U.S. Department of Transportation
Federal Transit Administration

Zero-Emission Transit Bus Evaluations

King County Metro Battery Electric Bus Demonstration—
Preliminary Project Results

Overview of NREL Work

The U.S. Federal Transit Administration (FTA) funds a variety of research projects that support the commercialization of zero-emission bus technology. Recent programs include the National Fuel Cell Bus program, the Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) program, and the Low or No Emission Vehicle Deployment (Low-No) program. To evaluate projects funded through these programs, FTA has enlisted the help of the National Renewable Energy Laboratory (NREL) to conduct third-party evaluations of the technologies deployed under the FTA programs. NREL is a U.S. Department of Energy (DOE) national laboratory focused on renewable energy and energy efficiency research.

NREL works with the selected agencies to evaluate the performance of the zero-emission buses compared to baseline conventional buses in similar service. The evaluation effort will advance the knowledge base of zero-emission technologies in transit bus applications and provide "lessons learned" to aid other fleets in incrementally introducing next generation zero-emission buses into their operations. NREL developed this preliminary results report to quickly disseminate evaluation results to stakeholders. Detailed evaluation results will be published in future reports.

KCM Battery Electric Bus Project

KCM received funding from a 2010 TIGGER award to add three zero-emission battery electric buses (BEBs) to its fleet to reduce energy consumption and greenhouse gas emissions. 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.

Fleet Profile—King County Metro

King County Metro (KCM) 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. KCM's bus fleet operates on 215 routes and serves approximately 395,000 passengers each weekday, on average. This fleet of 1500+ vehicles contains buses of several different propulsion types, including standard and hybrid diesel buses, battery electric buses, and electric trolley buses.

Early in the project, KCM conducted a comprehensive test on a leased Catalyst BEB. Over a 106-day period the agency accumulated more than 32,000 miles on the bus under 130% standing load. The bus operated 24 hours per day and averaged 325 miles per day. The bus achieved 98% uptime during the 106-day period. The strong performance during the testing helped KCM decide to go with the Catalyst BEB. In February 2016, KCM placed three Catalyst BEBs into service on two interlined routes that travel an 18.6 mile loop between the Eastgate Park and Ride and the Bellevue Transit Center. KCM installed a fast charge station at the Eastgate Park and Ride where the buses charge during a layover.

Bus Technology Descriptions

The buses selected for baseline comparison to the BEBs include 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. Table 1 provides selected specifications for each bus type.

Performance Evaluation Results

The baseline fleets were already in service when King County began operating the three Proterra BEBs in February 2016. The results presented here focus on data from the evaluation clean point established in April 2016 through November 2016.

For this evaluation, data are being collected on a sample of ten buses from KCM's diesel hybrid fleet and three buses from the standard diesel fleet for baseline comparison to the three-bus BEB fleet. Limited data are also being collected on ten electric trolley buses to provide an additional baseline comparison for select cost and performance characteristics.

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage may indicate downtime for maintenance. Since first going into service, the three-bus BEB fleet has accumulated a total of 70,691 miles over 6,688 hours of operation, indicating an overall average speed of 10.6 miles per hour. The BEBs operated consistently during the data period, averaging between 1,984 and 2,702 miles per bus each month. Figure 1 shows the average mileage per month for each bus type. The average monthly mileage for the evaluation period is 3,503 miles for the hybrid buses, 2,467 miles for the BEBs, 1,837 miles for the diesel buses, and 1,515 miles for the trolley buses. The BEBs operate on a dedicated route with fast-charging infrastructure, while the hybrid and diesel buses are randomly dispatched on all routes (including the BEB route), many of which have higher average speeds that allow miles to be accumulated faster than the BEBs. So, the difference in monthly mileage is expected and not a limitation of the battery technology.

