Table 3-9 shows the propulsion-related system maintenance costs by category for the four fleets during the data period. Parts for scheduled maintenance, such as filters and fluids, are included in the specific system categories. For example, oil and oil filters are included in the power plant (engine) subsystem parts costs, while air filters are included in the air intake subsystem parts costs.

- **Total propulsion-related** – The battery fleet’s total propulsion-related maintenance cost was 60% lower than that of the hybrid buses, 63% lower than that of the diesel buses, and 72% lower than that of the trolley buses.
- **Exhaust system** – Costs for the hybrid and diesel buses were low. The battery buses and trolley buses do not have exhaust systems.
- **Fuel system** – Costs for this system for the hybrid and diesel buses were low. The battery buses and trolley buses do not have liquid fueling systems.

- **Power plant and electric propulsion** – For the battery buses, the electric propulsion system accounted for 60% of the total propulsion system costs. Power plant (engine) repairs made up 5% of the hybrid costs and the electric propulsion costs made up 21%. Power plant repairs made up 10% of the total propulsion system costs for the diesel buses; there are no electric propulsion costs for the diesel buses. Current collection system costs made up 66.5% of the trolley costs followed by the electric propulsion system at 21%.
- **Non-lighting electrical (charging, cranking, and ignition)** – Costs for this system for the battery buses were slightly lower than that of the hybrid buses. The battery fleet costs were 80% lower than the costs for the diesel fleet and 22% lower than the costs for the trolley fleet.
- **Air intake** – Costs for this system for the battery buses, diesel buses, and trolley buses were low or zero. For the hybrid buses, air intake system repairs made up 9.8% of the propulsion system costs.
- **Cooling** – Costs for this system for the battery buses, diesel buses, and trolley buses were low or zero. For the hybrid buses, cooling system repairs made up 37% of the costs.
- **Transmission** – Costs for this system were low for all four bus fleets.
- **Hydraulic** – Costs for this system were low or zero for all four bus fleets.

Table 3-9

*Propulsion-
Related
Work Order
Maintenance
Costs by System*

Maintenance System Costs		Battery	Hybrid	Diesel	Trolley
Mileage		83,127	432,538	69,329	180,554
Total Propulsion-Related Systems (Roll-up)	Parts cost (\$)	111.98	15,528.60	3,049.69	5,862.78
	Labor hours	78.3	733.0	118.3	501.7
	Total cost (\$)	4,024.48	52,176.10	8,962.19	30,947.78
	Total cost (\$) per mile	0.048	0.120	0.129	0.171
Exhaust System Repairs	Parts cost (\$)	0.00	184.84	100.64	0.00
	Labor hours	0.0	107.1	2.0	0.0
	Total cost (\$)	0.00	5,537.34	200.64	0.00
	Total cost (\$) per mile	0.000	0.013	0.003	0.000
Fuel System Repairs	Parts cost (\$)	0.00	2,516.79	272.41	0.00
	Labor hours	0.0	2.8	1.0	0.0
	Total cost (\$)	0.00	2,654.29	322.41	0.00
	Total cost (\$) per mile	0.000	0.006	0.005	0.000
Power Plant System Repairs	Parts cost (\$)	0.00	1,016.14	342.22	0.00
	Labor hours	0.0	30.5	10.5	0.0
	Total cost (\$)	0.00	2,541.14	867.22	0.00
	Total cost (\$) per mile	0.000	0.006	0.013	0.000

Table 3-9
cont'd

*Propulsion-
Related
Work Order
Maintenance
Costs by
System*

Maintenance System Costs		Battery	Hybrid	Diesel	Trolley
Electric Propulsion System Repairs	Parts cost (\$)	0.00	1833.51	0.00	0.00
	Labor hours	48.0	179.7	0.0	128.9
	Total cost (\$)	2,400.00	10,818.51	0.00	6,442.50
	Total cost (\$) per mile	0.029	0.025	0.000	0.036
Current Collection	Parts cost (\$)	0.00	0.00	0.00	5,296.17
	Labor hours	0.00	0.00	0.00	306.10
	Total cost (\$)	0.00	0.00	0.00	20,601.17
	Total cost (\$) per mile	0.000	0.000	0.000	0.114
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)	Parts cost (\$)	111.98	536.32	2,203.47	566.61
	Labor hours	25.8	114.5	71.0	66.75
	Total cost (\$)	1,399.48	6,258.82	5,753.47	3,904.11
	Total cost (\$) per mile	0.017	0.014	0.083	0.022
Air Intake System Repairs	Parts cost (\$)	0.00	2,347.63	121.63	0.00
	Labor hours	0.0	55.6	2.8	0.0
	Total cost (\$)	0.00	5,127.63	259.13	0.00
	Total cost (\$) per mile	0.000	0.012	0.004	0.000
Cooling System Repairs	Parts cost (\$)	0.00	7,083.05	5.70	0.00
	Labor hours	4.0	239.9	10.3	0.0
	Total cost (\$)	200.00	19,078.05	518.20	0.00
	Total cost (\$) per mile	0.002	0.044	0.007	0.000
Transmission System Repairs	Parts cost (\$)	0.00	0.00	3.62	0.00
	Labor hours	0.5	0.0	20.8	0.0
	Total cost (\$)	25.00	0.00	1,041.12	0.00
	Total cost (\$) per mile	0.000	0.000	0.015	0.000
Hydraulic	Parts cost (\$)	0.00	10.32	0.00	0.00
	Labor hours	0	3	0	0.00
	Total cost (\$)	0.00	160.32	0.00	0.00
	Total cost (\$) per mile	0.000	0.000	0.000	0.000

