NATIONAL RENEWABLE ENERGY LABORATORY

BC Transit Fuel Cell Bus Project Evaluation Results: Second Report

L. Eudy and M. Post
National Renewable Energy Laboratory

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Technical Report
NREL/TP-5400-62317
September 2014

Contract No. DE-AC36-08GO28308

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Prepared under Task No. WW4K.1000

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Acronyms and Abbreviations

CARB	California Air Resources Board
CAD	Canadian dollar
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
FCEB	fuel cell electric bus
FCPP	fuel cell power plant
ft	feet
FTA	Federal Transit Administration
GVWR	gross vehicle weight rating
hp	horsepower
HVAC	heating, ventilation, and air conditioning
in.	inches
KBRC	kilometers between roadcall
kg	kilograms
kW	kilowatts
kWh	kilowatt hour
lb	pounds
MBRC	miles between roadcall
mi/DGE	miles per diesel gallon equivalent
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PMI	preventive maintenance inspection
psi	pounds per square inch
SI	International System of Units
USD	U.S. dollar

Definition of Terms

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.

Balance of plant: The components of the fuel cell system—such as air compressor, fans, and pumps—that support the operation of the fuel cell stack.

Fast-fill: Completion of a full fill of a hydrogen-fueled bus in 10 minutes or less.

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

- MBRC – bus: 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.
- MBRC – propulsion-related: Includes roadcalls that are attributed to the propulsion system. Propulsion-related roadcalls can be caused by issues with the power system (fuel cell), batteries, and hybrid systems.
- MBRC – fuel-cell-related: Includes roadcalls attributed to the fuel cell power plant and balance of plant 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.

Executive Summary

Beginning in 2009, British Columbia Transit (BC Transit) led a project to conduct a 5-year demonstration of 20 fuel cell electric buses (FCEB) in Whistler, Canada. The FCEB fleet was introduced during the 2010 Winter Olympic Games and operated through March 2014. The primary goals of the project were to investigate the status of the technology, to demonstrate that FCEBs could provide daily service in an urban transit operation, and to contribute to the provincial government's climate action goals. During the demonstration it was the world's largest FCEB fleet in a single location.

BC Transit collaborated with the California Air Resources Board (CARB) and the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. CARB enlisted NREL to conduct a third-party evaluation of the BC Transit fleet to aid in understanding the status of the technology in transit. CARB staff has been gathering data on zero-emission buses to assess the status of the technologies as directed by its Board during the July 2009 hearing. While the BC Transit fleet is located outside of the United States, the operation of transit fleets within Canada is similar to that of fleets in the United States. The bus is designed for the North American market, and future models could be built to meet 'Buy America' requirements for U.S. transit agencies. NREL published its first report on the demonstration in February 2014.[1] This report is an update to the previous report and covers 3 full years of revenue service data on the buses from April 2011 through March 2014.

The FCEBs are 42-foot, low-floor buses built by New Flyer with a hybrid electric propulsion system that includes a Ballard Power Systems fuel cell and Valence lithium phosphate batteries. During the demonstration, the buses were fueled at a liquid hydrogen storage and gaseous dispensing station designed, built, and maintained by Air Liquide Canada.

Table ES-1 provides a summary of the data included in this evaluation report in international (SI) and U.S. units. During the 3-year data period analyzed for the report, the FCEB fleet accumulated more than 3 million kilometers (1.88 million miles) and approximately 150,500 hours on the fuel cell power plants.[2] Also the FCEBs have an average fuel consumption of 15.67 kilograms of hydrogen per 100 kilometers. This equates to a fuel economy of 4.48 miles per diesel gallon equivalent (mi/DGE). The buses achieved an average availability of 64%. Toward the end of the planned demonstration, several buses developed durability issues with the air supply system that resulted in the agency permanently removing them from service. BC Transit decided to remove the buses from service because the repair cost and wait time for parts was not suitable considering the time left in the demonstration. If the demonstration had been scheduled for a longer time period, the agency would have repaired the buses and placed them back in service. NREL calculated an adjusted availability to account for the buses pulled from service. Overall adjusted average availability for the fleet during the third year was 71%, which is consistent with the first two years (69% for both years). The adjusted availability for the entire 3-year period is 70%.

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[1] *BC Transit Fuel Cell Bus Project: Evaluation Results Report*, NREL/TP-5400-60603, February 2014, www.nrel.gov/docs/fy14osti/60603.pdf.

[2] Hours data include time accumulated on a total of 22 fuel cell power plants; two are used as spares.

Table ES-1. Summary of Evaluation Results

Data Item	SI Units	U.S. Units
Number of buses	20	20
Data period	4/11–3/14	4/11–3/14
Number of months	36	36
Total distance traveled in period	3,026,778 km	1,880,753 mi
Average monthly distance per bus	4,204 km	2,612 mi
Total fuel cell operating hours	150,500	150,500
Availability (85% is target)	64% (70% adjusted)	
Fuel consumption/fuel economy	15.67 kg/100 km	3.97 mi/kg
Diesel equivalent fuel consumption/fuel economy	52.49 L/100 km	4.48 mi/DGE
Distance between roadcalls[3]—bus	2,393 km	1,487 mi
Distance between roadcalls—propulsion-related	3,082 km	1,915 mi
Distance between roadcalls—fuel-cell-related	14,277 km	8,871 mi
Total maintenance	$1.10 CAD/km	$1.70 USD/mi
Maintenance—propulsion only	$0.62 CAD/km	$0.97 USD/mi

From BC Transit's perspective, there have been many achievements for the demonstration, including the following:

- The project was delivered on-time and on-budget.
- The FCEBs accumulated more than 4 million kilometers (2.485 million miles) in revenue service over the 4-year demonstration and more than 201,000 fuel cell hours, operating up to 22 hours a day in temperatures ranging from -20°C to 34.7°C (-4°F to 94.5°F).
- By operating the FCEBs, the agency has avoided emitting more than 5,835 tonnes of CO_2 compared to operating diesel buses.
- The FCEBs formed the backbone of the fleet—20 of 23 buses or 26 during peak season. (During the peak winter season, three more conventional buses were added to accommodate mid-day fueling requirements for the FCEBs.)
- The FCEBs were incorporated into the fleet and were fully supported by Whistler Transit staff.
- The hydrogen station operated reliably with very few issues, none of which resulted in downtime for the buses.
- The station dispensed more than 591,594 kilograms of fuel over 23,671 fills without a safety incident.
- The FCEBs were accepted by the drivers, maintenance staff, passengers, and the local community.

[3] A roadcall is a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule.

The challenges and lessons learned from the demonstration included bus-related problems as well as programmatic issues.

Delivery schedule—The demonstration was planned to begin during the 2010 Winter Olympic Games. The agency reports that planning advanced technology bus procurements around a non-movable target increases risk. While the manufacturer team met the target, the final design was not fully optimized by the deadline. Once the buses were delivered to Whistler for regular operations, it took additional time for the manufacturers to modify the buses.

Integrator bankruptcy—Early in the demonstration, the integrator of the bus design, ISE Corporation, declared bankruptcy. As the primary system supplier for the contract, ISE was responsible for the majority of the design/build effort. The company's demise had a significant impact on the project, resulting in the remaining manufacturer partners having to take on the responsibility for supporting the demonstration.

Evolution of technology and components—As technology development for FCEBs has progressed, components and parts are being modified for new designs. While this evolution is expected, it results in parts obsolescence for current FCEBs. In some cases, replacement parts become hard to locate because manufacturers have stopped producing the older designs. In other cases, parts are not common and are costly with long lead times for delivery.

Air compressor/motor/controller—The air supply system for the fuel cell proved to be one of the biggest technical issues on the buses. These components provide a vital function for the performance and longevity of the fuel cell stack. The components were sourced and integrated into the system by the original integrator. As a result, the air supply system was not optimized and the sub-components were not as durable as expected. The lessons learned from this issue will result in improvements in future designs. Ballard reports that it will supply the air system along with the fuel cell power plant for future FCEB models.

Bus suspension—The buses had issues with the suspension because of the weight and the difficult duty cycle. Components within the suspension, such as sway bars, experienced higher wear and tear compared to similar components on conventional buses. To address the issue of early failures, Whistler Transit added these components to its parts inventory and integrated replacements into the normal preventive maintenance schedule. The issue became more prevalent over time.

BC Transit summarizes its key lessons learned for the project as follows:

1. Manage expectations for the technology and plan for needed resources. Based on early input from other demonstrations, BC Transit set high expectations for performance that the buses didn't meet at the beginning of the project.
2. Allow ample time for further development if planning an introduction around a major event where time deadlines cannot be moved. Planning the BC Transit FCEB fleet roll-out while building project support around the Olympics compressed the development time and resulted in a product that needed additional improvements after deployment.
3. Establish a project team with all stakeholders and develop clear objectives and milestones.

4. Include on-site representatives from the major original equipment manufacturers (OEMs) in the project at least for the early portion of the demonstration. This facilitates communication between the project partners as well as the transfer of technical knowledge from OEM to transit maintenance staff.
5. Make a significant commitment and understand what you are trying to achieve with demonstrating a new technology. BC Transit demonstrated a FCEB fleet that was a large percentage of the entire fleet. The agency had to be committed to make the buses work to meet service requirements.

The demonstration ended as scheduled in March 2014. BC Transit will continue to investigate new technologies that can help meet corporate goals to lower emissions. The experience with FCEBs has provided the agency with valuable insight into how best to plan and execute a demonstration project.

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Introduction

British Columbia Transit (BC Transit) has been leading a demonstration of fuel cell electric buses (FCEB) in Whistler, Canada, since early 2010. This 20-bus demonstration fleet was introduced during the 2010 Winter Olympic Games. During the demonstration, it was the world's largest FCEB fleet in a single location.

BC Transit collaborated with the California Air Resources Board (CARB) and the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. NREL has been evaluating FCEBs under funding from DOE and the U.S. Department of Transportation's Federal Transit Administration (FTA). NREL uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations. This protocol was documented in a joint evaluation plan for transit bus evaluations.[4] The objectives of these evaluations are to provide comprehensive, unbiased evaluation results of fuel cell bus development and performance compared to conventional baseline vehicles.

CARB has enlisted NREL to conduct a third-party evaluation of the BC Transit fleet. CARB staff has been gathering data on zero-emission buses (ZBuses) to assess the status of the technologies as directed by the Board during the July 2009 hearing. While the BC Transit fleet is located outside of the United States, the operation of transit fleets within Canada is similar to that of fleets in the United States. The bus is designed for the North American market, and future models could be built to meet 'Buy America' requirements for U.S. transit agencies. As part of its Fleet Rule for Transit Agencies and Zero-Emission Buses, CARB has been gathering performance data on ZBuses to assess the status of the technology and prepare recommendations to the Board on how to move forward with the purchase requirements. The analysis of BC Transit's ZBus fleet adds performance results of a large scale demonstration and helps provide a much broader picture of the status of the technology.

NREL completed a first report in February 2014 that provided detailed descriptions of the project, bus, and fueling station technology, and early experiences, and summarized the results from April 2011 through March 2013.[5] This report is an update to the first report, covering the final year of revenue service data on the buses from April 2013 through March 2014 and focusing on the final experiences and lessons learned.

BC Transit Profile

BC Transit is the provincial Crown agency responsible for coordinating and providing public transportation throughout British Columbia, Canada, with the exception of the metro Vancouver area. Headquartered in Victoria, BC Transit provides service to more than 1.5 million residents in 130 communities around the province. Whistler Transit, funded by the Resort Municipality of Whistler and BC Transit, provides service to the Whistler/Blackcomb communities of British Columbia. Figure 1 shows the service area of Whistler Transit. The fleet at Whistler consists of 23 buses (or 26 during peak season—typically late November through mid-April). During the demonstration, 20 of the buses were FCEBs and 3 were conventional diesel buses. Whistler

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[4] *Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*, NREL/MP-560-49342-1, November 2010, www.nrel.gov/hydrogen/pdfs/49342-1.pdf.
[5] *BC Transit Fuel Cell Bus Project: Evaluation Results Report*, NREL/TP-5400-60603, February 2014, www.nrel.gov/docs/fy14osti/60603.pdf.

Transit operates nine fixed routes, including a commuter service to a local community. The FCEBs were not used on the commuter route.

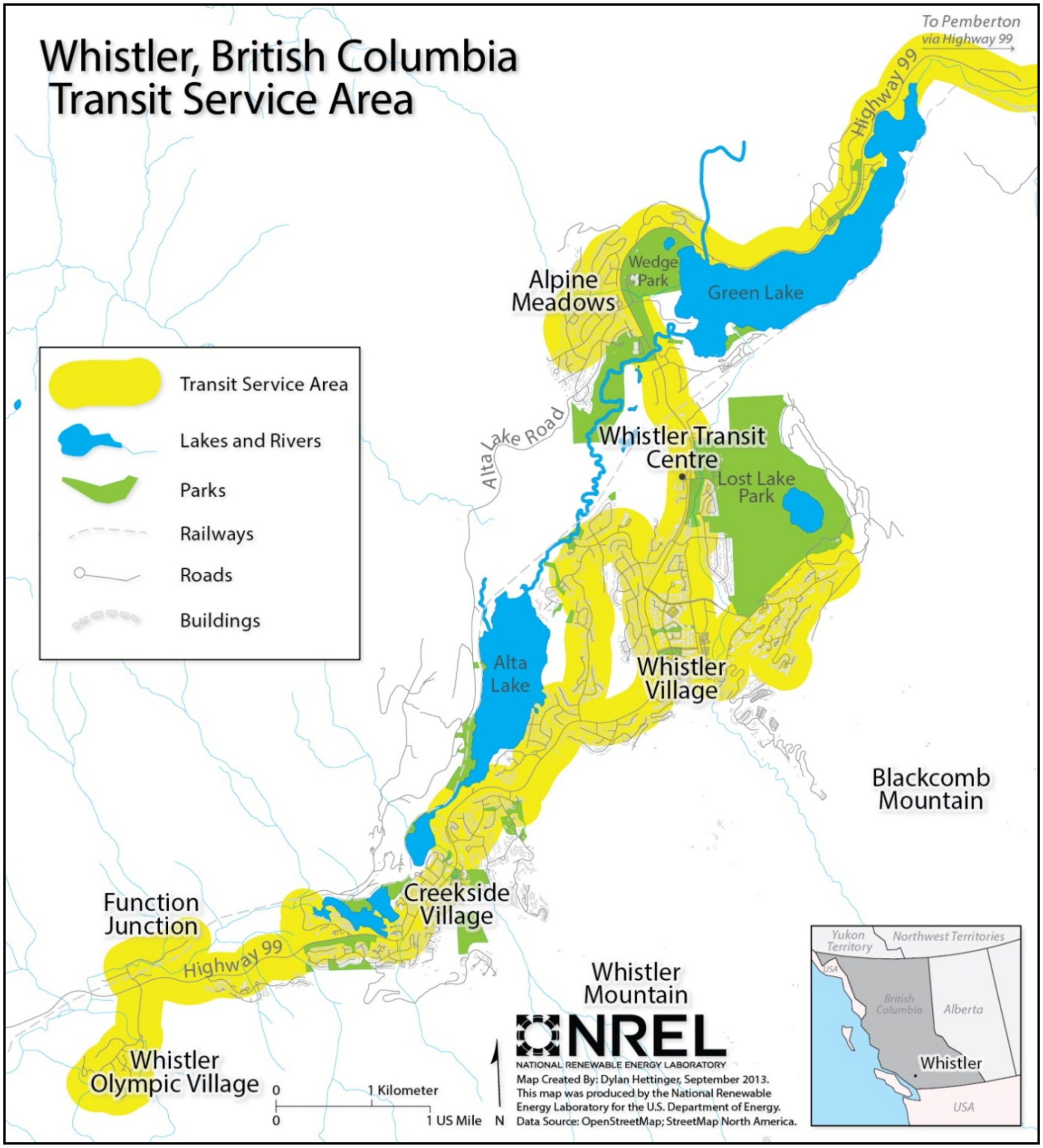

Figure 1. Map of Whistler Transit service area

Bus Technology Descriptions

The FCEBs at Whistler Transit (Figure 2) were 42-foot, low-floor buses built by New Flyer with a hybrid electric propulsion system that included a Ballard Power Systems fuel cell. Table 1 provides bus system descriptions for the BC Transit fuel cell electric buses.