Availability is measured as the percentage of days the buses are available for service out of days that the buses are planned for operation. Transit agencies typically target 85% availability for their fleets to allow for time to handle scheduled and unscheduled maintenance. KCM's planned operation varies by bus fleet. The baseline hybrid and trolley bus fleets are expected to be in service every day, including weekends. The standard diesel buses in the evaluation operate on weekdays only. The BEB fleet operates on weekdays, with one BEB also operating on Saturdays; the BEBs do not operate on Sundays. This availability analysis includes a 7-day week for the hybrid and trolley fleets and a 5-day week (weekdays only) for the battery and diesel fleets. The data presented are based on availability for morning pull-out and don't necessarily reflect all-day operation. Availability was determined from daily reports—generated at 8 a.m.—summarizing open work orders for the buses in the evaluation. Buses included in each report were deemed unavailable for service that day. NREL analyzed the work order descriptions to determine the primary reason for unavailability and highlight the degree to which each major vehicle system contributed to the total unavailability. This availability analysis was not initiated until August 2016, so the availability charts show a shorter date range than the full evaluation data period.

The line series in Figure 2 show the availability, by month, for the bus fleets in the evaluation. The overall average availability for each fleet is 84.3% for BEBs, 91.7% for hybrid buses, 87.7% for diesel buses, and 86.7% for trolley buses. The stacked columns in Figure 2 display the number of days of

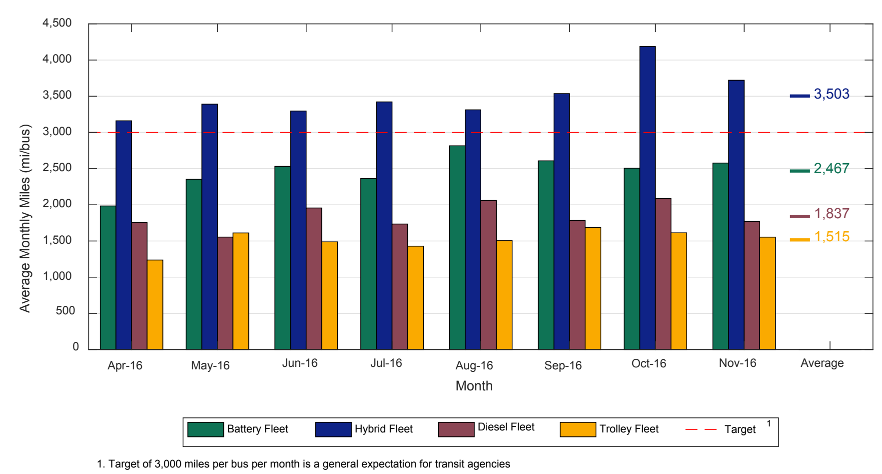


Figure 1. Average monthly mileage for the KCM buses by fleet

Table 1. System Descriptions for the Battery Electric, Hybrid, Diesel, and Trolley Buses

Vehicle System	Battery Electric	Hybrid	Diesel	Trolley
Number of buses	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

unavailability by category for the BEB fleet only. The majority of the unavailable days (35 out of 41) are categorized as general bus maintenance issues not associated with the battery technology or related subsystems. The electric drive system accounts for the remainder of unavailable days (6 out of 41). Categories with no unavailable days (such as energy storage system (ESS), charging issues, and preventive maintenance (PM)) are not yet included in the chart.

Figure 3 shows the overall fraction of time the buses were available for service as well as the fraction of unavailable days, categorized by vehicle system, for each bus fleet. For the hybrid and diesel bus fleets, the overwhelming majority of down time was for general bus maintenance items; both fleets also had a little down time due to scheduled PM work. For the trolley fleet, a significant portion of the down time was due to issues with the current collection system.