Total Cost

Figure 3-24 shows the monthly total operational cost per mile, including maintenance and fuel cost, for the battery, hybrid, and diesel fleets. Trolley costs are excluded because electricity use data were not available. Energy costs dominate the battery fleet's overall operational costs and show a general increase in the latter half of the data period, during colder months. Diesel fuel costs are consistent over the data period and are higher for the standard diesel buses compared to the hybrid buses due to the lower fuel economy. Table 4-10 summarizes the overall fuel and maintenance costs per mile by bus fleet. These parameters are also listed in the Appendix.

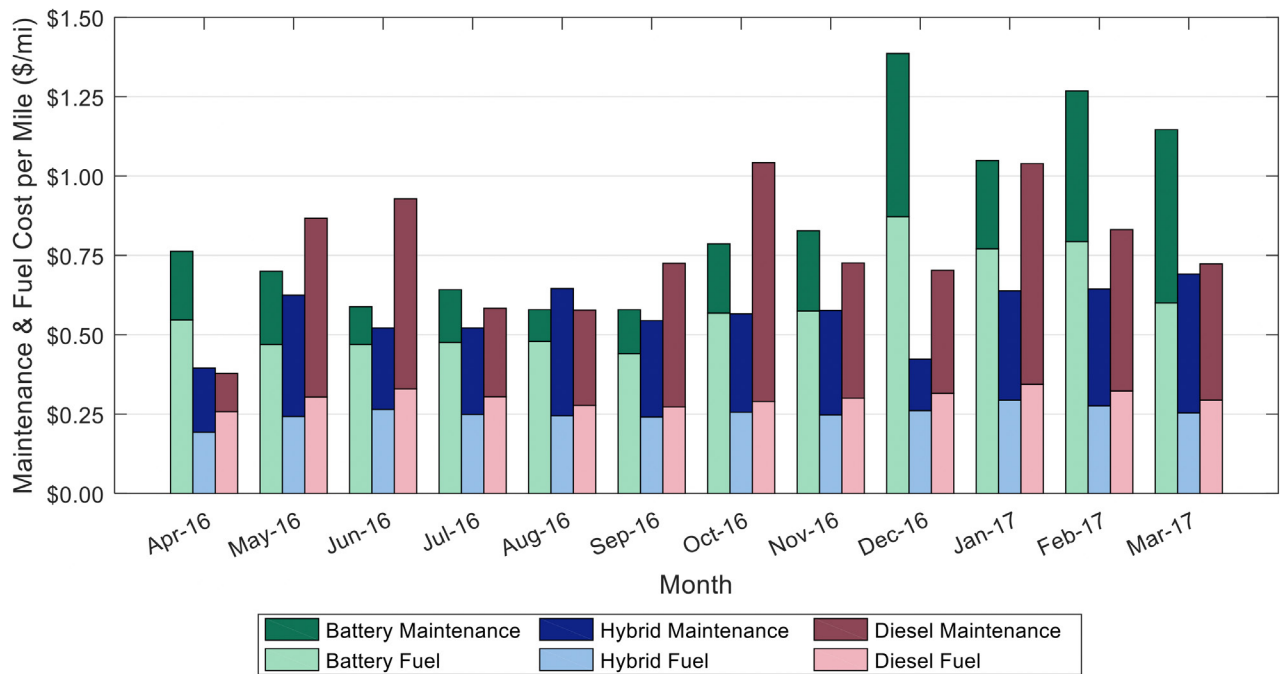


Figure 3-24 Monthly Operations (Maintenance and Fuel) Cost for Battery, Hybrid, and Diesel Bus Fleets