Figure 2. One of Whistler Transit's fuel cell buses

Table 1. Fuel Cell Bus System Description

Vehicle System	Fuel Cell
Number of buses	20
Bus manufacturer and model	New Flyer H40LFR
Model year	2009
Length/width/height	12.5 m/2.59 m/3.35 m (42 ft/102 in./132 in.)
GVWR/curb weight	20,185 kg/15,422 kg (44,500 lb/34,000 lb)
Wheelbase	7.44 m (293 in.)
Passenger capacity	37 seats or 33 passengers with 2 wheelchair positions; 23 standees (maximum capacity 60 + 1 driver)
Fuel cell manufacturer and model	Ballard FCvelocity[6]-HD6 fuel cell power system
Rated power	Fuel cell power system: 150 kW
Hybrid type	Series, charge sustaining
Drive system	Siemens ELFA, integrated by ISE
Propulsion motor	2-AC induction, 85 kW each
Energy storage	Battery: Valence, lithium phosphate, 2 packs, 16 batteries each Rated energy: 47 kWh
Accessories	Electrical
Fuel storage	Eight roof mounted, Dynetek, type 3 tanks; 5,000 psi rated; 56 kg hydrogen (useable)
Range[7]	337–381 km (210–237 miles)
Bus purchase cost	$2.1 million each

The FCEBs have a fuel cell-dominant hybrid-electric propulsion system in a series configuration. In a series configuration, the fuel cell power system is not mechanically coupled to the drive axle. The 150 kW fuel cell power system and the 47 kWh energy storage system work together to provide power to two 85 kW electric drive motors, which are coupled to the driveline through a combining gearbox. When the bus needs extra power, the fuel cell power system and energy storage system provide power to the drive motors. When the power requirements of the bus are low, the fuel cell power system provides power and recharges the energy storage system. The hybrid system is also capable of regenerative braking, which captures the energy typically expended during braking and uses it to recharge the energy storage system.

[6] FCvelocity is a registered trademark of Ballard Power Systems.
[7] Range calculations are based on the minimum and maximum monthly average fuel economy and useful fuel.

The fuel cell power plant (FCPP), which is the primary power source for the hybrid system, is Ballard Power Systems' 150 kW FCvelocity-HD6. The energy storage system consists of two lithium phosphate battery packs from Valence. The Whistler buses required a supplemental 20 kW heater to meet winter heating demands.

FCEB Development Process—Technology Readiness Levels

NREL has developed a guideline for assessing the technology readiness level (TRL) for FCEBs.[8] Figure 3 provides a graphic representation of this process. (Appendix A provides the TRL guideline table tailored for FCEB commercialization.) The guideline considers the FCEB as a whole and does not account for differing TRLs for separate components or sub-systems. Some sub-systems may include off-the-shelf components that are considered commercial, while other sub-systems may feature newly designed components at an earlier TRL.

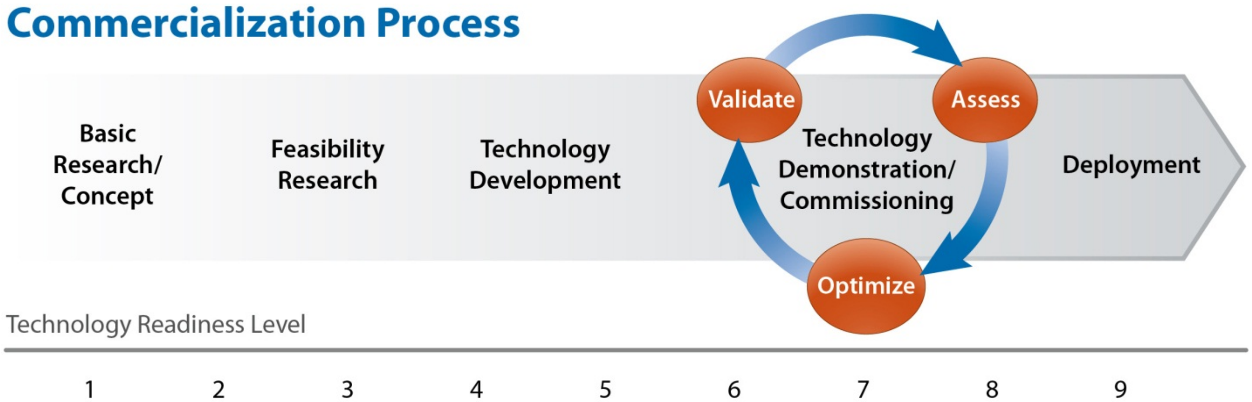

Figure 3. Graphic representation of the commercialization process for FCEBs

The technology demonstration/ commissioning phase that includes TRLs 6 through 8 begins the iterative process to validate the design, analyze the results, and reconfigure or optimize the design as needed. The manufacturer typically works with a transit agency partner to conduct in-service tests on the bus. Updates to the design are made based on the performance results, and the buses go back into demonstration and through the cycle until the design meets the performance requirements. This can be a time-consuming process as manufacturers work through technical difficulties.

NREL considers the BC Transit FCEBs to be at TRL 7 because the design of the bus was led by manufacturers experienced with FCEB development and the deployment includes the 20-bus BC Transit fleet. These buses represent a full-scale validation in a relevant environment.

Fueling Station and Maintenance Facilities

As part of the program, Air Liquide built a hydrogen station in Whistler. As part of constructing a new maintenance facility, BC Transit included upgrading the building for safe use of hydrogen-fueled buses. The station is a liquid hydrogen storage and gaseous dispensing station and is designed to fast-fill up to 20 buses per day. Figure 4 shows the station installed at the Whistler Transit Centre.

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[8] *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012*, NREL/TP-5600-56406, November 2012, http://www.nrel.gov/docs/fy13osti/56406.pdf.

Figure 4. Air Liquide hydrogen station at Whistler Transit Centre

The liquid hydrogen was trucked from Air Liquide's production facility in Becancour, Quebec. The Quebec plant produces hydrogen using renewable methods—through electrolysis of water and using a chlor alkali waste recuperation process. Power for these processes comes from the local electric grid, which is 98% hydro-electric or other renewable sources. A detailed description of the station was provided in the previous report. No significant changes were made to the station during the demonstration. Table 2 provides a summary of the station specifications.

Table 2. Summary of Hydrogen Station Specifications

Item	Description
Station type	Liquid delivery, storage, and gaseous dispensing
Hydrogen storage tanks	2 liquid tanks, 10,000 kg total storage
Pumps	3 liquid pumps, ACD Inc., 20 L/ min
Vaporizer	Thermax Inc.
Dispensing pressure	5,000 psi
High-pressure storage tanks	CP Industries, 6 tanks, 20 kg each for a total of 120 kg at 6,667 psi at 200°F[9]
Remote monitoring	Interface to review station parameters and allow control of main valves and subsystems

[9] ASME Section VIII Division I Appendix 22.

Figure 5 shows a basic schematic of the station and primary components. There were three liquid pumps, two of which were required for operation. The third pump built in redundancy to avoid station downtime.

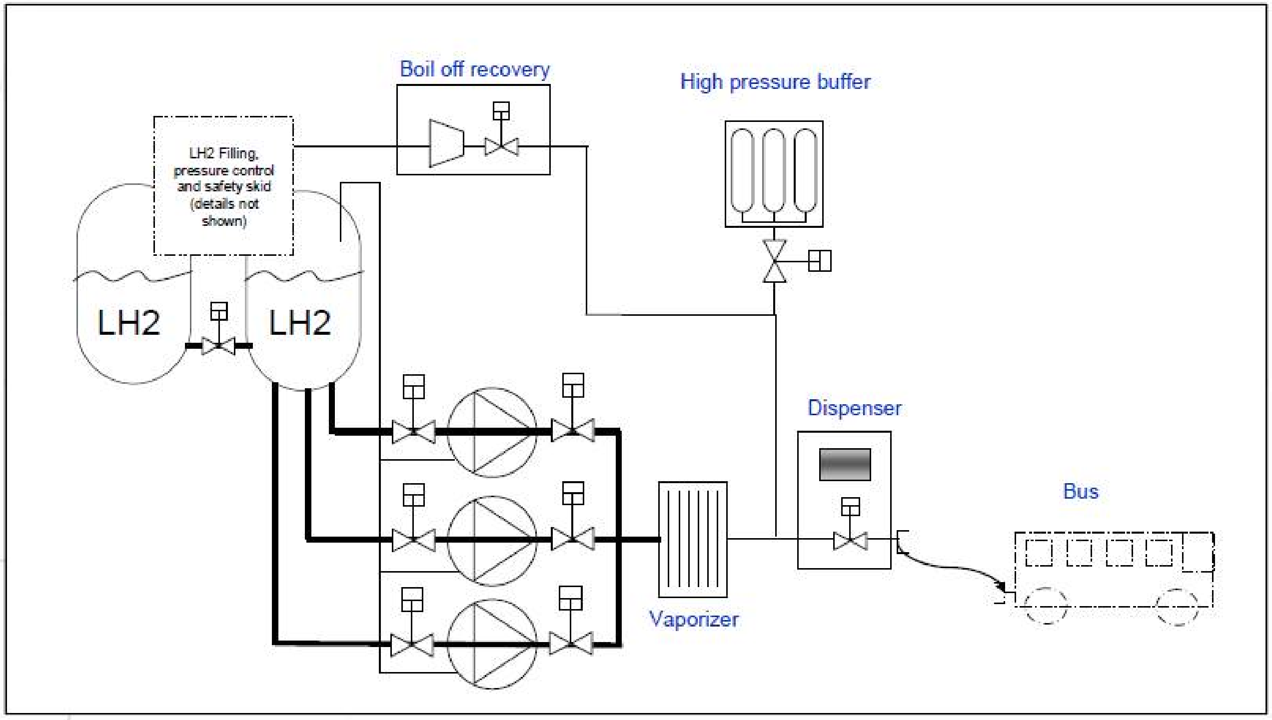

Figure 5. Block diagram of the Air Liquide station. ***Diagram courtesy of Air Liquide***

BC Transit reports that the station operated reliably throughout the demonstration. During the planning stage of the demonstration, BC Transit believed the hydrogen station would be one of the bigger challenges for the overall project. The agency's actual experience with the station was very positive. There were few issues, none of which resulted in downtime for the FCEBs. The station dispensed more than 591,594 kilograms of fuel over 23,671 fills without a safety incident.

The Whistler Transit maintenance facility was equipped for safe handling of hydrogen fueled buses. Figure 6 shows the maintenance facility, which has six bays for maintaining the buses. Figure 7 shows the interior of the facility. In addition to increased air flow and hydrogen sensors, each maintenance bay is equipped with vent lines that are connected to a bus's hydrogen system while it is parked inside. Detailed descriptions were provided in the previous report.

Figure 6. Whistler Transit maintenance facility

Figure 7. Maintenance facility. *Photo courtesy of BC Transit*

Implementation Experience

The previous report outlined BC Transit's early experience in procuring and demonstrating the FCEB fleet. For this report, the focus is on the overall experience, lessons learned, and final impressions of the technology.

Summary of the Transit Operator Experience

Moving a new technology into the commercial transit market takes education and awareness at several levels, from transit upper management to maintenance and operational staff. BC Transit and its project partners worked through the early technical issues and were successful in transitioning the required knowledge on operation and maintenance for the FCEBs to staff at Whistler Transit. This transition of knowledge from the manufacturers to the transit staff is essential to commercializing the technology. This section describes the experiences from the perspective of management, operators, and maintenance technicians for Whistler Transit.

Operator Perspective

Whistler Transit drivers felt that operating an electric drive bus was very different from operating a diesel bus. Once they completed training, they were comfortable with the operation. The drivers liked the braking and noted that the FCEBs were quiet and had a smooth ride. Drivers reported that the winter traction was exceptional on snow, but not as good when conditions were icy. One driver noted that the buses had some issues with power on specific routes. If the bus was not at the best speed when approaching certain hills, the driver had issues climbing steeper grades.

The operators experienced problems in the early stage of the demonstration when the manufacturers were working through the early technical issues. During this period, the buses had frequent breakdowns and drivers expressed concerns over stranding passengers. Over time the technical issues were addressed and the project partners developed defined procedures on how to address issues while on-route. After that, drivers could typically get to a stop-over point before calling in an issue.

Overall, the operators liked being part of the project and were very interested in the technology. One driver reported that he enjoyed educating the passengers on this zero-emission technology.

Maintenance Technician Perspective

Whistler Transit maintenance technicians were enthusiastic about the technology. They enjoyed being part of the project and working on a cutting edge technology. Learning the new systems was a welcome challenge—one mechanic relocated so that he could be involved with the project. Technicians reported that working on the buses required a heightened sense of awareness about safety because of the high voltage systems and use of compressed hydrogen gas as a fuel.

Early on in the project, the technicians had issues with troubleshooting and diagnosing the cause of failures partly because problems were intermittent. Not having the final system drawings or a complete maintenance manual contributed to the difficulties. After the first 2 years, the mechanics were comfortable with the system and were adept at making repairs. They reported an excellent working relationship with Ballard and New Flyer support staff when needing help with troubleshooting new issues.

One technician remarked that the system did not appear to be designed with maintenance in mind. Some issues were difficult and time consuming to repair because major dismantling or removal of other components was required to reach the affected part. The technician suggested that maintenance requirements should be considered carefully when new designs are being developed.

Management Perspective

Whistler Transit management reports that the FCEB project was a great learning experience and that the technology was embraced by staff even though it was new. The technical difficulties, especially during the early part of the demonstration, made the program a challenge to operate. During the first year, Ballard, New Flyer, and ISE had support staff on site in Whistler to help with troubleshooting and maintenance. They also provided training to Whistler Transit staff. By the end of 2011, the transit maintenance technicians were comfortable working on the buses and needed less on-site support. Management felt this transition went well considering the new technology was more technically advanced compared to the diesel buses the staff was used to maintaining. Maintaining the FCEBs took more technicians than was needed for an all-diesel fleet—12 mechanics for the FCEBs compared to 6 for diesel buses.

Operational issues with the buses meant the schedulers and other support staff needed to be flexible to ensure that the fleet could meet daily service requirements. Weather conditions caused issues such as cold start failures in winter and air conditioning failures in the summer. Transit staff adjusted procedures to address these problems. For example, Whistler Transit addressed the cold start issue by starting the buses earlier in the day and reallocating which buses were used for the early routes to give time to get the other buses started.