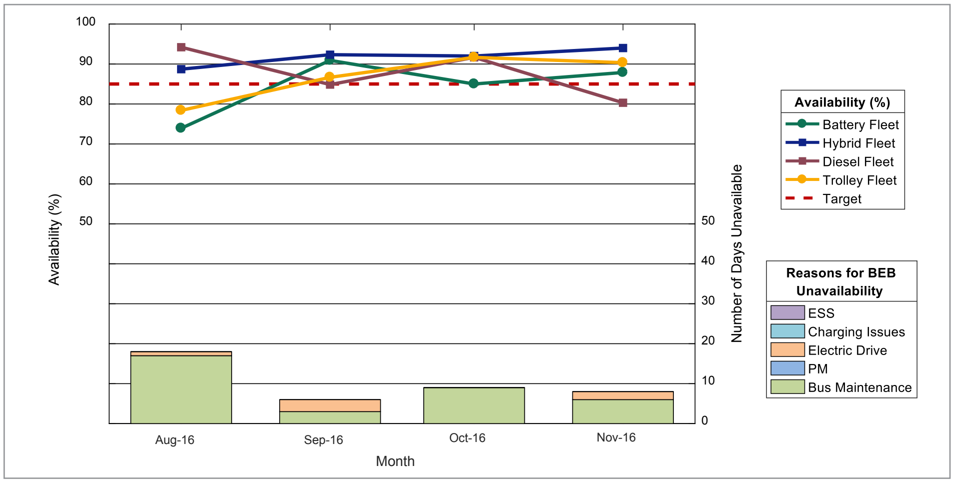


Figure 2. Availability for all fleets and reasons for unavailable days for the BEBs

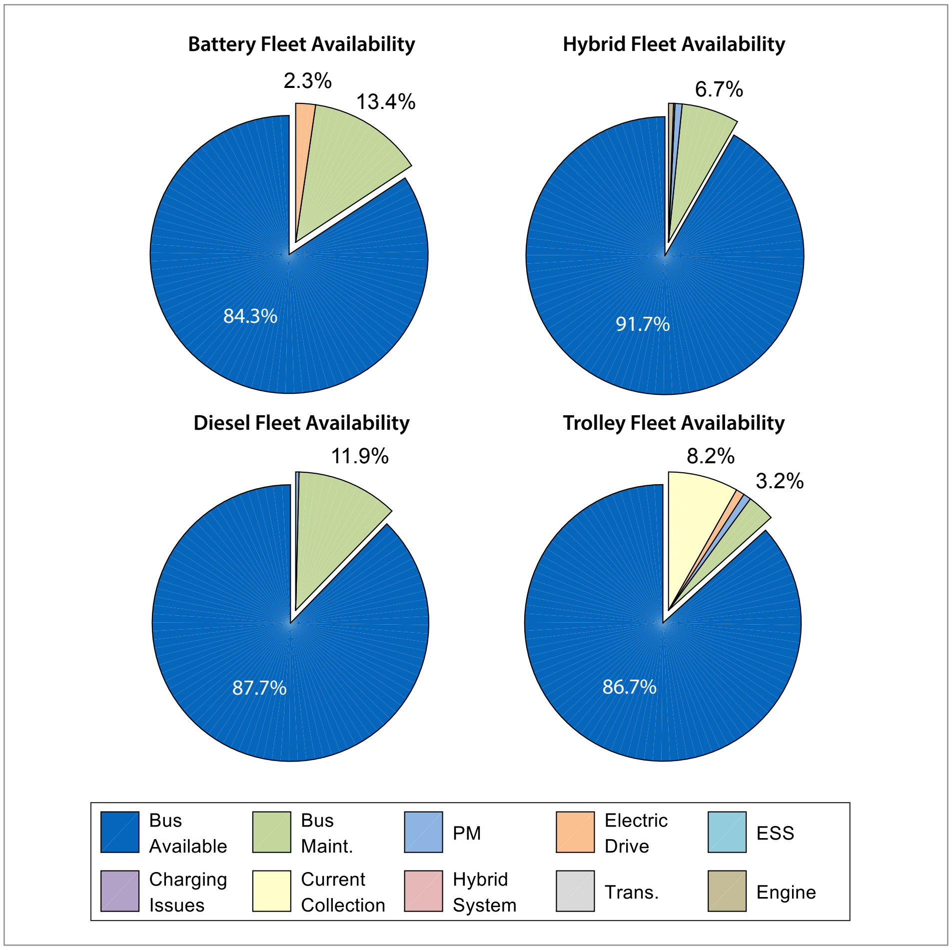


Figure 3. Overall availability and reasons for unavailability for all four fleets

Reliability

The transit industry measures reliability as mean distance between failures, also documented as miles between roadcalls (MBRC). Table 2 provides the MBRC for the battery electric, hybrid, diesel, and trolley buses categorized by bus-related roadcalls and propulsion-related roadcalls. Bus-related roadcalls include all chargeable roadcalls. Propulsion-related roadcalls include all roadcalls due to propulsion-related systems including the battery system (or engine for a conventional bus) and the electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, and transmission systems.