Table 3-10

Overall Operations
(Maintenance and
Fuel) Cost per Mile

	Battery	Hybrid	Diesel	Trolley
Fuel cost per mile (\$/mi)	0.57	0.25	0.30	N/A
Total maintenance cost per mile (\$/mi)	0.26	0.32	0.46	0.46
Total operating cost per mile (\$/mi)	0.82	0.57	0.77	N/A

Summary of Achievements and Challenges

As with all new technology development, lessons learned during this project could aid other agencies considering BEB technology. KC Metro reports that it has had a positive experience with Proterra and that the OEM is very responsive when any issue arises. Proterra has expressed appreciation with KC Metro's feedback on the bus design and has used that input to make improvements to its product. The team reports a number of successes that include the following:

- Implemented the agency's first BEB fleet
- Accumulated more than 100,000 miles on the battery buses in the first 15 months of revenue service

- Increased operation of the battery fleet since the end of NREL's data collection period
- Initiated an order of eight more fast charge BEBs through a Low-No award.

KC Metro is committed to an environmentally friendly fleet and plans to purchase 120 BEBs by 2020. In 2017, the agency entered into a contract with Proterra to purchase up to 73 BEBs.

Summary of Challenges

Advanced-technology demonstrations typically experience challenges and issues that need to be resolved. KC Metro reports that management and scheduling differences for the BEBs compared to conventional technologies resulted in many of the challenges. Issues and lessons learned for KC Metro include the following.

- **Charger availability** – When deploying a fast-charge BEB fleet, availability of the on-route charger is critical for operation. Downtime of the charger results in downtime for the fleet. KC Metro experienced this issue when the charger was damaged. A bolt in the rooftop charging assembly on one of the buses backed out and the charger head became stuck. While the issue was minor, the resulting downtime of the charger caused a major service interruption for the battery fleet during the two weeks it took to repair the charger. Proterra has not determined the root cause for the bolt backing out. Although the PM schedule does include a regular inspection, the OEM has also issued a bulletin to add adhesive to the bolt to ensure the issue does not happen again.
- **Operator training** – Driver training is an ongoing challenge because the BEBs operate differently from the conventional buses in the agency's fleet. The primary training differences are learning the docking procedure and ensuring the BEBs are fully charged before returning to the depot at the end of a shift. KC Metro plans to install a fast charger at the Bellevue Base, which will incorporate the procedure for end-of-shift charging of their battery buses into the general servicing and fueling process at the base. Fully charging the buses before returning to the base will no longer be necessary. At the onset of the project, KC Metro trained a number of drivers to operate the battery buses. The agency has service changes three times each year where operators may elect to move to a different route. Any new operators for the routes serviced by the battery buses need to be trained on the operational differences. Transit agencies deploying electric buses should consider this when planning training programs.
- **Operations planning** – The scheduling department needs to understand the operational differences for on-route-charged BEBs. The short range of these buses requires them to operate on a selection of routes that return to the charging station regularly. Schedulers need to limit service to the

selected routes until the agency adds chargers to other locations. The agency also has layovers planned in its route schedules. With conventional buses, an operator can shorten the layover to make up lost time and keep buses on schedule. For BEBs, however, that planned layover includes time for charging. Shortening the layover to make up schedule slip could result in the bus not getting a full charge.

- **Parts list for inventory** – Parts availability is a common issue with agencies deploying advanced-technology buses. KC Metro reports that Proterra has delivered parts quickly, but the agency needs to keep some parts on hand to speed up the process. The agency is working with Proterra to develop a better list of parts for on-site inventory.
- **Extended downtime** – KC Metro experienced a few issues with specific battery buses that resulted in downtime.
- **Tow damage** – In December 2016, the electric drive system on one of the battery buses was damaged during towing. KC Metro considers the situation a training issue. While Proterra had trained KC Metro employees at Bellevue Base on the proper towing procedures, the staff that responded to the roadcall were from another base. The damage took about 5 weeks to repair.
- **Traction motor** – KC Metro's battery buses were produced with a new version of traction motor. The agency experienced several issues with motors overheating. Proterra traced the root cause to a damaged crimp in the motor windings. The traction motor supplier modified the production process to eliminate the issue for future products. Proterra proactively replaced motors on all three of KC Metro's battery buses to prevent the issue from reoccurring.