Some repairs resulted in lengthy downtimes, requiring Whistler Transit to shift buses to other routes or bring in backup buses. Many times these situations were supply-chain issues where less common parts had long lead times and were costly to replace. Management reports that they had great support from Ballard and New Flyer during the demonstration.

Management also reports a good experience with the hydrogen fueling station. The station was reliable and Air Liquide worked closely with Whistler Transit to meet operational requirements. There were no interrupted service days for the station during the demonstration.

Summary of Achievements and Challenges

This section focuses on the achievements and challenges of BC Transit and its partners in implementing operation of the FCEB fleet. As with all new technology development, there have been many lessons learned that can be used by other agencies considering FCEB technology. From BC Transit's perspective, there have been many achievements for the demonstration, including the following:

- The project was delivered on-time and on-budget.
- The FCEBs accumulated more than 4 million kilometers (2.49 million miles) in revenue service and more than 201,000 fuel cell hours, operating up to 22 hours a day in temperatures ranging from -20°C to 34.7°C (-4°F to 94.5°F).[10]

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[10] Data are the actual minimum and maximum daily temperature recorded each month during the 4-year demonstration period. Climate data from the Government of Canada web site, Whistler-Nestors weather station. http://climate.weather.gc.ca/prods_servs/cdn_climate_summary_e.html.

- By operating the FCEBs, the agency has avoided emitting more than 5,835 metric tonnes of CO_2 compared to operating diesel buses.
- The FCEBs formed the backbone of the fleet—20 of 23 buses or 26 during peak season. (During the peak winter season, three more conventional buses were added to accommodate mid-day fueling requirements for the FCEBs.)
- The FCEBs were incorporated into the fleet and were fully supported by Whistler Transit staff.
- The hydrogen station operated reliably with very few issues, none of which resulted in downtime for the buses.
- The station dispensed more than 591,590 kilograms of fuel over 23,671 fills without a safety incident.
- The FCEBs were accepted by the drivers, maintenance staff, passengers, and the local community.

The challenges and lessons learned from the demonstration included bus-related problems as well as programmatic issues. The previous report provided details on some of the bus-related issues that were experienced such as lower than expected range, suspension problems, battery balancing issues, and air handling system component failures. The remainder of this section summarizes the primary issues that affected the demonstration as a whole, beginning with the programmatic issues followed by the technical issues.

Delivery schedule—BC Transit planned for the demonstration to begin during the 2010 Winter Olympic Games. The agency reports that planning advanced technology bus procurements around a non-movable target date increases risk. While the manufacturer team met the target, the final design was not fully optimized by the deadline and there were design issues that would likely have been worked through given more time. Once the buses were delivered to Whistler for regular operations, it took additional time for the manufacturers to modify the buses. BC Transit estimates that the first year and a half of the demonstration was dedicated to addressing the issues, which took a significant number of technical staff from the manufacturers. During that time, the majority of issues were either fixed or addressed through establishing regular maintenance procedures—such as routine battery charging.

Integrator bankruptcy—Early in the demonstration, the integrator of the bus design, ISE Corporation, declared bankruptcy. As the primary manufacturer for the contract, ISE was responsible for the majority of the design/build effort. The company's demise had a significant impact on the project, resulting in the remaining manufacturer partners having to take on the responsibility for supporting the demonstration. BC Transit was not provided with a final manual on the bus design or any of the system drawings that would have helped with diagnosing and repairing issues as they developed. The controlling software for the bus systems was also developed by ISE, and the remaining manufacturer partners did not have access to the code. This situation was a major challenge for the project and was a likely cause for some of the extended downtimes for the buses.

Evolution of technology and components—As technology development for FCEBs progresses, components and parts are being modified for new designs. While this evolution is expected, it results in parts obsolescence for current FCEBs. In some cases, replacement parts become hard to locate because manufacturers have stopped producing the older designs. In other cases, parts are not common and are costly with long lead times for delivery. BC Transit had difficulty with getting replacement parts for the FCEBs during the demonstration. Obtaining replacement battery modules proved to be challenging because the manufacturer discontinued the model used in the BC Transit buses. The manufacturer's new design could not be used because it was not the same size as the original modules and had different operating characteristics.

Air compressor/motor/controller—The air supply system for the fuel cell is made up of three main components: air compressor, motor, and controller assembly. This system proved to be one of the biggest technical issues on the buses. These components provide a vital function for the health and longevity of the fuel cell stack. The components were sourced and integrated into the system by the original integrator (ISE Corporation). As a result, the air supply system was not optimized and the sub-components were not as durable as expected. The first problems were quality related due to water getting into the motor controllers. The team retrofit the systems to eliminate this failure mode during the first year of operation. The compressors then began to fail at about 1,200 to 1,500 hours because they ran low on oil. The maintenance staff did not have the information needed to understand the maintenance cycle for adding oil to the compressors and there was no easy way to tell when the oil was low. To address this issue, the compressors were upgraded to include a sight glass and port for adding oil. After that, the motors began to fail around 3,000 to 4,000 hours. Problems encountered with each component stressed the other components in the system, eventually causing them to fail also. The project partners learned a lot from this issue that will result in improvements in future designs. Ballard reports that it will supply the air supply system along with the FCPP for future FCEB models.

Bus suspension—The buses had issues with the suspension because of the weight and the difficult duty cycle. Components within the suspension, such as sway bars, experienced higher wear and tear compared to similar components on conventional buses. To address the issue of early failures, Whistler Transit added these components to its parts inventory and integrated replacements into the normal preventive maintenance schedule. The issue became more prevalent over time. Prior to June 2012, there had been no failures. Between June 2012 and April 2013 the fleet experienced four failures related to the issue. In the last year of the demonstration, a total of 10 incidents were recorded that involved cracked or broken sway bars or brackets.

Lessons Learned

BC Transit completed the 5-year FCEB demonstration project in March 2014. The agency reports that the project met its key goals, which included demonstrating FCEBs in daily service and contributing to the provincial government's climate action goals. In a letter to the president of Ballard Power Systems, the British Columbia Minister of Transportation and Infrastructure outlined the accomplishments of the program and congratulated the fuel cell manufacturer for its role in contributing to the success.[11] The project demonstrated that FCEBs could be fully integrated into a transit fleet, providing daily service in one of the most challenging environments in the province.

[11] Letter from the British Columbia Minister of Transportation to Ballard Power Systems, November 2013, available at http://www.ballard.com/files/PDF/Media/Minister_Todd_Stone_Ltr.pdf.

BC Transit and its manufacturer partners had to overcome many challenges during the demonstration. The project provided an opportunity for all partners to learn about the status of the technology and what steps are needed to move FCEBs into the next stage of commercialization. BC Transit summarizes its key lessons learned for the project as follows:

1. Manage expectations for the technology and plan for needed resources. Based on early input from other demonstrations, BC Transit set high expectations for performance that the buses didn't meet during the project (in particular operating and maintenance cost and availability).
2. Allow ample time for further development if planning an introduction around a major event where time deadlines cannot be moved. The time taken to assemble project support for the FCEB fleet to be rolled-out ahead of the Olympics impacted development time and resulted in additional product improvements being introduced after deployment.
3. Establish a project team with all stakeholders and develop clear objectives and milestones.
4. Include on-site representatives from the major original equipment manufacturers (OEMs) in the project at least for the early portion of the demonstration. This facilitates communication between the project partners as well as the transfer of technical knowledge from OEM to transit maintenance staff.
5. Make a significant commitment and understand what you are trying to achieve with demonstrating a new technology. BC Transit demonstrated an FCEB fleet that was a large percentage of the entire fleet. The agency had to be committed to make the buses work to meet service requirements.

The demonstration ended as scheduled at the end of March 2014. BC Transit will continue to investigate new technologies that can help meet corporate goals to lower emissions. The experience with FCEBs has provided the agency with valuable insight into how best to plan and execute a demonstration project.

Evaluation Results

From the time the buses were deployed in January 2010 through March 2014, the FCEBs operated more than 4 million kilometers and the FCPPs accumulated more than 201,000 hours. The results presented in this section cover 3 years of FCEB operations from April 2011 through March 2014.

FCEB Route Assignments

Whistler Transit operates the FCEB and diesel bus fleet on eight fixed routes in the Whistler/Blackcomb area. The diesel buses are used primarily as a fill-in when the FCEBs are out of service for maintenance. Because the diesel buses and FCEBs are not used in similar service, a direct comparison is not necessarily accurate—especially when comparing fuel economy. BC Transit has provided averages for diesel buses within its fleet that operate in a duty cycle more similar to that of the FCEBs. NREL has included those averages where appropriate for comparison to a baseline.

The Whistler resort area has a particularly challenging duty cycle for buses; extreme grades,[12] seasonal crush loading, cold temperatures, and wet conditions can cause high wear and tear on a transit bus.

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. This section summarizes bus usage and availability for the FCEBs during the 3-year data period.

Table 3 summarizes the average monthly distance traveled in kilometers and miles for the FCEBs for the 3-year data period. During this period, the buses traveled more than 3 million kilometers (1.8 million miles) for a monthly average per bus of 4,204 kilometers (2,612 miles).

Table 3. Average Monthly Distance Traveled (Evaluation Period)

Bus	Total Kilometers 4/11–3/12	Total Kilometers 4/12–3/13	Total Kilometers 4/13–3/14	Total Kilometers 4/11–3/14	Total Miles 4/11–3/14	Months	Average Monthly Kilometers	Average Monthly Miles
1000	45,278	45,295	12,981	103,554	64,345	36	2,877	1,787
1001	45,611	50,460	3,985	100,056	62,172	36	2,779	1,727
1002	62,080	53,887	65,162	181,129	112,548	36	5,031	3,126
1003	47,530	56,787	53,074	157,391	97,798	36	4,372	2,717
1004	57,791	56,753	23,503	138,047	85,778	36	3,835	2,383
1005	61,342	48,887	23,808	134,037	83,287	36	3,723	2,314
1006	54,749	59,526	53,089	167,364	103,995	36	4,649	2,889
1007	61,551	40,100	65,471	167,122	103,845	36	4,642	2,885
1008	47,837	54,035	53,823	155,695	96,744	36	4,325	2,687
1009	55,345	67,942	64,811	188,098	116,879	36	5,225	3,247
1010	43,375	60,652	61,764	165,791	103,018	36	4,605	2,862
1011	51,046	59,455	62,608	173,109	107,565	36	4,809	2,988
1012	48,809	60,890	33,121	142,820	88,744	36	3,967	2,465
1013	49,109	55,026	32,629	136,764	84,981	36	3,799	2,361
1014	39,454	48,927	8,424	96,805	60,152	36	2,689	1,671
1015	55,787	52,470	64,333	172,590	107,242	36	4,794	2,979
1016	48,234	47,111	62,056	157,401	97,804	36	4,372	2,717
1017	54,320	55,146	32,638	142,104	88,299	36	3,947	2,453
1018	48,561	61,906	62,095	172,562	107,225	36	4,793	2,978
1019	46,238	63,149	64,952	174,339	108,329	36	4,843	3,009
Total	**1,024,047**	**1,098,404**	**904,327**	**3,026,778**	**1,880,753**	**720**	**4,204**	**2,612**

During the final year of the demonstration, several buses developed issues that resulted in the agency permanently removing them from service. The majority of those buses had issues with the air supply system for the fuel cell (as described in the previous section). BC Transit decided to remove the buses from service because the repair cost and wait time for parts was not cost effective considering the time remaining in the demonstration. If the demonstration had been scheduled for a longer time period, the agency would have repaired the buses and placed them

[12] The maximum ascent grade for the fleet is 16.3%.

back in service. The monthly distance traveled is calculated using the total number of buses for the entire data period. As a result, the aggregate monthly distance traveled for the fleet over the last year showed a steady decrease. To account for this difference, NREL adjusted the average monthly kilometers by reducing the number of months used for the calculation as the buses were pulled from service.

Table 4 provides the adjusted numbers for each bus as well as the total for the fleet. The only year that was affected was the final year of the data period. The monthly distance traveled during the last year was 25% higher (4,710 km per month compared to 3,768 km per month) when accounting for the buses that were permanently removed from service.

Table 4. Monthly Distance Traveled Adjusted for Out of Service Buses

Bus	4/11–3/12		4/12–3/13		4/13–3/14			Adjusted Monthly km	Adjusted Monthly mi
	Total km	Average Monthly km	Total km	Average Monthly km	Total km	Months	Average Monthly km		
1000[a]	45,278	3,773	45,295	3,775	12,981	3	4,327	3,835	2,383
1001[a]	45,611	3,801	50,460	4,205	3,985	1	3,985	4,002	2,487
1002	62,080	5,173	53,887	4,491	65,162	12	5,430	5,031	3,126
1003[a]	47,530	3,961	56,787	4,732	53,074	11	4,825	4,497	2,794
1004[a]	57,791	4,816	56,753	4,729	23,503	9	2,611	4,183	2,599
1005[a]	61,342	5,112	48,887	4,074	23,808	9	2,645	4,062	2,524
1006	54,749	4,562	59,526	4,961	53,089	12	4,424	4,649	2,889
1007	61,551	5,129	40,100	3,342	65,471	12	5,456	4,642	2,885
1008	47,837	3,986	54,035	4,503	53,823	12	4,485	4,325	2,687
1009	55,345	4,612	67,942	5,662	64,811	12	5,401	5,225	3,247
1010	43,375	3,615	60,652	5,054	61,764	12	5,147	4,605	2,862
1011	51,046	4,254	59,455	4,955	62,608	12	5,217	4,809	2,988
1012[a]	48,809	4,067	60,890	5,074	33,121	9	3,680	4,328	2,689
1013[a]	49,109	4,092	55,026	4,586	32,629	9	3,625	4,144	2,575
1014[a]	39,454	3,288	48,927	4,077	8,424	2	4,212	3,723	2,314
1015	55,787	4,649	52,470	4,373	64,333	12	5,361	4,794	2,979
1016	48,234	4,020	47,111	3,926	62,056	12	5,171	4,372	2,717
1017[a]	54,320	4,527	55,146	4,596	32,638	7	4,663	4,584	2,848
1018	48,561	4,047	61,906	5,159	62,095	12	5,175	4,793	2,978
1019	46,238	3,853	63,149	5,262	64,952	12	5,413	4,843	3,009
Total	**1,024,047**	**4,267**	**1,098,404**	**4,577**	**904,327**	**192**	**4,710**	**4,504**	**2,799**

[a] Buses removed from service prior to the end of the demonstration period.

Figure 8 charts the average distance traveled by month for the fleet in kilometers and miles. The general target of 3,000 miles per month is included as a line on the chart (the target of 3,000 miles per month is a general target for U.S transit buses and does not reflect a goal for BC Transit). The figure clearly shows the seasonal nature of the service in Whistler, with the highest monthly distance traveled during the winter months and the lower averages during the summer months. During peak season, the fleet's average monthly mileage exceeds the target. The green portion of the bars in the final year of service shows the adjusted monthly distance traveled when accounting for the buses that were permanently removed from service. This shows that the remaining buses continued to operate similar to the previous 2 years of service.