DOE and FTA have not established performance targets specific to electric drive buses; however, the MBRC targets for fuel cell electric buses are based on typical

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 things such as problems with radios, fareboxes, or destination signs.

conventional buses and could be considered appropriate for any advanced technology. The ultimate target for bus-related MBRC is 4,000. The BEBs in this evaluation, with 2,433 MBRC, are still below the bus-related MBRC target. The hybrid and diesel baseline fleets are both over 10,000 MBRC for bus-related roadcalls.

Table 2. Roadcalls and MBRC

	Battery Electric	Hybrid	Diesel	Trolley
Total mileage in data period	58,391	280,263	44,096	121,225
Average miles accumulated per bus	19,464	28,026	14,699	12,123
Bus-related roadcalls	24	28	3	73
Bus-related MBRC	2,433	10,009	14,699	1,661
Propulsion-related roadcalls	9	6	0	50
Propulsion-related MBRC	6,488	46,711	n/a	2,425

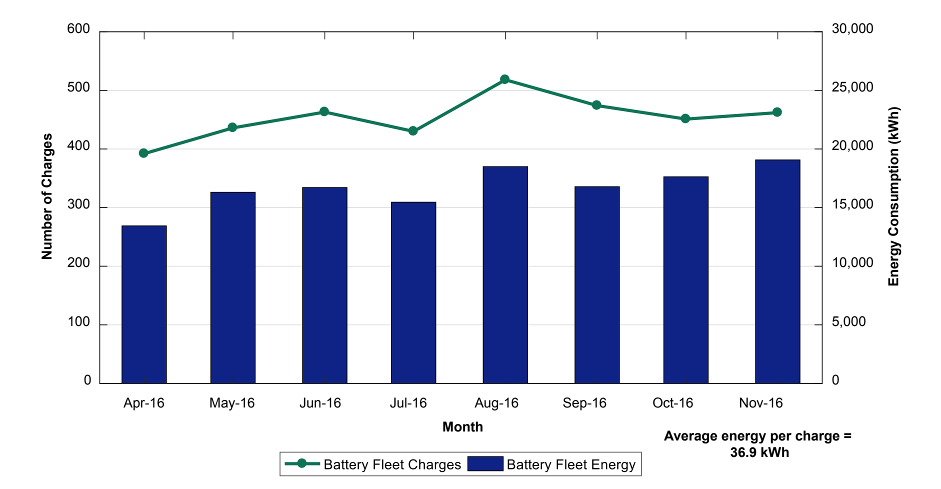
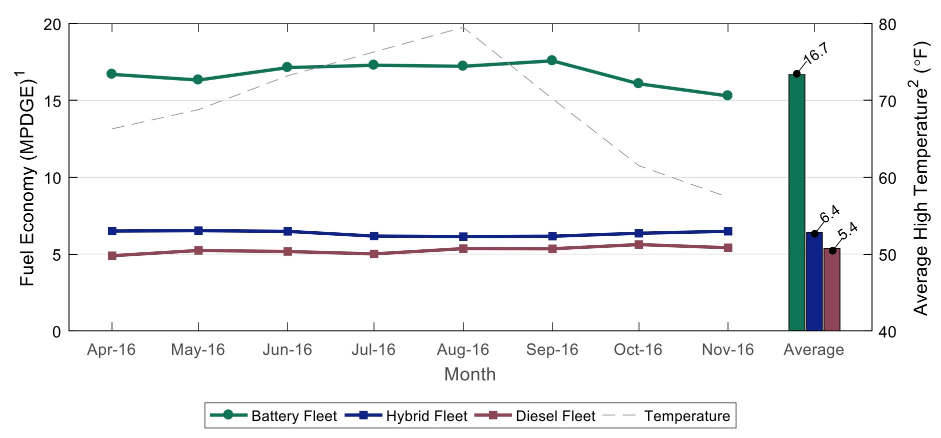