KC Metro Fleet Summary Statistics

Table A-1 *Fleet Operations and Economics*

	Battery	Hybrid	Diesel	Trolley
Number of vehicles	3	10	3	10
Period used for fuel and energy analysis	4/16-3/17	4/16-3/17	4/16-3/17	4/16-3/17
Total number of months in period	12	12	12	12
Fuel and energy analysis base fleet mileage	77,563	429,836	68,212	61,780 ^a
Period used for maintenance analysis	4/16-3/17	4/16-3/17	4/16-3/17	4/16-3/17
Total number of months in period	12	12	12	12
Maintenance analysis base fleet mileage	83,127	435,552	69,329	180,554
Average monthly mileage per vehicle	2,309	3,630	1,926	1,505
Availability	80.6	90.5	86.4	84.9
Fleet fuel usage (kWh electricity or gal diesel)	183,255	67,874	12,909	158,484 ^a
Roadcalls	30	57	4	110
Total MBRC	2,771	7,641	17,332	1,641
Propulsion roadcalls	12	15	2	61
Propulsion MBRC	6,927	29,037	34,665	2,960
Fleet kWh/mile	2.36			2.57 ^a
Representative fleet fuel economy (mpdgc)	15.9	6.3	5.3	14.7 ^a
Electricity cost per kWh (\$)	0.20			N/A
Diesel cost per gal (\$)		1.60	1.60	
Fuel cost per mile (\$)	0.57	0.25	0.30	N/A
Total scheduled repair cost per mile (\$)	0.04	0.09	0.08	0.04
Total unscheduled repair cost per mile (\$)	0.22	0.22	0.39	0.42
Total maintenance cost per mile (\$)	0.26	0.32	0.46	0.46
Total operating cost per mile (\$)	0.82	0.57	0.77	N/A

^a Trolley fleet fuel economy is estimated based on data from two trolley buses during 13 months of operation.

Table A-2
Maintenance Costs

	Battery	Hybrid	Diesel	Trolley
Fleet mileage	83,127	432,538	69,329	180,554
Total parts cost (\$)	1,974.69	29,511.45	5,937.19	11,464.65
Total labor hours	394.3	2,157.1	524.3	1,421.0
Average labor cost (@ \$50.00 per hour) (\$)	19,712.50	107,852.50	26,215.00	71,050.00
Total maintenance cost (\$)	21,687.19	137,363.95	32,152.19	82,514.65
Total maintenance cost per bus (\$)	7,229.06	13,736.39	3,215.22	8,251.46
Total maintenance cost per mile (\$)	0.26	0.32	0.46	0.46

Table A-3

*Breakdown of
Maintenance
Costs by System*

	Battery	Hybrid	Diesel	Trolley
Fleet mileage	83,127	432,538	69,329	180,554
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost (\$)	111.98	15,528.60	3,028.89	5,862.78
Labor hours	78.25	732.95	118.25	501.70
Average labor cost (\$)	3,912.50	36,647.50	5,912.50	25,085.00
Total cost (for system) (\$)	4,024.48	52,176.10	8,941.39	30,947.78
Total cost (for system) per bus (\$)	1,341.49	17,392.03	2,980.46	10,315.93
Total cost (for system) per mile (\$)	0.048	0.121	0.129	0.171
Exhaust System Repairs (ATA VMRS 43)				
Parts cost (\$)	0.00	184.84	100.64	0.00
Labor hours	0.0	107.1	2.0	0.0
Average labor cost (\$)	0.00	5,352.50	100.00	0.00
Total cost (for system) (\$)	0.00	5,537.34	200.64	0.00
Total cost (for system) per bus (\$)	0.00	1,845.78	66.88	0.00
Total cost (for system) per mile (\$)	0.000	0.013	0.003	0.000
Fuel System Repairs (ATA VMRS 44)				
Parts cost (\$)	0.00	2,516.79	272.41	0.00
Labor hours	0.0	2.8	1.0	0.0
Average labor cost (\$)	0.00	137.50	50.00	0.00
Total cost (for system) (\$)	0.00	2,654.29	322.41	0.00
Total cost (for system) per bus (\$)	0.00	884.76	107.47	0.00
Total cost (for system) per mile (\$)	0.000	0.006	0.005	0.000
Power Plant (Engine or ESS) Repairs (ATA VMRS 45)				
Parts cost (\$)	0.00	1,016.14	321.42	0.00
Labor hours	0.0	30.5	10.5	0.0
Average labor cost (\$)	0.00	1,525.00	525.00	0.00
Total cost (for system) (\$)	0.00	2,541.14	846.42	0.00
Total cost (for system) per bus (\$)	0.00	847.05	282.14	0.00
Total cost (for system) per mile (\$)	0.000	0.006	0.012	0.000
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost (\$)	0.00	1,833.51	0.00	0.00
Labor hours	48.0	179.7	0.0	128.9
Average labor cost (\$)	2,400.00	8,985.00	0.00	6,442.50
Total cost (for system) (\$)	2,400.00	10,818.51	0.00	6,442.50
Total cost (for system) per bus (\$)	800.00	3,606.17	0.00	2,147.50
Total cost (for system) per mile (\$)	0.029	0.025	0.000	0.036
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost (\$)	111.98	536.32	2,203.47	566.61
Labor hours	25.8	114.5	71.0	66.8
Average labor cost (\$)	1,287.50	5,722.50	3,550.00	3,337.50