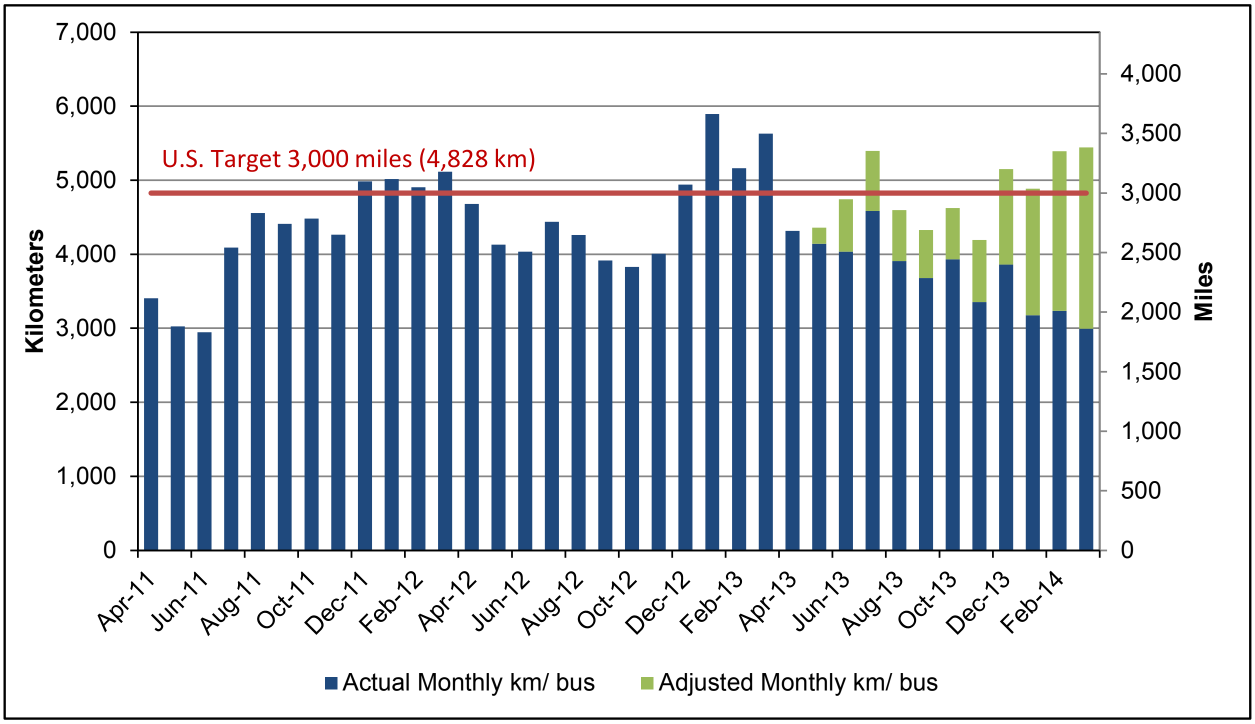

Figure 8. Average distance traveled by month

Another measure of reliability is availability—the number of days the buses are actually available for service compared to days that the buses are planned for operation. For the BC Transit FCEB fleet, the buses are planned to operate every day, including weekends. To calculate daily availability, NREL used the daily bus allocation sheets provided by Whistler Transit. These daily allocation sheets provide a history of which buses were scheduled for service, which buses were available as spares, and which buses failed in service (roadcall). Because the daily allocation sheets have been filed as paper records, not all of the sheets were available for analysis. Whistler Transit provided approximately 76% of the daily allocation sheets, which is considered to be a sufficient sample size to be representative of the total.

The data presented are based on availability for morning pull-out and don't necessarily reflect all-day availability. Figure 9 shows the monthly availability for the FCEBs during the entire 3-year period. The target of 85% is included as a dashed line. Average monthly availability ranged from a low of 38% up to a high of 80%. The overall average availability for the period was 64%. Overall availability for each bus varied from 38% up to 77%. As the agency removed buses from service in the final year of the demonstration (due to unavailability of parts), the overall fleet availability decreased. The red diamonds on the figure indicate each time a bus was removed from service. The light green line traces the availability of the remaining buses in service, showing a similar pattern as the rest of the demonstration. By the end of the data period a total of 13 buses were pulled from service. Four of the buses were pulled in the last week of March. Because they were operated the majority of that month, they were not removed from the adjusted calculations. Overall adjusted average availability for the fleet during the third year was 71%, which is consistent with the first two years (69% for both years). The adjusted availability for the entire 3-year period was 70%.

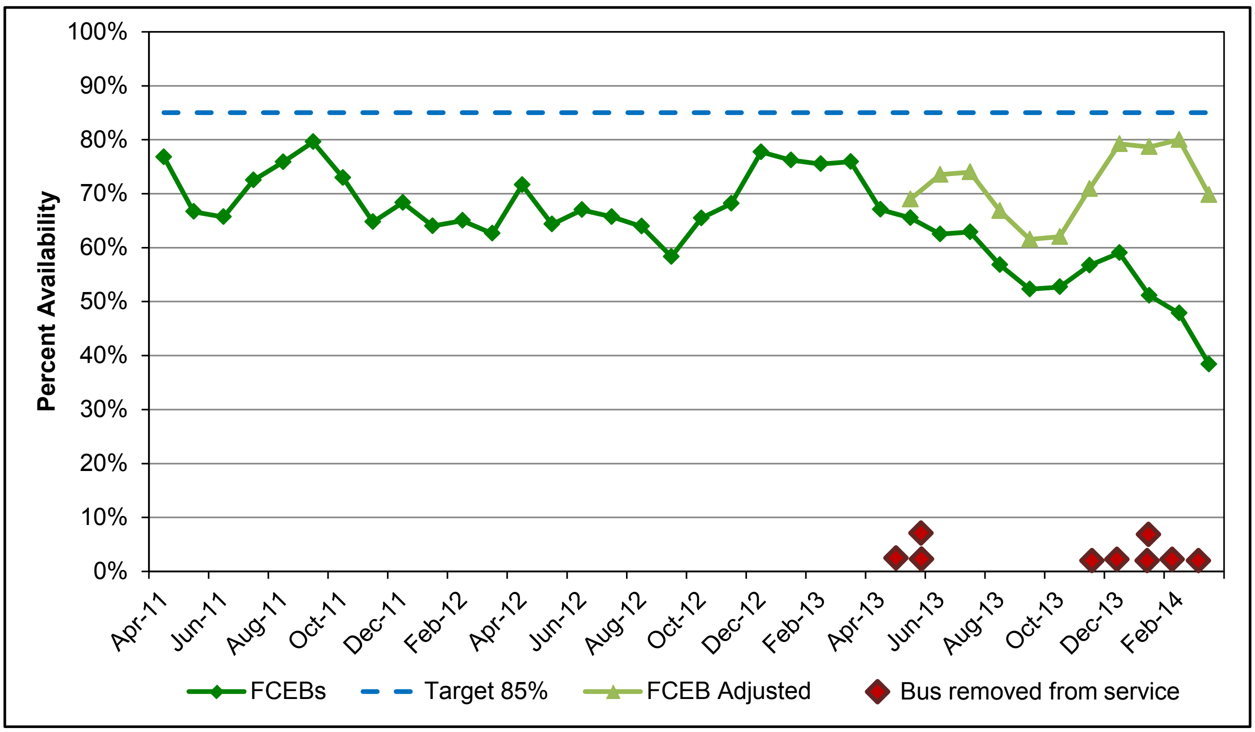

Figure 9. Average monthly availability for the FCEBs

The daily bus allocation sheets track available buses but do not indicate the reasons why a bus is not available. Because of this, a categorization of unavailability reasons is not possible. NREL has included a breakdown of labor hours by category later in the analysis to indicate the systems that are causing downtime.

Fuel Cell Power Plant Hours

The FTA minimum life cycle requirement for a full-size bus is 12 years or 500,000 miles.[13] An FCPP needs to last about half of that time; this is similar to a diesel engine that is typically rebuilt at about mid-life of the bus. DOE/FTA set an ultimate performance target of 4–6 years (or 25,000 hours) durability for the fuel cell propulsion system, with an interim target of 18,000 hours by 2016.[14] Figure 10 graphs the final accumulated hours on each of the 22 FCPPs (20 bus FCPPs plus two spares) during the demonstration. The spare fuel cell modules were swapped out as needed to minimize downtime for the fleet when FCPP maintenance was required. During the entire 4-year demonstration period, the FCPPs accumulated significant hours—a total of more than 201,000 hours for the fleet with an average of 9,178 hours. The hours on the separate FCPPs ranged from low of 6,759 to a high of 11,302 hours. All but two of the FCPPs (91%) achieved more than 8,000 hours. This is a significant accomplishment toward meeting DOE/FTA targets. According to Ballard, none of these 22 FCPPs have reached the end of life based on voltage degradation or leakage criteria.

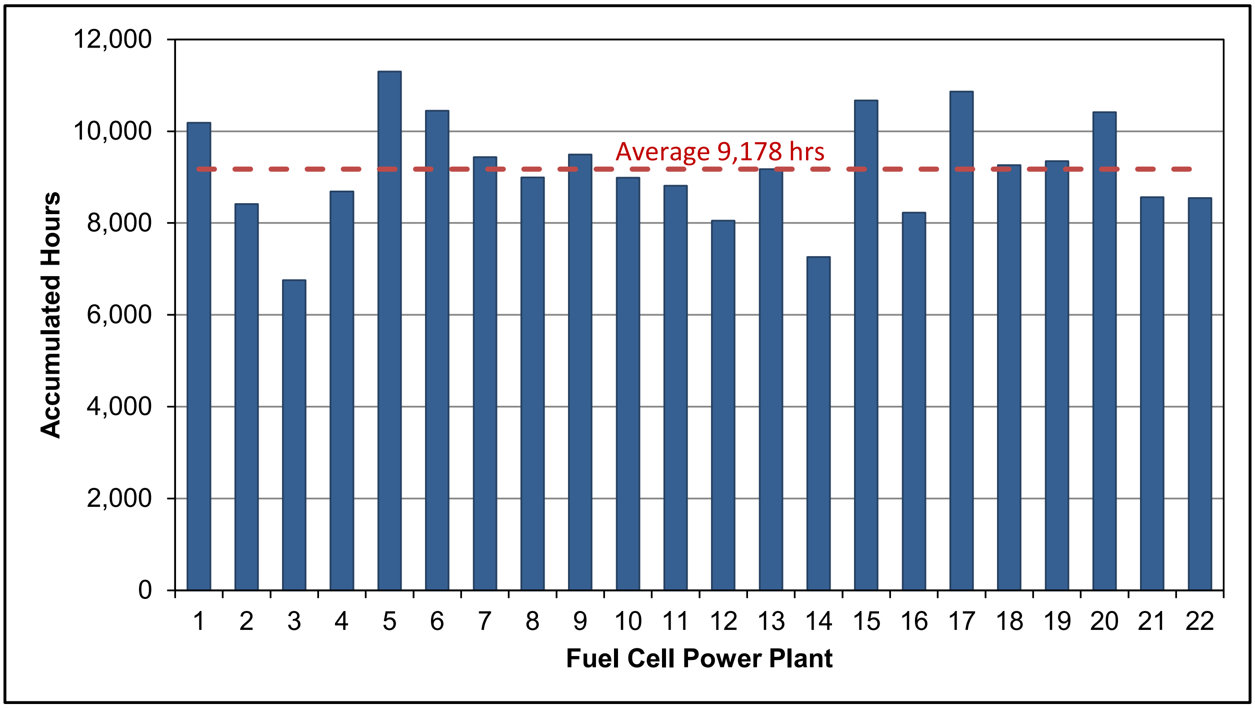

Figure 10. Accumulated FCPP hours

Fuel Consumption, Fuel Economy, and Cost

BC Transit provided individual fueling records for all of the buses during the data period. NREL analyzed these records to determine fuel consumption for each bus and the fleet as a whole. BC Transit tracks fuel consumption as kilograms per 100 kilometers (kg/100 km). To compare the

[13] FTA Circular 5010.1D: Grant Management Requirements, page IV-17, http://www.fta.dot.gov/legislation_law/12349_8640.html.
[14] Fuel Cell Technologies Program Record # 12012, September 12, 2012, http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf.

FCEB fleet to conventional diesel buses, NREL also calculated fuel consumption in liters per 100 kilometers. BC Transit reports that its diesel buses operating in similar service to the FCEBs in Whistler have an average fuel consumption of 55 L/100 km. Table 5 provides the calculated fuel consumption for each bus and the fleet as a whole in both units. For comparison to the FCEBs in the United States, the table also includes fuel economy in miles per kilogram and miles per diesel gallon equivalent (mi/DGE).

Table 5. Fuel Consumption and Fuel Economy (Evaluation Period)

Bus	Kilograms per 100 km	Liters per 100 km	Miles per kg	Miles per DGE
1000	16.59	55.58	3.74	4.23
1001	15.62	52.33	3.98	4.49
1002	16.19	54.23	3.84	4.34
1003	15.81	52.96	3.93	4.44
1004	15.19	50.89	4.09	4.62
1005	15.26	51.10	4.07	4.60
1006	16.33	54.69	3.81	4.30
1007	15.44	51.70	4.03	4.55
1008	14.95	50.08	4.16	4.70
1009	15.90	53.27	3.91	4.41
1010	15.23	51.03	4.08	4.61
1011	15.25	51.07	4.08	4.61
1012	15.47	51.83	4.02	4.54
1013	15.75	52.74	3.95	4.46
1014	14.99	50.21	4.15	4.68
1015	15.40	51.58	4.04	4.56
1016	16.74	56.08	3.71	4.19
1017	15.66	52.44	3.97	4.49
1018	16.12	53.99	3.85	4.36
1019	15.28	51.19	4.07	4.59
Total	**15.67**	**52.49**	**3.97**	**4.48**
Diesel comparison		**55.00**		**4.28**

Figure 11 shows the monthly fuel consumption for the fleet in kilograms per 100 kilometers. Each year of the 3-year data period is presented as a separate line on the chart. The monthly mean ambient temperature for each year is included on the graph to show the seasonal variation. This seasonal variation results in a swing for fuel consumption from a low of around 12.6 kg/100 km in the summer months up to a high of 17.8 kg/100 km during the winter. The average fuel consumption during the entire period is 15.7 kg/100 km. (For a U.S. comparison, the fuel economy varies seasonally from a low of 4.2 mi/DGE up to 4.7 mi/DGE. The overall fleet average is 4.48 mi/DGE.) Figure 10 clearly shows the correlation between temperature and fuel consumption. This is primarily a function of the energy use of the heating system, which was not optimally designed for the Whistler environment.