Figure 4. Monthly total energy use and number of charges for the BEB fleet



1. BEB electrical energy converted to diesel gallon equivalent (DGE); conversion factor = 37.7 kWh/diesel gallon, based on the energy content of electricity (3,412 Btu) and diesel fuel LHV (128,488 Btu).
2. Renton Municipal Airport average daily high temperatures; data acquired from: *https://www.ncdc.noaa.gov/*

Figure 5. Monthly average fuel economy for the battery electric, hybrid, and diesel buses

Energy Use and Fuel Economy

KCM is operating the BEBs on routes that pass through the Eastgate Park and Ride, and each BEB is typically charged every time it stops at that station. Figure 4 shows the total energy consumption and number of charges for the three-bus BEB fleet by month. The fleet averages 16,736 kWh and 453 charges per month, with an average charge of 36.9 kWh.

Figure 5 shows the monthly average fuel economy, in miles per diesel gallon equivalent (mpdge), for the battery electric, hybrid, and diesel buses (the trolley bus fuel economy is not included because the energy use data are not yet available). To compare the fuel economy of all the bus fleets on an energy equivalent basis, NREL converted kWh of electricity to diesel gallon equivalent using a conversion factor of 37.7 kWh/gallon based on the energy content of electricity and diesel fuel. The monthly average high temperature is included in the figure to track any seasonal variations in the fuel economy due to additional heating or cooling on the bus.

The fuel economy trends are stable over the data period. The subtle increase in fuel economy for the BEB fleet likely is due partly to the operators becoming more familiar with the new buses (better utilizing regenerative braking) and partly to the ambient temperature increase throughout the summer (less auxiliary heating). The Proterra BEBs use the battery energy for electrical auxiliary heating rather than using a diesel-fuel-fired heater. The BEB fuel economy decreases slightly in October and November as the average high temperature drops to around 60°F, indicating more heating was required. The BEBs had an overall average efficiency of 2.26 kWh per mile, which equates to 16.7 mpdge. The equivalent fuel economy of the BEBs is significantly higher than that of the hybrid buses (6.4 mpdge) and more than three times that of the standard diesel buses (5.4 mpdge).

Operation and Maintenance Costs

NREL collected all work orders for the four fleets to analyze the maintenance costs. Those for accident-related repair, which are extremely variable from bus to bus, were eliminated from the analysis. Work covered under warranty was also removed from the calculations. For consistency, the maintenance labor rate was held at a constant $50 per hour; this does not reflect an average rate for KCM. Table 3 shows the maintenance costs by vehicle system for each bus fleet. The systems with the highest percentage of maintenance costs for the battery electric and diesel buses, in order from greatest to least, were cab, body, and accessories; propulsion-related; and PM inspections. For the hybrid and trolley buses, the systems with the highest percentage of maintenance costs were propulsion-related; cab, body, and accessories; and PM inspections.

The most important comparison is the propulsion-related costs because the propulsion system is the primary difference between fleets. The propulsion-related category includes repairs for engine, fuel, exhaust, electric motors, battery modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, and transmission. The propulsion-related costs for the BEBs are much lower than that of the baseline buses. PM inspection costs include the labor for scheduled maintenance. Costs for the other systems should be similar from fleet to fleet.

NREL also analyzed data on the cost of operation for the battery electric, hybrid, and diesel buses. Operation costs include the energy cost of the buses—fuel for the hybrid and diesel buses and electricity for the battery electric and trolley buses. Figure 6 shows the monthly per-mile costs for the battery electric, hybrid, and diesel bus fleets. The stacked bars separate the costs for energy and maintenance. Although the BEBs have much better equivalent fuel economy, the electricity for the BEBs (at $0.50/mi) costs nearly twice as much, on a per-mile basis, as the diesel fuel for the hybrid and diesel buses