**Table A-3
cont'd**

*Breakdown of
Maintenance
Costs by System*

	Battery	Hybrid	Diesel	Trolley
Total cost (for system) (\$)	1,399.48	6,258.82	5,753.47	3,904.11
Total cost (for system) per bus (\$)	466.49	2,086.27	1,917.82	1,301.37
Total cost (for system) per mile (\$)	0.017	0.014	0.083	0.022
Air Intake System Repairs (ATA VMRS 41)				
Parts cost (\$)	0.00	2,347.63	121.63	0.00
Labor hours	0.0	55.6	2.8	0.0
Average labor cost (\$)	0.00	2,780.00	137.50	0.00
Total cost (for system) (\$)	0.00	5,127.63	259.13	0.00
Total cost (for system) per bus (\$)	0.00	1,709.21	86.38	0.00
Total cost (for system) per mile (\$)	0.000	0.012	0.004	0.000
Cooling System Repairs (ATA VMRS 42)				
Parts cost (\$)	0.00	7,083.05	5.70	0.00
Labor hours	4.0	239.9	10.3	0.0
Average labor cost (\$)	200.00	11,995.00	512.50	0.00
Total cost (for system) (\$)	200.00	19,078.05	518.20	0.00
Total cost (for system) per bus (\$)	66.67	6,359.35	172.73	0.00
Total cost (for system) per mile (\$)	0.002	0.044	0.007	0.000
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost (\$)	0.00	10.32	0.00	0.00
Labor hours	0.0	3.0	0.0	0.0
Average labor cost (\$)	0.00	150.00	0.00	0.00
Total cost (for system) (\$)	0.00	160.32	0.00	0.00
Total cost (for system) per bus (\$)	0.00	53.44	0.00	0.00
Total cost (for system) per mile (\$)	0.000	0.000	0.000	0.000
General Air System Repairs (ATA VMRS 10)				
Parts cost (\$)	73.80	710.18	25.32	7.49
Labor hours	16.5	72.8	6.3	27.5
Average labor cost (\$)	825.00	3,637.50	312.50	1,375.00
Total cost (for system) (\$)	898.80	4,347.68	337.82	1,382.49
Total cost (for system) per bus (\$)	299.60	1,449.23	112.61	460.83
Total cost (for system) per mile (\$)	0.011	0.010	0.005	0.008
Brake System Repairs (ATA VMRS 13)				
Parts cost (\$)	84.91	877.00	0.00	509.38
Labor hours	18.0	43.6	38.0	21.4
Average labor cost (\$)	900.00	2,177.50	1,900.00	1,067.50
Total cost (for system) (\$)	984.91	3,054.50	1,900.00	1,576.88
Total cost (for system) per bus (\$)	328.30	1,018.17	633.33	525.63
Total cost (for system) per mile (\$)	0.012	0.007	0.027	0.009
Transmission Repairs (ATA VMRS 27)				
Parts cost (\$)	0.00	0.00	3.62	0.00
Labor hours	0.5	0.0	20.8	0.0