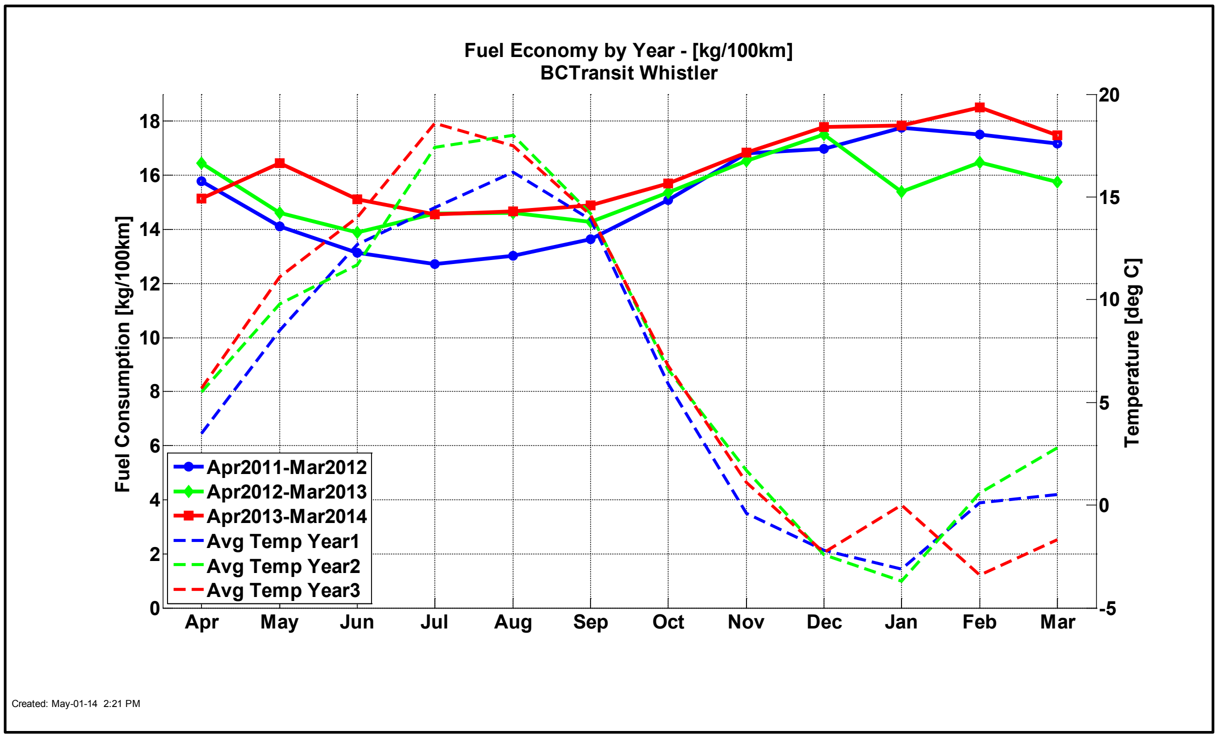

Figure 11. Fuel consumption for the FCEBs in kilograms per 100 kilometers

Figure 12 presents the same information in diesel equivalent liters per 100 kilometers. For comparison, the average diesel fuel consumption of 55 L/100 km is included as a black line on the chart. The FCEBs have fuel consumption that is 4.8% less than that of the diesel buses. Figure 13 presents the fuel economy in miles per diesel gallon equivalent.

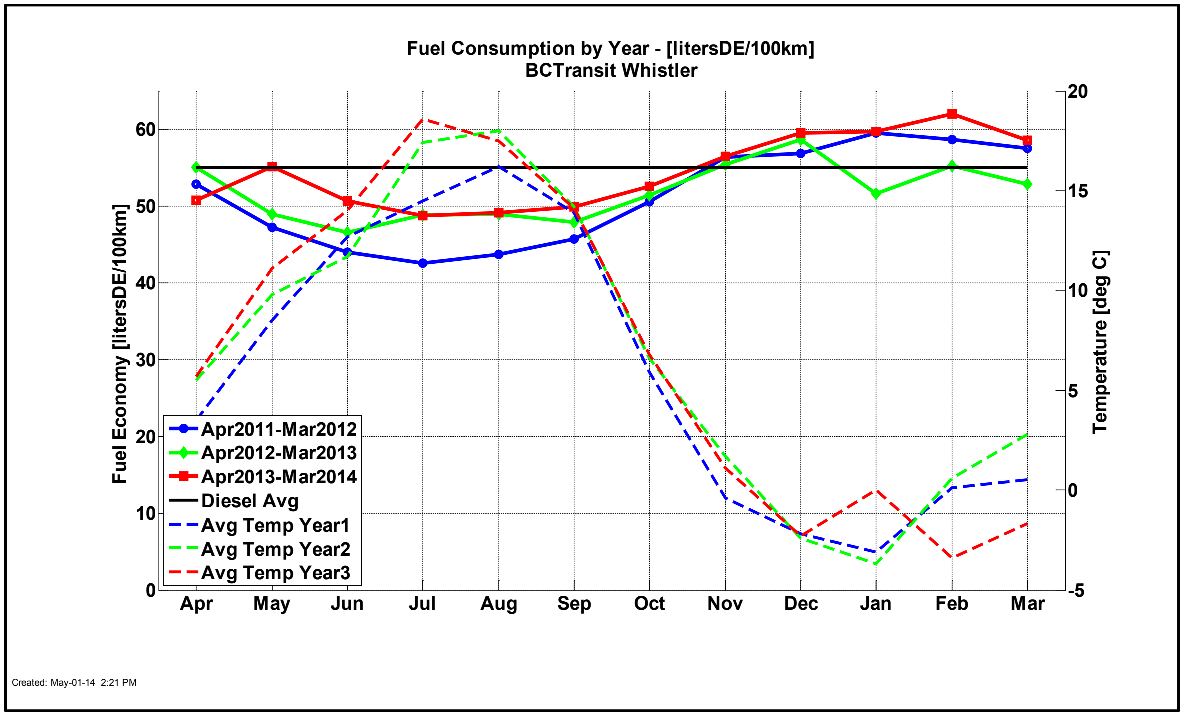

Figure 12. Fuel consumption for the FCEBs in liters per 100 kilometers

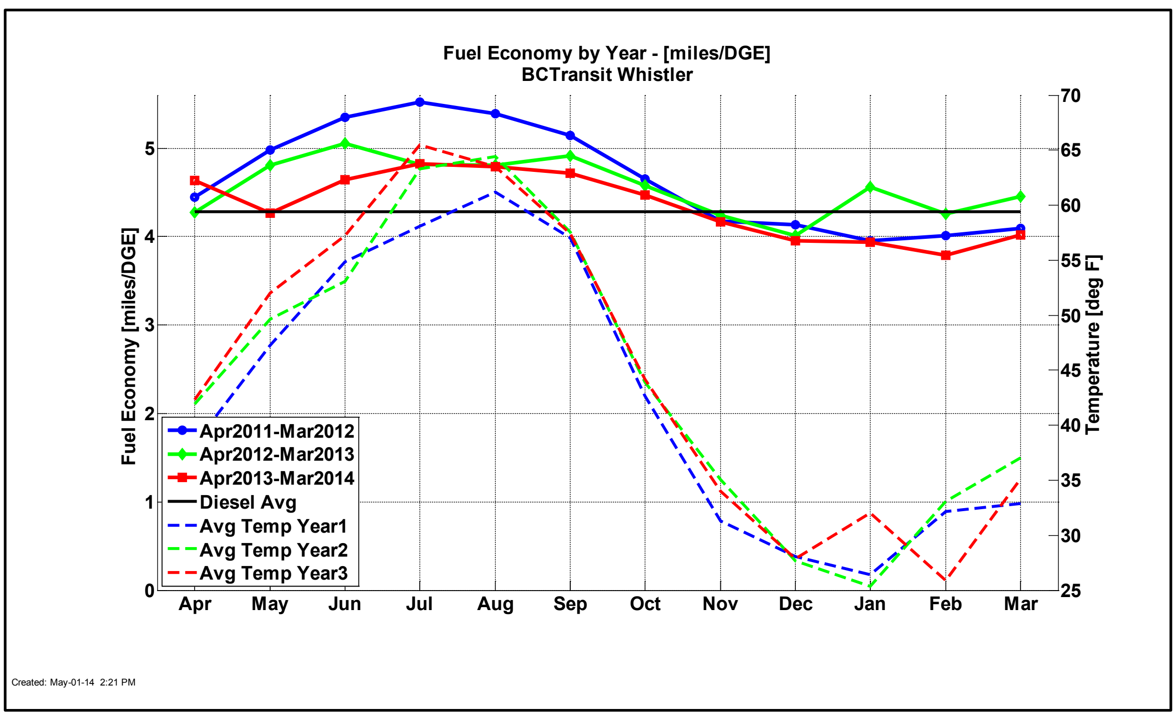

Figure 13. Fuel economy for the FCEBs in miles per diesel gallon equivalent

BC Transit paid a fixed monthly fee for hydrogen that was based on an estimated usage of 460 kg per day. The actual cost per kilogram varied depending on how much hydrogen was used each month. The average cost of dispensed hydrogen was $10.55 per kg. This does not include any capital or other costs that were paid by BC Transit at the beginning of the project. Based on $10.55 per kg, the hydrogen fuel cost per kilometer is $1.65 CAD ($2.66 USD per mile).

Maintenance Analysis

All work orders for the study buses were collected and analyzed for this evaluation. The maintenance labor costs are the actual costs for BC Transit. Labor hours reported are for Whistler Transit staff only—any labor hours by the manufacturers are not captured in the work orders and therefore are not included in the data analysis. It should be emphasized that the FCEBs were under warranty until February 2013. This section first covers total maintenance costs and then maintenance costs by bus system.

Total Maintenance Costs

Total maintenance costs include the price of parts and labor rates for BC Transit. The labor hours are listed in the tables and can be used by other agencies to estimate the cost for their specific labor rates. Table 6 shows total maintenance costs for the fuel cell buses in cost per kilometer, $1.10, and cost per mile, $1.70. This is the cost for the entire 3-year data period. Scheduled and unscheduled maintenance costs are provided in Table 7. BC Transit reports that the average maintenance cost for diesel buses in similar service is $0.65 CAD per kilometer ($1.01 USD per mile). Using this for comparison, the FCEBs in this demonstration have a total maintenance cost that is 68% higher than that of diesel buses.

Table 6. Total Maintenance Costs (Evaluation Period)

Bus	Kilometers	Parts ($)	Labor Hours	Total Cost per Kilometer (CAD)	Miles	Total Cost per Mile (USD)
1000	103,554	25,421.94	1,809.5	1.26	64,345	1.96
1001	100,056	26,091.03	1,907.4	1.36	62,172	2.11
1002	181,129	34,919.79	2,548.0	1.01	112,548	1.57
1003	157,391	32,666.41	2,614.1	1.22	97,798	1.90
1004	138,047	31,633.97	2,007.2	1.11	85,778	1.73
1005	134,037	35,007.64	2,175.2	1.19	83,287	1.85
1006	167,364	30,999.18	2,366.6	1.04	103,995	1.62
1007	167,122	39,222.54	2,372.2	1.10	103,845	1.72
1008	155,695	30,643.31	2,950.8	1.23	96,744	1.91
1009	188,098	41,646.23	2,626.8	1.03	116,879	1.61
1010	165,791	30,681.93	2,824.2	1.18	103,018	1.83
1011	173,109	24,020.96	2,347.9	0.96	107,565	1.49
1012	142,820	21,503.22	2,171.7	1.01	88,744	1.58
1013	136,764	19,579.77	2,303.5	1.08	84,981	1.69
1014	96,805	43,832.62	1,961.2	1.60	60,152	2.50
1015	172,590	26,648.15	2,235.9	0.94	107,242	1.46
1016	157,401	40,572.50	2,451.9	1.16	97,804	1.80
1017	142,104	20,011.97	1,988.1	0.99	88,299	1.54
1018	172,562	29,759.87	2,517.3	1.01	107,225	1.57
1019	174,339	25,187.69	2,089.7	0.86	108,329	1.34
Total	**3,026,778**	**610,050.70**	**46,269.2**	**1.10**	**1,880,753**	**1.70**

Table 7. Scheduled and Unscheduled Maintenance Costs (Evaluation Period)

Bus	Kilometers	Scheduled Cost per Kilometer (CAD)	Unscheduled Cost per Kilometer (CAD)	Miles	Scheduled Cost per Mile (USD)	Unscheduled Cost per Mile (USD)
1000	103,554	0.21	1.05	64,345	0.33	1.64
1001	100,056	0.25	1.11	62,172	0.38	1.73
1002	181,129	0.19	0.82	112,548	0.29	1.27
1003	157,391	0.20	1.02	97,798	0.32	1.58
1004	138,047	0.22	0.89	85,778	0.34	1.38
1005	134,037	0.20	0.99	83,287	0.31	1.54
1006	167,364	0.19	0.85	103,995	0.29	1.33
1007	167,122	0.21	0.89	103,845	0.32	1.39
1008	155,695	0.20	1.02	96,744	0.32	1.59
1009	188,098	0.18	0.86	116,879	0.27	1.33
1010	165,791	0.19	0.99	103,018	0.29	1.54
1011	173,109	0.18	0.77	107,565	0.28	1.21
1012	142,820	0.20	0.82	88,744	0.31	1.27
1013	136,764	0.21	0.87	84,981	0.33	1.36
1014	96,805	0.20	1.40	60,152	0.32	2.18
1015	172,590	0.19	0.75	107,242	0.29	1.17
1016	157,401	0.18	0.98	97,804	0.28	1.52
1017	142,104	0.21	0.77	88,299	0.33	1.20
1018	172,562	0.19	0.82	107,225	0.30	1.27
1019	174,339	0.19	0.67	108,329	0.30	1.04
Total	**3,026,778**	**0.20**	**0.90**	**1,880,753**	**0.31**	**1.40**

Figure 14 shows the monthly scheduled and unscheduled maintenance cost (CAD) per kilometer for the FCEBs during the data period. Figure 15 presents the same data in cost (USD) per mile. For comparison, the dashed red line provides the average maintenance cost for BC Transit diesel buses in similar service. The data show an increase in cost once the buses went out of warranty in February 2013. In October 2013 costs began to drop, primarily because there were fewer buses in service. The dotted black line on each graph shows the number of buses in service by month.