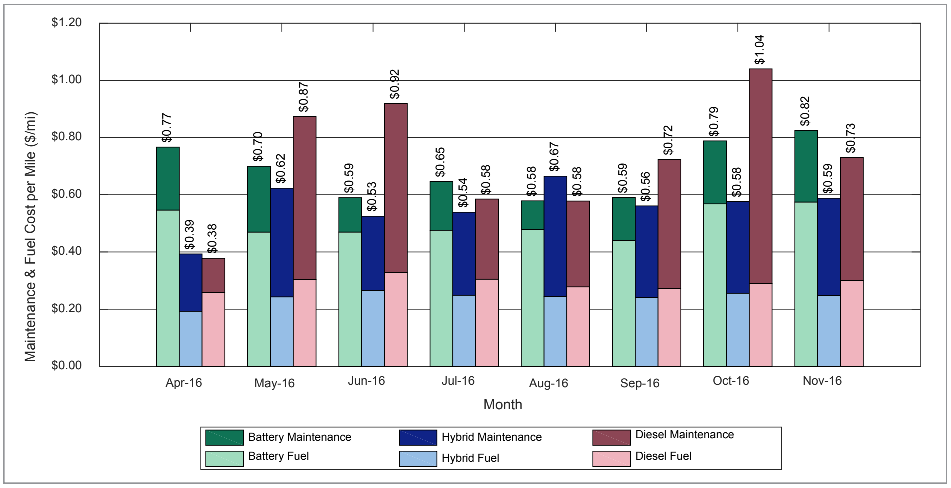


Figure 6. Monthly average fuel and maintenance cost per mile for the battery electric, hybrid, and diesel buses

(at $0.24/mi and $0.29/mi, respectively). During the evaluation period the average diesel price was $1.54/gal while the average electricity price was $0.20/kWh ($7.38/dge). KCM has very low base rates for electricity but is subject to time of use and demand charges that raise the average price per kWh. Due to this billing structure, the average energy cost per mile for the BEBs is expected to decrease as the utilization of the chargers increases, either by introducing more buses that charge at the same station or by increasing the operation time of the existing buses, or both.

The monthly per-mile maintenance costs shown in Figure 6 include scheduled and unscheduled maintenance. The BEB fleet had the lowest maintenance cost during the data period with an overall average of $0.18/mi. The maintenance cost for the hybrid and diesel bus fleets averaged $0.32/mi and $0.44/mi, respectively, over the data period. The BEBs are still under warranty and the majority of work on major systems is handled by an on-site Proterra technician. The BEB maintenance costs are expected to increase once the warranty period ends and KCM staff take over maintenance.

Future Analysis

KCM will continue operating the three BEBs, and NREL plans to continue evaluating the in-service performance of KCM's BEBs through at least one full year of operation. Future analyses will also include detailed maintenance costs for all buses in the evaluation. In 2016, KCM was awarded a grant under the second round of the FTA Low-No program to add eight more 40-foot Proterra Catalyst buses in 2017.

Table 3. Maintenance Costs by System

System	Battery Electric		Hybrid		Diesel		Trolley	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Propulsion-related	0.03	*18.5*	0.12	*36.7*	0.14	*30.8*	0.23	*43.7*
Cab, body, and accessories	0.09	*46.7*	0.12	*37.0*	0.21	*47.6*	0.19	*35.6*
PM inspections	0.02	*12.7*	0.04	*13.2*	0.03	*7.4*	0.03	*5.2*
Brakes	0.01	*5.4*	0.01	*2.0*	0.04	*9.4*	0.00	*0.5*
Frame, steering, and suspension	0.00	*0.2*	0.01	*2.2*	0.00	*0.3*	0.00	*0.9*
HVAC	0.01	*3.5*	0.01	*2.1*	0.01	*2.2*	0.06	*12.2*
Lighting	0.00	*1.9*	0.01	*1.7*	0.00	*0.5*	0.00	*0.5*
General air system repairs	0.01	*4.7*	0.01	*4.4*	0.01	*1.7*	0.01	*1.0*
Axles, wheels, and drive shaft	0.00	*0.0*	0.00	*0.0*	0.00	*0.3*	0.00	*0.3*
Tires	0.01	*6.4*	0.00	*0.8*	0.00	*0.0*	0.00	*0.2*
Total	***0.18***	*100*	***0.32***	*100*	***0.44***	*100*	***0.53***	*100*

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Prepared for FTA by the National Renewable Energy Laboratory

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