**Table A-3
cont'd***Breakdown of
Maintenance
Costs by System*

	Battery	Hybrid	Diesel	Trolley
Average labor cost (\$)	25.00	0.00	1,037.50	0.00
Total cost (for system) (\$)	25.00	0.00	1,041.12	0.00
Total cost (for system) per bus (\$)	8.33	0.00	347.04	0.00
Total cost (for system) per mile (\$)	0.000	0.000	0.015	0.000
Inspections Only – no parts replacements (101)				
Parts cost (\$)	0.00	0.00	0.00	0.00
Labor hours	47.0	329.8	54.3	94.3
Average labor cost (\$)	2,350.00	16,487.50	2,712.50	4,712.50
Total cost (for system) (\$)	2,350.00	16,487.50	2,712.50	4,712.50
Total cost (for system) per bus (\$)	783.33	5,495.83	904.17	1,570.83
Total cost (for system) per mile (\$)	0.028	0.038	0.039	0.026
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost (\$)	1,502.76	9,375.02	2,376.61	3,080.23
Labor hours	185.5	821.7	278.8	607.8
Average labor cost (\$)	9,275.00	41,085.00	13,940.00	30,390.00
Total cost (for system) (\$)	10,777.76	50,460.02	16,316.61	33,470.23
Total cost (for system) per bus (\$)	3,592.59	16,820.01	5,438.87	11,156.74
Total cost (for system) per mile (\$)	0.130	0.117	0.235	0.185
HVAC System Repairs (ATA VMRS 01)				
Parts cost (\$)	55.45	1,088.76	480.33	1,779.95
Labor hours	18.0	58.8	22.8	127.8
Average labor cost (\$)	900.00	2,940.00	1,137.50	6,387.50
Total cost (for system) (\$)	955.45	4,028.76	1,617.83	8,167.45
Total cost (for system) per bus (\$)	318.48	1,342.92	539.28	2,722.48
Total cost (for system) per mile (\$)	0.011	0.009	0.023	0.045
Lighting System Repairs (ATA VMRS 34)				
Parts cost (\$)	119.64	1,290.64	0.00	82.28
Labor hours	9.5	21.8	2.0	14.3
Average labor cost (\$)	475.00	1,090.00	100.00	712.50
Total cost (for system) (\$)	594.64	2,380.64	100.00	794.78
Total cost (for system) per bus (\$)	198.21	793.55	33.33	264.93
Total cost (for system) per mile (\$)	0.007	0.006	0.001	0.004
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost (\$)	22.36	337.73	26.04	142.53
Labor hours	4.0	53.3	2.0	20.9
Average labor cost (\$)	200.00	2,662.50	100.00	1,045.00
Total cost (for system) (\$)	222.36	3,000.23	126.04	1,187.53
Total cost (for system) per bus (\$)	74.12	1,000.08	42.01	395.84
Total cost (for system) per mile (\$)	0.003	0.007	0.002	0.007

Table A-3
cont'd*Breakdown of
Maintenance
Costs by System*

	Battery	Hybrid	Diesel	Trolley
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost (\$)	0.00	303.53	0.00	0.00
Labor hours	0.0	2.5	1.0	3.5
Average labor cost (\$)	0.00	125.00	50.00	175.00
Total cost (for system) (\$)	0.00	428.53	50.00	175.00
Total cost (for system) per bus (\$)	0.00	142.84	16.67	58.33
Total cost (for system) per mile (\$)	0.000	0.001	0.001	0.001
Tire Repairs (ATA VMRS 17)				
Parts cost (\$)	3.78	0.00	0.00	0.00
Labor hours	17.5	20.0	1.0	2.0
Average labor cost (\$)	875.00	1,000.00	50.00	100.00
Total cost (for system) (\$)	878.78	1,000.00	50.00	100.00
Total cost (for system) per bus (\$)	292.93	333.33	16.67	33.33
Total cost (for system) per mile (\$)	0.011	0.002	0.001	0.001
Current Collection				
Parts cost (\$)	0.00	0.00	0.00	5,296.17
Labor hours	0.0	0.0	0.0	306.1
Average labor cost (\$)	0.00	0.00	0.00	15,305.00
Total cost (for system) (\$)	0.00	0.00	0.00	20,601.17
Total cost (for system) per bus (\$)	0.00	0.00	0.00	6,867.06
Total cost (for system) per mile (\$)	0.000	0.000	0.000	0.114

Fleet Summary Statistics—SI Units

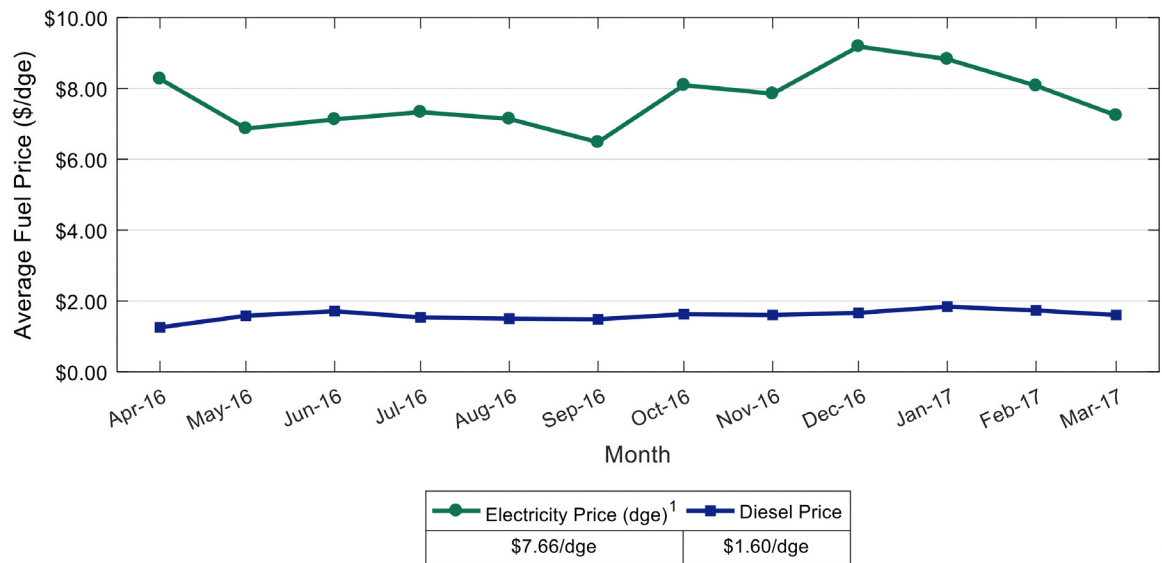
Table A-4
*Fleet Operations and
Economics (SI)*