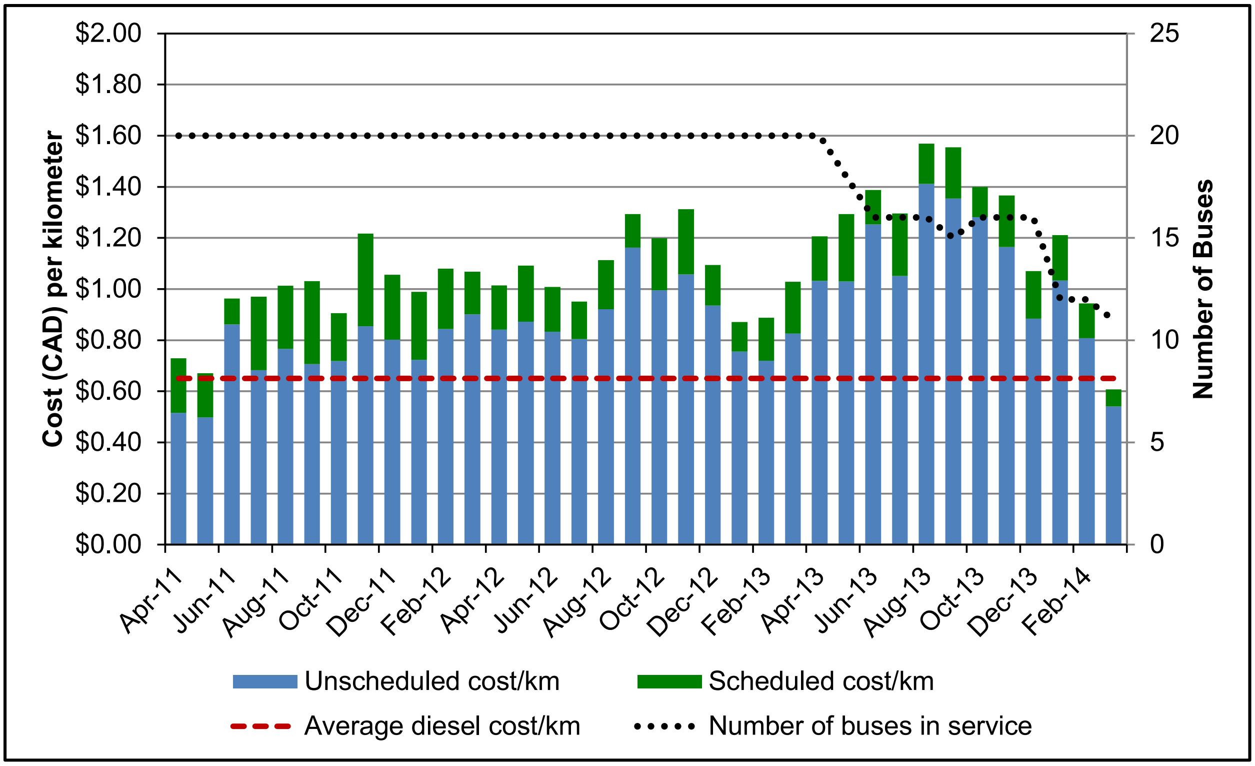

Figure 14. Monthly scheduled and unscheduled costs (CAD) per kilometer for the FCEBs

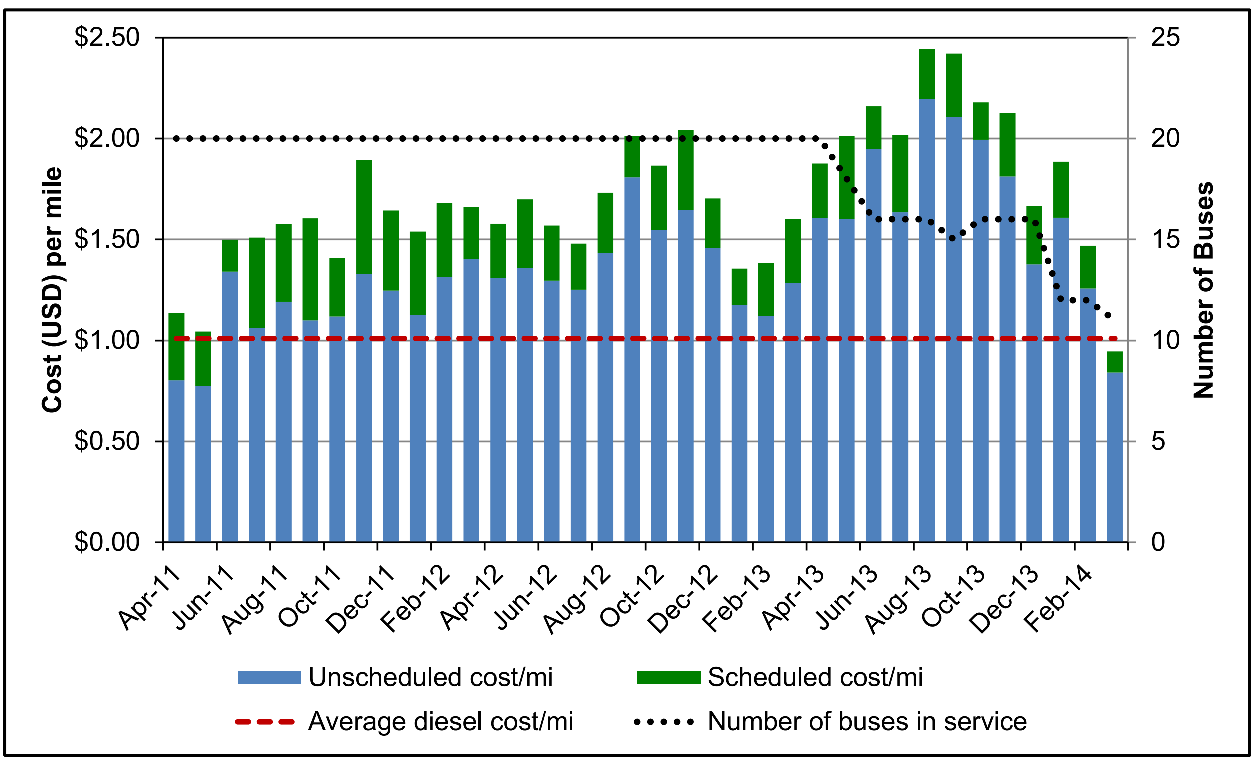

Figure 15. Monthly scheduled and unscheduled costs (USD) per mile for the FCEBs

Maintenance Costs Categorized by System

Table 8 shows maintenance costs itemized by vehicle system (without warranty costs). The vehicle systems shown in the table are as follows:

- **Cab, body, and accessories**—Includes body, glass, and paint repairs following accidents; cab and sheet metal repairs on seats and doors; and accessory repairs such as hubodometers and radios
- **Propulsion-related systems**—Repairs for exhaust, fuel, engine, electric motors, fuel cell modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, and transmission
- **Preventive maintenance inspections (PMI)**—Labor for inspections during preventive maintenance
- **Brakes**
- **Frame, steering, and suspension**
- **Heating, ventilation, and air conditioning (HVAC)**
- **Lighting**
- **Air system, general**
- **Axles, wheels, and drive shaft**
- **Tires.**

Table 8. Maintenance Cost by System (Evaluation Period)

System	Cost per Kilometer (CAD)	Cost per Mile (USD)	Percent of Total (%)
Cab, body, and accessories	0.14	0.22	13.0
Propulsion-related	0.62	0.97	56.9
PMI	0.12	0.19	11.0
Brakes	0.04	0.06	3.4
Frame, steering, and suspension	0.06	0.09	5.3
HVAC	0.04	0.06	3.5
Lighting	0.02	0.02	1.5
Air system, general	0.00	0.01	0.4
Axles, wheels, and drive shaft	0.02	0.04	2.2
Tires	0.03	0.05	2.9
Total	***1.10***	***1.70***	***100***

The propulsion system had the highest percentage of maintenance costs for the FCEBs at around 57% of the total costs. Cab, body, and accessories had approximately 13% of the total, and PMI had 11% of the maintenance costs. Figure 16 charts the monthly labor hours by system and clearly shows that throughout the data period the majority of labor was for the propulsion system.

Tracking the total labor hours by month shows some interesting trends. Transit service at Whistler is seasonal, with the highest level of service needed in winter. Because of this, the labor hours are typically lower in the summer when fewer buses are needed to meet service requirements. Labor hours are much higher for the first winter shown on the graph. During the winter of 2011, Whistler Transit staff was still learning how to troubleshoot and repair the FCEBs. Labor hours during the 2012 winter season were much lower and consistent from month to month. This indicates maintenance staff was well trained and comfortable with working on the technology. As the fleet began experiencing recurring issues with the air system, labor hours rose and then sharply dropped as buses were pulled permanently out of service.

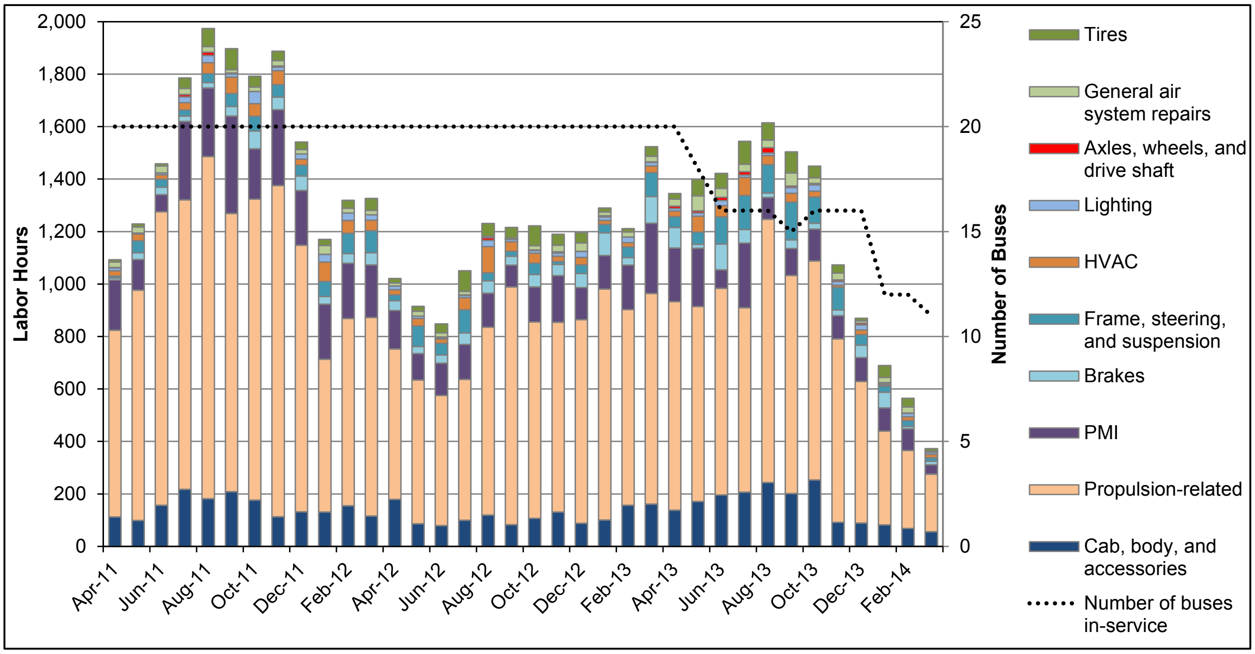

Figure 16. Monthly labor hours by maintenance category

Propulsion-Related Maintenance Costs

Propulsion-related vehicle systems include the exhaust, fuel, power plant, electric propulsion system components, air intake, cooling, non-lighting electrical, and transmission systems. These systems have been separated to highlight the maintenance costs most directly affected by the advanced propulsion system changes for the buses.

Table 9 shows the propulsion-related system repairs by category for the FCEBs during the reporting period in CAD per kilometer and USD per mile. The first section of the table shows the total for all categories within the propulsion system. The cooling system and compressor are part of the fuel cell balance of plant but have been separated out in the table. The labor costs for the battery charging have also been separated out to give an indication of the added time needed for this activity. The three categories with the highest repair cost were electric motor and propulsion repairs; power plant system repairs; and cooling system repairs. Figure 17 shows the monthly labor costs for the propulsion system by category.

Table 9. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Kilometers / CAD	Miles / USD
Distance traveled	3,026,778	1,880,753
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	337,978.93	326,825.62
Labor hours	27,918.2	27,918.2
Total cost ($)	1,886,163.90	1,823,920.49
Total cost ($) per unit distance	**0.62**	**0.97**
Fuel System Repairs		
Parts cost ($)	53,263.08	51,505.40
Labor hours	2,123.8	2,123.8
Total cost ($)	173,648.90	167,918.49
Total cost ($) per unit distance	**0.06**	**0.09**
Power Plant System Repairs (fuel cell system)		
Parts cost ($)	25,647.74	24,801.37
Labor hours	6,060.2	6,060.2
Total cost ($)	366,857.58	354,751.28
Total cost ($) per unit distance	**0.12**	**0.19**
Electric Motor and Propulsion Repairs		
Parts cost ($)	45,764.69	44,254.46
Labor hours	8,681.3	8,681.3
Total cost ($)	507,351.29	490,608.70
Total cost ($) per unit distance	**0.17**	**0.26**
Compressor Repairs		
Parts cost ($)	1,656.54	1,601.87
Labor hours	1,656.5	1,656.5
Total cost ($)	93,533.28	90,446.68
Total cost ($) per unit distance	**0.03**	**0.05**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	71,656.50	69,291.84
Labor hours	2,749.6	2,749.6
Total cost ($)	203,422.38	196,709.44
Total cost ($) per unit distance	**0.07**	**0.10**
Air Intake System Repairs		
Parts cost ($)	46,921.90	45,373.48
Labor hours	35.0	35.0
Total cost ($)	49,057.12	47,438.24
Total cost ($) per unit distance	**0.02**	**0.03**
Cooling System Repairs		
Parts cost ($)	92,922.57	89,856.12
Labor hours	3,641.3	3,641.3
Total cost ($)	307,387.91	297,244.11
Total cost ($) per unit distance	**0.10**	**0.16**
Battery Charging		
Parts cost ($)	0.00	0.00
Labor hours	2,970.5	2,970.5
Total cost ($)	182,785.57	176,753.65
Total cost ($) per unit distance	**0.06**	**0.09**

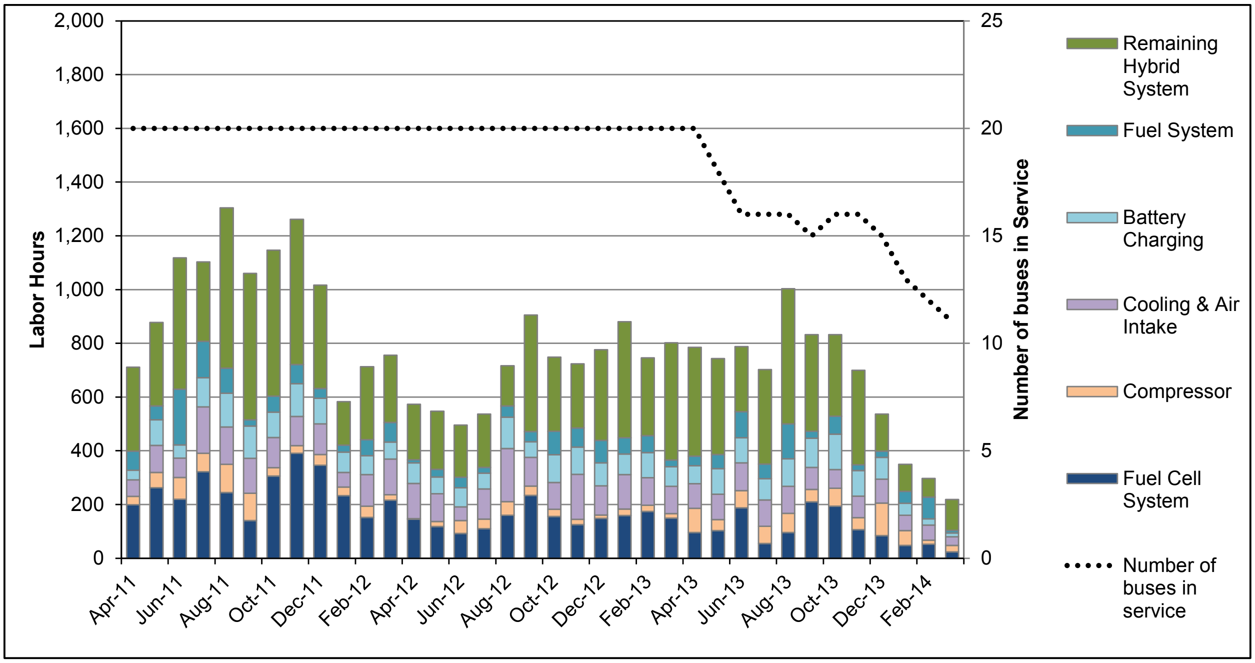

Figure 17. Monthly propulsion-related labor hours by category

Roadcall Analysis

A roadcall or revenue vehicle system failure (as named in the National Transit Database[15]) 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 or destination signs.

Table 10 shows the mean distance between roadcall for the FCEBs categorized by total bus roadcalls, propulsion-related roadcalls, and fuel-cell-related roadcalls. The results are presented in kilometers as well as miles. Figure 18 presents these data graphically, charting the cumulative mean distance between roadcall for each category. BC Transit's target of 5,000 kilometers between roadcall is included in the chart (orange dashed line). In the United States, DOE and FTA have set targets for miles between roadcall (MBRC) for FCEBs. These are also included on the graph for comparison.