	Battery	Hybrid	Diesel	Trolley
Number of vehicles	3	10	3	10
Period used for fuel and energy analysis	4/16–3/17	4/16–3/17	4/16–3/17	4/16–3/17
Total number of months in period	12	12	12	12
Fuel and energy analysis base fleet mileage	124,822	691,735	109,774	N/A
Period used for maintenance analysis	4/16–3/17	4/16–3/17	4/16–3/17	4/16–3/17
Total number of months in period	12	12	12	12
Maintenance analysis base fleet kilometers	133,776	700,934	111,571	290,566
Average monthly kilometers per vehicle	44,592	70,093	37,190	29,057
Availability	80.6	90.5	86.4	84.9
Fleet fuel usage (kWh electricity or liter diesel)	183,255	256,931	48,866	158,484
Roadcalls	30	57	4	110
Total KMBRC	4,459	12,297	27,893	2,642
Propulsion roadcalls	12	15	2	61
Propulsion KMBRC	11,148	46,729	55,786	4,763
Rep. fleet fuel consumption (L/100 km)	14.74	37.14	44.52	16.03
Energy cost per kWh (\$)	0.20			N/A
Diesel cost/liter (\$)		0.42	0.42	
Fuel cost per kilometer (\$)	0.35	0.16	0.19	N/A
Total scheduled repair cost per kilometer (\$)	0.02	0.06	0.05	0.02
Total unscheduled repair cost per kilometer (\$)	0.14	0.14	0.24	0.26
Total maintenance cost per kilometer (\$)	0.16	0.20	0.29	0.28
Total operating cost per kilometer (\$)	0.51	0.35	0.48	N/A

Table A-5
*Maintenance Costs
(SI)*

	Battery	Hybrid	Diesel	Trolley
Fleet mileage	133,776	696,083	111,571	290,566
Total parts cost (\$)	1,974.69	29,511.45	5,937.19	11,464.65
Total labor hours	394.25	2,157.05	524.30	1,421.00
Average labor cost (@ \$50.00 per hour) (\$)	19,712.50	107,852.50	26,215.00	71,050.00
Total maintenance cost (\$)	21,687.19	137,363.95	32,152.19	82,514.65
Total maintenance cost per bus (\$)	7,229.06	13,736.39	3,215.22	8,251.46
Total maintenance cost per kilometer (\$)	0.16	0.20	0.29	0.28

Additional Charts for KC Metro Evaluation



1. Electrical energy converted to diesel gallon equivalent (dgc), conversion factor = 37.6 kWh/diesel gallon; based on the energy content of electricity (3,414 Btu/kWh) and diesel fuel LHV (128,488 Btu/gal).