[15] National Transit Database website: www.ntdprogram.gov/ntdprogram/.

Table 10. Roadcalls and Mean Distance Between Roadcall (Evaluation Period)

	Kilometers	Miles
Mileage	3,026,778	1,880,753
All roadcalls	1,265	1,265
Bus mean distance between roadcall	2,393	1,487
Propulsion-related roadcalls	982	982
Propulsion mean distance between roadcall	3,082	1,915
Fuel-cell-related roadcalls	212	212
Fuel cell system mean distance between roadcall	14,277	8,871

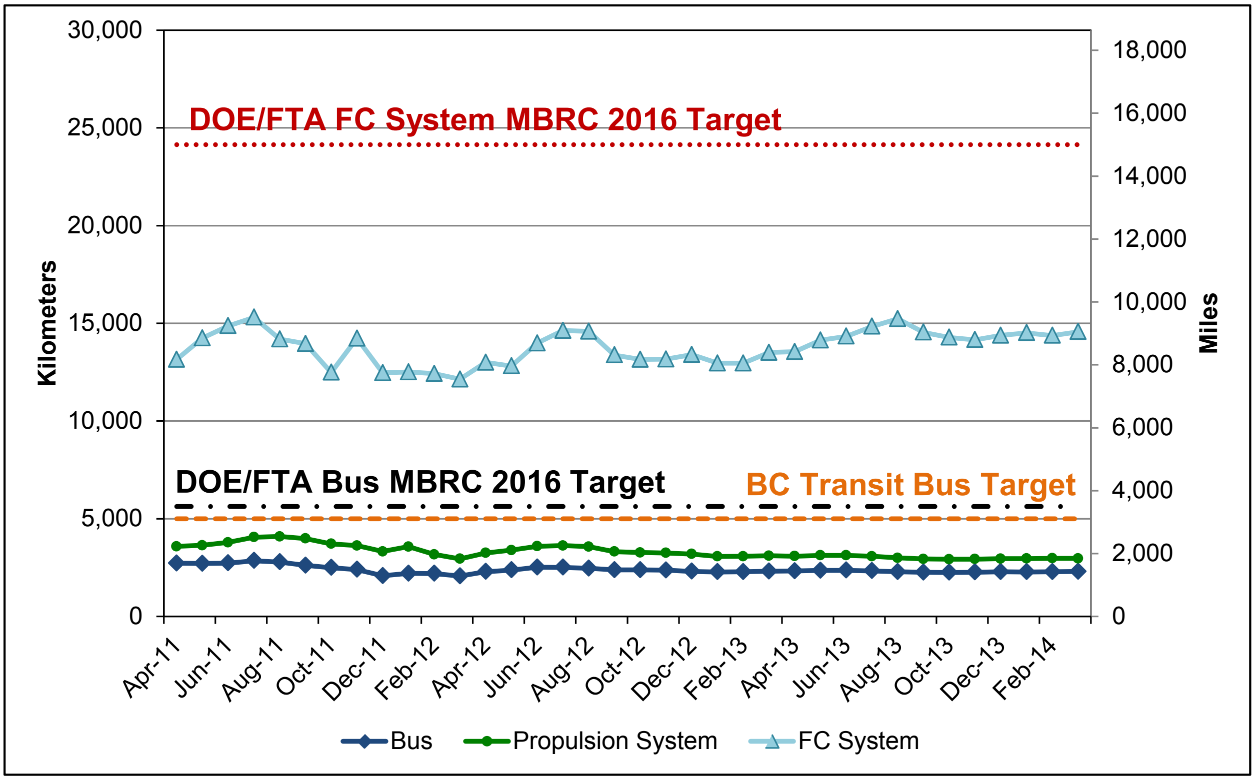

Figure 18. Cumulative distance between roadcall for the FCEBs

What’s Next

As of March 31, 2014 (the recognized end of the project), BC Transit has removed all 20 buses from service. The buses are currently parked at the Whistler Transit facility. BC Transit is addressing options for selling the buses or for converting them to a diesel propulsion system.

Ballard Power Systems continues to develop, manufacture, and service fuel cell systems for transit buses around the world and plans to introduce its seventh-generation FCPP before the end of 2014. New Flyer Industries is currently developing its next-generation FCEB for the North American market.

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References and Related Reports

All NREL hydrogen and fuel cell-related evaluation reports can be downloaded from the following website: www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

BC Transit

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Eudy, L.; Chandler, K. (2013). *American Fuel Cell Bus Project: First Analysis Report*. DOT/FTA Report No. 0047.

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Appendix A: TRL Guideline Table

Technology Readiness Levels for FCEB Commercialization

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Deployment	TRL 9	Actual system operated over the full range of expected conditions	The technology is in its final form. Deployment, marketing, and support begin for the first fully commercial products.
Technology Demonstration/ Commissioning	TRL 8	Actual system completed and qualified through test and demonstration	The last step in true system development. Demonstration of a limited production of 50 to 100 buses at a small number of locations. Beginning the transition of all maintenance to transit staff.
	TRL 7	Full-scale validation in relevant environment	A major step up from TRL 6 by adding larger numbers of buses and increasing the hours of service. Full-scale demonstration and reliability testing of 5 to 10 buses at several locations. Manufacturers begin to train larger numbers of transit staff in operation and maintenance.
	TRL 6	Engineering/pilot-scale validation in relevant environment	First tests of prototype buses in actual transit service. Field testing and design shakedown of 1 to 2 prototypes. Manufacturers assist in operation and typically handle all maintenance. Begin to introduce transit staff to technology.
Technology Development	TRL 5	Laboratory scale, similar system validation in relevant environment	Integrated system is tested in a laboratory under simulated conditions based on early modeling. System is integrated into an early prototype or mule platform for some on-road testing.
	TRL 4	Component and system validation in laboratory environment	Basic technological components are integrated into the system and begin laboratory testing and modeling of potential duty cycles.
Research to Prove Feasibility	TRL 3	Analytical and experimental critical function and/or proof of concept	Active research into components and system integration needs. Investigate what requirements might be met with existing commercial components.
	TRL 2	Technology concept and/or application formulated	Research technology needed to meet market requirements. Define strategy for moving through development stages.
Basic Technology Research	TRL 1	Basic principles observed and reported	Scientific research and early development of FCEB concepts.

Appendix B: Fleet Summary Statistics—SI Units

Fleet Summary Statistics: BC Transit FCEB

Fleet Operations and Economics

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Number of vehicles	20	20	20	20
Period used for fuel and oil op analysis	4/11–3/12	4/12–3/13	4/13–3/14	4/11–3/14
Total number of months in period	12	12	12	36
Fuel and oil analysis base fleet kilometers	962,253	1,097,634	677,491	2,737,378
Period used for maintenance op analysis	4/11–3/12	4/12–3/13	4/13–3/14	4/11–3/14
Total number of months in period	12	12	12	36
Maintenance analysis base fleet kilometers	1,024,047	1,098,404	904,327	3,026,778
Average monthly kilometers per vehicle	4,267	4,577	3,768	4,204
Availability	69%	69%	54%	64%
Fleet fuel usage (kg)	148,707.1	170,236.7	109,997.9	428,941.7
Roadcalls	412	454	399	1,265
Roadcalls KBRC	2,486	2,419	2,266	2,393
Propulsion roadcalls	308	347	327	982
Propulsion KBRC	3,325	3,165	2,766	3,082
Fleet kg hydrogen/100 km (1.13 kg H_2)	15.45	15.51	16.24	15.67
Rep. fleet fuel consumption (L/100 km)	51.76	51.95	54.38	52.49
Hydrogen cost per kg	10.55	10.55	10.55	10.55
Fuel cost per kilometer	**1.63**	**1.64**	**1.71**	**1.65**
Total scheduled repair cost per kilometer	0.24	0.18	0.18	0.20
Total unscheduled repair cost per kilometer	0.75	0.88	1.08	0.90
Total maintenance cost per kilometer	**0.99**	**1.06**	**1.26**	**1.10**
Total operating cost per kilometer	***2.62***	***2.69***	***2.97***	***2.75***

Maintenance Costs

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Fleet mileage	1,024,047	1,098,404	904,327	3,026,778
Total parts cost	157,442.68	249,563.62	203,044.40	610,050.70
Total labor hours	18,506.8	13,914.5	13,847.9	46,269.2
Labor cost	857,040.44	912,893.22	934,863.03	2,704,796.69
Total maintenance cost	1,014,483.12	1,162,456.84	1,137,907.43	3,314,847.39
Total maintenance cost per bus	50,724.16	58,122.84	56,895.37	165,742.37
Total maintenance cost per kilometer	***0.99***	***1.06***	***1.26***	***1.10***

Breakdown of Maintenance Costs by Vehicle System

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Fleet mileage	1,024,047	1,098,404	904,327	3,026,778
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	91,796.03	134,805.04	111,231.96	337,833.03
Labor hours	11,652.0	8,453.3	7,812.9	27,918.2
Labor cost	464,516.82	553,707.31	527,986.88	1,546,211.01
Total cost (for system)	556,312.85	688,512.35	639,218.84	1,884,044.04
Total cost (for system) per bus	27,815.64	34,425.62	31,960.94	94,202.20
Total cost (for system) per kilometer	***0.54***	***0.63***	***0.58***	***0.62***
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	0.0	0.0	0.0	0.0
Labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	0.00	0.00
Total cost (for system) per bus	0.00	0.00	0.00	0.00
Total cost (for system) per kilometer	***0.00***	***0.00***	***0.00***	***0.00***
Fuel System Repairs (ATA VMRS 44)				
Parts cost	13,679.26	19,825.15	19,758.67	53,263.08
Labor hours	910.1	572.2	641.5	2,123.8
Labor cost	40,204.24	37,379.52	42,802.06	120,385.82
Total cost (for system)	53,883.50	57,204.67	62,560.73	173,648.90
Total cost (for system) per bus	2,694.18	2,860.23	3,128.04	8,682.45
Total cost (for system) per kilometer	***0.05***	***0.05***	***0.06***	***0.06***
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	7,179.81	12,308.84	6,159.09	25,647.74
Labor hours	3,032.9	1,771.2	1,256.1	6,060.2
Labor cost	143,167.80	113,409.20	84,632.84	341,209.84
Total cost (for system)	150,347.61	125,718.04	90,791.93	366,857.58
Total cost (for system) per bus	7,517.38	6,285.90	4,539.60	18,342.88
Total cost (for system) per kilometer	***0.15***	***0.11***	***0.08***	***0.12***
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	8,529.89	17,360.08	19,874.72	45,764.69
Labor hours	3,348.2	2,551.4	2,781.7	8,681.3
Labor cost	108,543.96	165,931.88	187,110.76	461,586.60
Total cost (for system)	117,073.85	183,291.96	206,985.48	507,351.29
Total cost (for system) per bus	5,853.69	9,164.60	10,349.27	25,367.56
Total cost (for system) per kilometer	***0.11***	***0.17***	***0.19***	***0.17***

Breakdown of Maintenance Costs by Vehicle System (continued)

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	11,323.95	35,172.83	25,159.72	71,656.50
Labor hours	1,352.2	858.0	539.3	2,749.6
Labor cost	35,935.46	60,050.56	35,779.86	131,765.88
Total cost (for system)	47,259.41	95,223.39	60,939.58	203,422.38
Total cost (for system) per bus	2,362.97	4,761.17	3,046.98	10,171.12
Total cost (for system) per kilometer	***0.05***	***0.09***	***0.06***	***0.07***
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	29,037.50	11,702.89	6,181.51	46,921.90
Labor hours	8.4	14.3	12.3	35.0
Labor cost	390.95	931	813.27	2,135.22
Total cost (for system)	29,428.45	12,633.89	6,994.78	49,057.12
Total cost (for system) per bus	1,471.42	631.69	349.74	2,452.86
Total cost (for system) per kilometer	***0.03***	***0.01***	***0.01***	***0.02***
Cooling System Repairs (ATA VMRS 42)				
Parts cost	21,842.21	38,321.04	32,759.32	92,922.57
Labor hours	1,306.5	1,393.2	941.7	3,641.4
Labor cost	59,895.70	90,918.45	63,651.19	214,465.34
Total cost (for system)	81,737.91	129,239.49	96,410.51	307,387.91
Total cost (for system) per bus	4,086.90	6,461.97	4,820.53	15,369.40
Total cost (for system) per kilometer	***0.08***	***0.12***	***0.09***	***0.10***
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0	0	145.9	145.90
Labor hours	0	0	0.02	0.0
Labor cost	0	0	0	0.00
Total cost (for system)	0.00	0.00	145.90	145.90
Total cost (for system) per bus	0.00	0.00	7.30	7.30
Total cost (for system) per kilometer	***0.00***	***0.00***	***0.00***	***0.00***
General Air System Repairs (ATA VMRS 10)				
Parts cost	2,382.51	18,718.36	3,567.59	24,668.46
Labor hours	249.3	196.7	329.6	775.5
Labor cost	12,688.91	12,998.21	22,020.95	47,708.07
Total cost (for system)	15,071.42	31,716.57	25,588.54	72,376.53
Total cost (for system) per bus	753.57	1,585.83	1,279.43	3,618.83
Total cost (for system) per kilometer	***0.01***	***0.03***	***0.02***	***0.02***

Breakdown of Maintenance Costs by Vehicle System (continued)

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Brake System Repairs (ATA VMRS 13)				
Parts cost	4,616.92	6,803.82	5,784.55	17,205.29
Labor hours	425.8	582.8	465.0	1,473.7
Labor cost	24,479.90	37,289.78	32,703.49	94,473.17
Total cost (for system)	29,096.82	44,093.60	38,488.04	111,678.46
Total cost (for system) per bus	1,454.84	2,204.68	1,924.40	5,583.92
Total cost (for system) per kilometer	***0.03***	***0.04***	***0.04***	***0.04***
Compressor Repairs				
Parts cost	203.41	114.20	1,338.93	1,656.54
Labor hours	638.6	314.6	703.3	1,656.5
Labor cost	24,904.85	19,988.33	46,983.56	91,876.74
Total cost (for system)	25,108.26	20,102.53	48,322.49	93,533.28
Total cost (for system) per bus	1,255.41	1,005.13	2,416.12	4,676.66
Total cost (for system) per kilometer	***0.02***	***0.02***	***0.04***	***0.03***
Inspections Only - no parts replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	2,614.8	1,713.6	1,438.0	5,766.4
Labor cost	156,939.12	113,659.32	93,231.07	363,829.51
Total cost (for system)	156,939.12	113,659.32	93,231.07	363,829.51
Total cost (for system) per bus	7,846.96	5,682.97	4,661.55	18,191.48
Total cost (for system) per kilometer	***0.15***	***0.10***	***0.08***	***0.12***
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	25,976.18	46,745.29	43,811.85	116,533.32
Labor hours	1,799.8	1,391.1	1,796.7	4,987.6
Labor cost	100,719.03	91,164.24	124,055.62	315,938.89
Total cost (for system)	126,695.21	137,909.53	167,867.47	432,472.21
Total cost (for system) per bus	6,334.76	6,895.48	8,393.37	21,623.61
Total cost (for system) per kilometer	***0.12***	***0.13***	***0.15***	***0.14***
HVAC System Repairs (ATA VMRS 01)				
Parts cost	14,943.56	15,206.91	11,388.28	41,538.75
Labor hours	481.7	392.8	344.9	1,219.4
Labor cost	25,344.98	26,131.17	22,940.95	74,417.10
Total cost (for system)	40,288.54	41,338.08	34,329.23	115,955.85
Total cost (for system) per bus	2,014.43	2,066.90	1,716.46	5,797.79
Total cost (for system) per kilometer	***0.04***	***0.04***	***0.03***	***0.04***