Figure A-1 Monthly Average Price for Electricity and Diesel Fuel

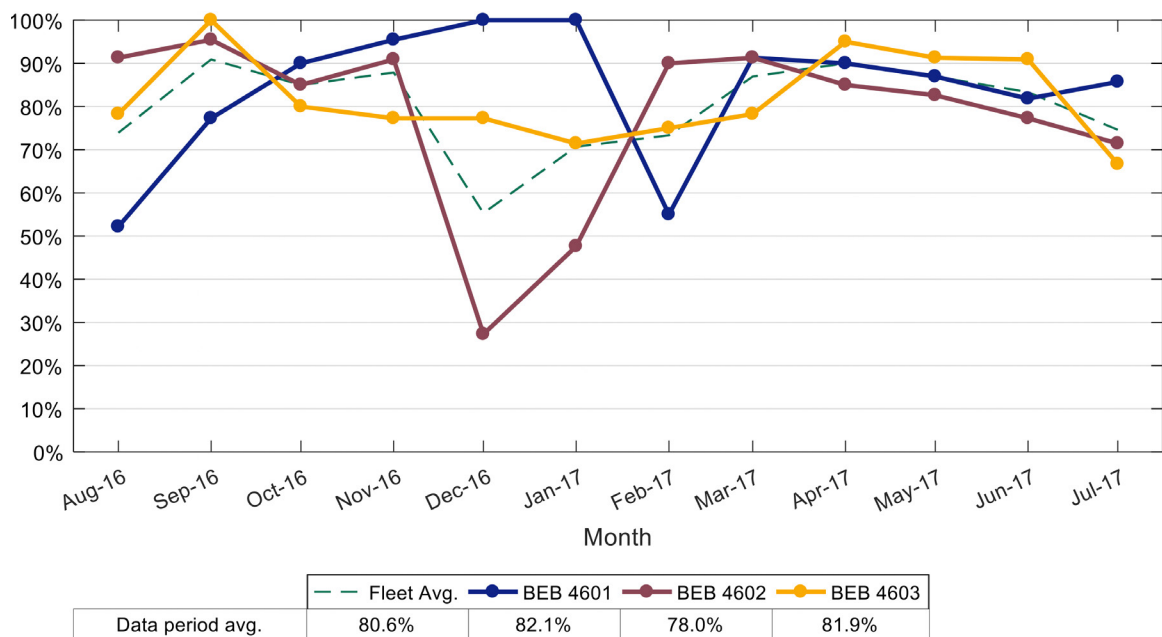


Figure A-2 Monthly Availability for Battery Buses

ACRONYMS

AC	alternating current
ATA VMRS	American Trucking Association Vehicle Maintenance Reporting Standards
BEB	battery electric bus
Btu	British thermal units
CNG	compressed natural gas
dge	diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ESS	energy storage system
FCEB	fuel cell electric bus
FePO ₄	Iron Phosphate
FTA	Federal Transit Administration
ft	feet
gal	gallon
GPS	global positioning system
hp	horse power
HVAC	heating, ventilation, and air conditioning
in	inches
KC Metro	King County Metro
KMBRC	kilometers between roadcall
kW	kilowatt
kWh	kilowatt hour
lb	pound
Low-No	Low or No Emission Vehicle Deployment Program
MBRC	miles between roadcall
mi	mile
mpdge	miles per diesel gallon equivalent
NFCBP	National Fuel Cell Bus Program
NO _x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
NTD	National Transit Database
OEM	original equipment manufacturer
OST-R	DOT's Research, Development, and Technology Office
PMI/PM	preventive maintenance inspections
RC	roadcall
rpm	revolutions per minute
SI	International System of Units
SOC	state of charge
TIGGER	Transit Investments for Greenhouse Gas and Energy Reduction
ZEB	zero-emission bus

GLOSSARY

Availability – The number of days the buses are actually available compared to the days that the buses are planned for operation, expressed as percent availability.

Clean point – For each evaluation, NREL works with the project partners to determine a starting point—or clean point—for the data analysis period. The clean point is chosen to avoid some of the early and expected operations problems with a new vehicle going into service, such as early maintenance campaigns. In some cases, reaching the clean point may require 3 to 6 months of operation before the evaluation can start. This applies to new technology buses as well as conventional buses.

Deadhead – The miles and hours that a vehicle travels when out of revenue service with no expectation of carrying revenue passengers. Deadhead includes leaving or returning to the garage or yard facility and changing routes.

Miles between roadcalls (MBRC) – A measure of reliability calculated by dividing the number of miles traveled by the total number of roadcalls, also known as mean distance between failures. MBRC results in the report are categorized as follows:

- **Bus MBRC** – Includes all chargeable roadcalls. Includes propulsion-related issues as well as problems with bus-related systems such as brakes, suspension, steering, windows, doors, and tires.
- **Propulsion-related MBRC** – Includes roadcalls that are attributed to the propulsion system. Propulsion-related roadcalls can be caused by issues with the transmission, batteries, and electric drive.
- **Energy storage system (ESS)-related MBRC** – Includes roadcalls attributed to the energy storage system only.

Revenue service – The time when a vehicle is available to the general public with an expectation of carrying fare-paying passengers. Vehicles operated in a fare-free service are also considered revenue service.

Roadcall – A failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. The analysis includes chargeable roadcalls that affect the operation of the bus or may cause a safety hazard. Non-chargeable roadcalls can be passenger incidents that require the bus to be cleaned before going back into service, or problems with an accessory such as a farebox or radio.



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