Breakdown of Maintenance Costs by Vehicle System (continued)

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Lighting System Repairs (ATA VMRS 34)				
Parts cost	7,692.95	3,322.30	1,992.69	13,007.94
Labor hours	241.3	163.3	167.4	572.0
Labor cost	13,413.74	10,585.95	11,128.05	35,127.74
Total cost (for system)	21,106.69	13,908.25	13,120.74	48,135.68
Total cost (for system) per bus	1,055.33	695.41	656.04	2,406.78
Total cost (for system) per kilometer	***0.02***	***0.01***	***0.01***	***0.02***
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	9,701.70	23,772.59	20,323.36	53,797.65
Labor hours	551.5	530.2	855.7	1937.4
Labor cost	30,462.76	34,660.60	56,450.91	121,574.27
Total cost (for system)	40,164.46	58,433.19	76,774.27	175,371.92
Total cost (for system) per bus	2,008.22	2,921.66	3,838.71	8,768.60
Total cost (for system) per kilometer	***0.04***	***0.05***	***0.07***	***0.06***
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	289.25	152.54	3737.69	4,179.48
Labor hours	33.2	30.7	89.7	153.6
Labor cost	1,422.56	2,082.57	5,981.72	9,486.85
Total cost (for system)	1,711.81	2,235.11	9,719.41	13,666.33
Total cost (for system) per bus	85.59	111.76	485.97	683.32
Total cost (for system) per kilometer	***0.00***	***0.00***	***0.01***	***0.00***
Tire Repairs (ATA VMRS 17)				
Parts cost	43.58	36.78	1060.53	1,140.89
Labor hours	423.8	459.9	548.0	1431.7
Labor cost	25,078.66	30,614.07	38,363.39	94,056.12
Total cost (for system)	25,122.24	30,650.85	39,423.92	95,197.01
Total cost (for system) per bus	1,256.11	1,532.54	1,971.20	4,759.85
Total cost (for system) per kilometer	***0.02***	***0.03***	***0.04***	***0.03***
Battery Charging				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	1,055.0	978.5	937.0	2,970.5
Labor cost	51,473.86	65,098.37	66,213.34	182,785.57
Total cost (for system)	51,473.86	65,098.37	66,213.34	182,785.57
Total cost (for system) per bus	2,573.69	3,254.92	3,310.67	9,139.28
Total cost (for system) per kilometer	***0.05***	***0.06***	***0.06***	***0.06***

Notes

1. To compare the hydrogen fuel dispensed and fuel economy to diesel, the hydrogen dispensed was also converted into diesel energy equivalent gallons. Actual diesel energy content will vary by locations, but the general energy conversions are as follows:

> Lower heating value (LHV) for hydrogen = 51,532 Btu/lb
> LHV for diesel = 128,400 Btu/lb
> 1 kg = 2.205 * lb
> 51,532 Btu/lb * 2.205 lb/kg = 113,628 Btu/kg
> Diesel/hydrogen = 128,400 Btu/gal /113,628 Btu/kg = 1.13 kg/diesel gal

2. 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/advanced technology.

3. ATA VMRS coding is based on parts that were replaced. If there was no part replaced in a given repair, then the code was chosen by the system being worked on.

4. In general, inspections (with no part replacements) were included only in the overall totals (not by system). Category 101 was created to track labor costs for PM inspections.

5. ATA VMRS 02-Cab and Sheet Metal represents seats, doors, etc.; ATA VMRS 50-Accessories represents things like fire extinguishers, test kits, etc.; ATA VMRS 71-Body represents mostly windows and windshields.

6. Warranty costs are not included.

Appendix C: Fleet Summary Statistics—U.S. Units

Fleet Summary Statistics: BC Transit FCEB

Fleet Operations and Economics

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Number of vehicles	20	20	20	20
Period used for fuel and oil op analysis	4/11–3/12	4/12–3/13	4/13–3/14	4/11–3/14
Total number of months in period	12	12	12	36
Fuel and oil analysis base fleet miles	597,916	682,038	420,973	1,700,928
Period used for maintenance op analysis	4/11–3/12	4/12–3/13	4/13–3/14	4/11–3/14
Total number of months in period	12	12	12	36
Maintenance analysis base fleet miles	636,313	682,517	561,923	1,880,753
Average monthly miles per vehicle	2,651	2,844	2,341	2,612
Availability	69%	69%	54%	64%
Fleet fuel usage (kg)	148,707.1	170,236.7	109,997.9	428,941.7
Roadcalls	412	454	399	1,265
Roadcalls MBRC	1,544	1,503	1,408	1,487
Propulsion roadcalls	308	347	327	982
Propulsion MBRC	2,066	1,967	1,718	1,915
Fleet mi/kg hydrogen (1.13 kg H_2)	4.02	4.01	3.83	3.97
Rep. fleet fuel consumption (mi/DGE)	4.54	4.53	4.32	4.48
Hydrogen cost per kg	10.55	10.55	10.55	10.55
Fuel cost per mile	**2.62**	**2.63**	**2.76**	**2.66**
Total scheduled repair cost per mile	0.37	0.27	0.27	0.31
Total unscheduled repair cost per mile	1.17	1.37	1.69	1.40
Total maintenance cost per mile	**1.54**	**1.65**	**1.96**	**1.70**
Total operating cost per mile	***4.17***	***4.28***	***4.71***	***4.36***

Maintenance Costs

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Fleet mileage	636,313	682,517	561,923	1,880,753
Total parts cost	152,247.07	241,328.02	196,343.93	589,919.03
Total labor hours	18,506.8	13,914.5	13,847.9	46,269.2
Labor cost	828,758.11	882,767.74	904,012.55	2,615,538.40
Total maintenance cost	981,005.18	1,124,095.77	1,100,356.48	3,205,457.43
Total maintenance cost per bus	49,050.26	56,204.79	55,017.82	160,272.87
Total maintenance cost per mile	***1.54***	***1.65***	***1.96***	***1.70***

Breakdown of Maintenance Costs by Vehicle System

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Fleet mileage	636,313	682,517	561,923	1,880,753
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	88,766.76	130,356.47	107,561.31	326,684.54
Labor hours	11,652.0	8,453.3	7,812.9	27,918.2
Labor cost	449,187.76	535,434.97	510,563.31	1,495,186.05
Total cost (for system)	537,954.53	665,791.44	618,124.62	1,821,870.58
Total cost (for system) per bus	26,897.73	33,289.57	30,906.23	91,093.53
Total cost (for system) per mile	**0.85**	**0.98**	**1.10**	**0.97**
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	0.0	0.0	0.0	0.0
Labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	0.00	0.00
Total cost (for system) per bus	0.00	0.00	0.00	0.00
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Fuel System Repairs (ATA VMRS 44)				
Parts cost	13,227.84	19,170.92	19,106.63	51,505.40
Labor hours	910.1	572.2	641.5	2,123.8
Labor cost	38,877.50	36,146.00	41,389.59	116,413.09
Total cost (for system)	52,105.34	55,316.92	60,496.23	167,918.49
Total cost (for system) per bus	2,605.27	2,765.85	3,024.81	8,395.92
Total cost (for system) per mile	**0.08**	**0.08**	**0.11**	**0.09**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	6,942.88	11,902.65	5,955.84	24,801.37
Labor hours	3,032.9	1,771.2	1,256.1	6,060.2
Labor cost	138,443.26	109,666.70	81,839.96	329,949.92
Total cost (for system)	145,386.14	121,569.35	87,795.80	354,751.28
Total cost (for system) per bus	7,269.31	6,078.47	4,389.79	17,737.56
Total cost (for system) per mile	**0.23**	**0.18**	**0.16**	**0.19**
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	8,248.40	16,787.20	19,218.85	44,254.46
Labor hours	3,348.2	2,551.4	2,781.7	8,681.3
Labor cost	104,962.01	160,456.13	180,936.10	446,354.24
Total cost (for system)	113,210.41	177,243.33	200,154.96	490,608.70
Total cost (for system) per bus	5,660.52	8,862.17	10,007.75	24,530.44
Total cost (for system) per mile	**0.18**	**0.26**	**0.36**	**0.26**

Breakdown of Maintenance Costs by Vehicle System (continued)

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	10,950.26	34,012.13	24,329.45	69,291.84
Labor hours	1,352.2	858.0	539.3	2,749.6
Labor cost	34,749.59	58,068.89	34,599.12	127,417.61
Total cost (for system)	45,699.85	92,081.02	58,928.57	196,709.44
Total cost (for system) per bus	2,284.99	4,604.05	2,946.43	9,835.47
Total cost (for system) per mile	**0.07**	**0.13**	**0.10**	**0.10**
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	28,079.26	11,316.69	5,977.52	45,373.48
Labor hours	8.4	14.3	12.3	35.0
Labor cost	378.05	900.28	786.43	2,064.76
Total cost (for system)	28,457.31	12,216.97	6,763.95	47,438.24
Total cost (for system) per bus	1,422.87	610.85	338.20	2,371.91
Total cost (for system) per mile	**0.04**	**0.02**	**0.01**	**0.03**
Cooling System Repairs (ATA VMRS 42)				
Parts cost	21,121.42	37,056.44	31,678.26	89,856.12
Labor hours	1,306.5	1,393.2	941.7	3,641.4
Labor cost	57,919.14	87,918.14	61,550.70	207,387.98
Total cost (for system)	79,040.56	124,974.58	93,228.96	297,244.11
Total cost (for system) per bus	3,952.03	6,248.73	4,661.45	14,862.21
Total cost (for system) per mile	**0.12**	**0.18**	**0.17**	**0.16**
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0.00	0.00	141.09	141.09
Labor hours	0.0	0.0	0.0	0.0
Labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	141.09	141.09
Total cost (for system) per bus	0.00	0.00	7.05	7.05
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)				
Parts cost	2,303.89	18,100.65	3,449.86	23,854.40
Labor hours	249.3	196.7	329.6	775.5
Labor cost	12,270.18	12,569.27	21,294.26	46,133.70
Total cost (for system)	14,574.06	30,669.92	24,744.12	69,988.10
Total cost (for system) per bus	728.70	1,533.50	1,237.21	3,499.40
Total cost (for system) per mile	**0.02**	**0.04**	**0.04**	**0.04**

Breakdown of Maintenance Costs by Vehicle System (continued)

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Brake System Repairs (ATA VMRS 13)				
Parts cost	4,464.56	6,579.29	5,593.66	16,637.52
Labor hours	425.8	582.8	465.0	1,473.7
Labor cost	23,672.06	36,059.22	31,624.27	91,355.56
Total cost (for system)	28,136.62	42,638.51	37,217.93	107,993.07
Total cost (for system) per bus	1,406.83	2,131.93	1,860.90	5,399.65
Total cost (for system) per mile	**0.04**	**0.06**	**0.07**	**0.06**
Compressor Repairs				
Parts cost	196.70	110.43	1,294.75	1,601.87
Labor hours	638.6	314.6	703.3	1,656.5
Labor cost	24,082.99	19,328.72	45,433.10	88,844.81
Total cost (for system)	24,279.69	19,439.15	46,727.85	90,446.68
Total cost (for system) per bus	1,213.98	971.96	2,336.39	4,522.33
Total cost (for system) per mile	**0.04**	**0.03**	**0.08**	**0.05**
Inspections Only - no parts replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	2,614.8	1,713.6	1,438.0	5,766.4
Labor cost	151,760.13	109,908.56	90,154.44	351,823.14
Total cost (for system)	151,760.13	109,908.56	90,154.44	351,823.14
Total cost (for system) per bus	7,588.01	5,495.43	4,507.72	17,591.16
Total cost (for system) per mile	**0.24**	**0.16**	**0.16**	**0.19**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	25,118.97	45,202.70	42,366.06	112,687.72
Labor hours	1,799.8	1,391.1	1,796.7	4,987.6
Labor cost	97,395.30	88,155.82	119,961.78	305,512.91
Total cost (for system)	122,514.27	133,358.52	162,327.84	418,200.63
Total cost (for system) per bus	6,125.71	6,667.93	8,116.39	20,910.03
Total cost (for system) per mile	**0.19**	**0.20**	**0.29**	**0.22**
HVAC System Repairs (ATA VMRS 01)				
Parts cost	14,450.42	14,705.08	11,012.47	40,167.97
Labor hours	481.7	392.8	344.9	1,219.4
Labor cost	24,508.60	25,268.84	22,183.90	71,961.34
Total cost (for system)	38,959.02	39,973.93	33,196.37	112,129.31
Total cost (for system) per bus	1,947.95	1,998.70	1,659.82	5,606.47
Total cost (for system) per mile	**0.06**	**0.06**	**0.06**	**0.06**

Breakdown of Maintenance Costs by Vehicle System (continued)

	FCEB Year 1	FCEB Year 2	FCEB Year 3	FCEB Total
Lighting System Repairs (ATA VMRS 34)				
Parts cost	7,439.08	3,212.67	1,926.93	12,578.68
Labor hours	241.3	163.3	167.4	572.0
Labor cost	12,971.09	10,236.61	10,760.82	33,968.52
Total cost (for system)	20,410.17	13,449.28	12,687.76	46,547.20
Total cost (for system) per bus	1,020.51	672.46	634.39	2,327.36
Total cost (for system) per mile	**0.03**	**0.02**	**0.02**	**0.02**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	9,381.54	22,988.09	19,652.69	52,022.32
Labor hours	551.5	530.2	855.7	1,937.4
Labor cost	29,457.49	33,516.80	54,588.03	117,562.32
Total cost (for system)	38,839.03	56,504.89	74,240.72	169,584.64
Total cost (for system) per bus	1,941.95	2,825.24	3,712.04	8,479.23
Total cost (for system) per mile	**0.06**	**0.08**	**0.13**	**0.09**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	279.70	147.51	3,614.35	4,041.56
Labor hours	33.2	30.7	89.7	153.6
Labor cost	1,375.62	2,013.85	5,784.32	9,173.78
Total cost (for system)	1,655.32	2,161.35	9,398.67	13,215.34
Total cost (for system) per bus	82.77	108.07	469.93	660.77
Total cost (for system) per mile	**0.00**	**0.00**	**0.02**	**0.01**
Tire Repairs (ATA VMRS 17)				
Parts cost	42.14	35.57	1,025.53	1,103.24
Labor hours	423.8	459.9	548.0	1,431.7
Labor cost	24,251.06	29,603.81	37,097.40	90,952.27
Total cost (for system)	24,293.21	29,639.37	38,122.93	92,055.51
Total cost (for system) per bus	1,214.66	1,481.97	1,906.15	4,602.78
Total cost (for system) per mile	**0.04**	**0.04**	**0.07**	**0.05**
Battery Charging				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	1,055.0	978.5	937.0	2,970.5
Labor cost	49,775.22	62,950.12	64,028.30	176,753.65
Total cost (for system)	49,775.22	62,950.12	64,028.30	176,753.65
Total cost (for system) per bus	2,488.76	3,147.51	3,201.41	8,837.68
Total cost (for system) per mile	**0.08**	**0.09**	**0.11**	**0.09**