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Technical Report
NREL/TP-5400-62683
December 2014

Contract No. DE-AC36-08GO28308

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Acknowledgments

This document includes results and experiences from several U.S. fuel cell electric bus evaluation projects. The active participation of our project partners is greatly appreciated. Contributors to this report included staff members of federal and state government agencies, manufacturing firms, and transit authorities. The authors especially thank the following individuals:

Doug Byrne and Salvador Llamas, Alameda-Contra Costa Transit District

Mike Frost, Aaron Lamb, Stephen Brydon, and Bob Hall, BC Transit

Juan Carlos Gomez and Todd Peterson, Whistler Transit

Tommy Edwards, Polo Del Toro, Mike Morrow, and Mike Hayes, SunLine Transit Agency

Steve Miller, Golden Gate Transit

Bruce Rothwell, Reid Rothwell & Associates

Jason Marcinkoski, U.S. Department of Energy

Sean Ricketson, U.S. Department of Transportation, Federal Transit Administration

Abas Goodarzi and Matthew Riley, US Hybrid

Byron Somerville, Jeff Grant, and Silvano Pozzi, Ballard Power Systems

Robert Devine and Yesh Premkumar, BAE Systems

Nico Bouwkamp, California Fuel Cell Partnership

Erik Bigelow, Center for Transportation and the Environment

Keith Wipke and Jen Kurtz, National Renewable Energy Laboratory

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Acronyms and Abbreviations

AC Transit	Alameda-Contra Costa Transit District
AFCB	American Fuel Cell Bus
AT	advanced technology
CARB	California Air Resources Board
CNG	compressed natural gas
CTE	Center for Transportation and the Environment
CTTRANSIT	Connecticut Transit
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
FC	fuel cell
FCEB	fuel cell electric bus
FCPP	fuel cell power plant
ft	feet
FTA	Federal Transit Administration
GGE	gasoline gallon equivalent
GNHTD	Greater New Haven Transit District
kg	kilograms
MBRC	miles between roadcalls
mpdge	miles per diesel gallon equivalent
mph	miles per hour
NAVC	Northeast Advanced Vehicle Consortium
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
SFMTA	San Francisco Municipal Transportation Agency
TRL	technology readiness level
UT	University of Texas
ZEBA	Zero Emission Bay Area

Executive Summary

This report, published annually, summarizes the progress of fuel cell electric bus (FCEB) development in the United States and discusses the achievements and challenges of introducing fuel cell propulsion in transit. Various stakeholders, including developers, transit agencies, and system integrators, have expressed the value of this annual status report, which provides a summary of results from evaluations performed by the National Renewable Energy Laboratory (NREL). Funding for this effort is provided by the U.S. Department of Energy's (DOE's) Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy and the U.S. Department of Transportation's (DOT's) Federal Transit Administration (FTA). This 2014 status report also includes results from an evaluation funded by the California Air Resources Board (CARB).

NREL publishes individual reports on each demonstration that focus on the results and experiences for that specific project. The annual status report combines results from all of those FCEB demonstrations, tracks the progress of the FCEB industry toward meeting technical targets (as shown in Table ES-1), documents the lessons learned, and discusses the path forward for commercial viability of fuel cell technology for transit buses. Its intent is to inform FTA and DOE decision makers who direct research and funding; state and local government agencies that fund new propulsion technology transit buses; and interested transit agencies and industry manufacturers.

The 2014 summary results primarily focus on the most recent year for each demonstration, generally from August 2013 through July 2014. The results for these buses account for more than 938,444 miles traveled and 85,061 hours of fuel cell power system operation. The summary results are from four demonstrations at three transit agencies:

- Zero Emission Bay Area (ZEBA) Demonstration Group led by Alameda-Contra Costa Transit District (AC Transit) in California
- BC Transit Fuel Cell Bus Project (final year of in-service operation) in Whistler, British Columbia, Canada
- Advanced Technology FCEB and American Fuel Cell Bus Project at SunLine Transit Agency in California.

NREL also collected and analyzed conventional baseline bus data from each site for comparison with the FCEB data. At AC Transit and BC Transit, the baseline buses are diesel buses. The baseline buses at SunLine are CNG because the agency does not operate diesel buses. The baseline buses are selected to be as close a match to the FCEBs as possible and operated in similar service.

DOE and FTA have established performance, cost, and durability targets for FCEBs. These targets, established with industry input, include interim targets for 2016 and ultimate targets for commercialization. FCEB technology continues to show progress toward meeting technical targets for increasing reliability and durability as well as reducing costs. Table ES-1 summarizes the performance of the FCEBs in the report compared to these targets.

Table ES-1. Summary of FCEB Performance Compared to DOE/FTA Targets[1]

	Units	Current Status[a] (Range)	2016 Target[1]	Ultimate Target[1]
Bus lifetime	years/miles	2.5–5 / 49,296–151,000[b]	12/500,000	12/500,000
Power plant lifetime[c]	hours	5,557–17,211[b,d,e]	18,000	25,000
Bus availability	%	45–72	85	90
Fuel fills[f]	per day	1	1 (<10 min)	1 (<10 min)
Bus cost[g]	$	2,000,000	1,000,000	600,000
Power plant cost[c,g]	$	N/A[h]	450,000	200,000
Hydrogen storage cost	$	N/A[h]	75,000	50,000
Roadcall frequency (bus/fuel cell system)	miles between roadcalls	1,408–6,363 / 10,406–37,471	3,500/ 15,000	4,000/ 20,000
Operation time	hours per day/days per week	7–19 / 5–7	20/7	20/7
Scheduled and unscheduled maintenance cost[i]	$/mile	N/A[j]	0.75	0.40
Range	miles	145–294[k]	300	300
Fuel economy	miles per gallon diesel equivalent	4.32–7.26	8	8

[a] The summary of results in this report represents a snapshot from the included demonstrations: data generally from August 2013–July 2014 with the exception of BC Transit, which covers April 2013 through March 2014.
[b] Accumulated totals for existing fleet through July 2014; these buses have not reached end of life.
[c] For the DOE/FTA targets, the power plant is defined as the fuel cell system and the battery system. The fuel cell system includes supporting subsystems such as the air, fuel, coolant, and control subsystems. Power electronics, electric drive, and hydrogen storage tanks are excluded.
[d] The status for power plant hours is for the fuel cell system only; battery lifetime hours were not available.
[e] The highest-hour power plant was transferred from an older-generation bus that had accumulated more than 6,000 hours prior to transfer.
[f] Multiple sequential fuel fills should be possible without an increase in fill time.
[g] Cost targets are projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only and does not represent an anticipated level of sales.
[h] Capital costs for subsystems are not currently reported by the manufacturers.
[i] Excludes mid-life overhaul of power plant.
[j] Maintenance costs are not available for this report. See individual project reports on the NREL website.
[k] Based on fuel economy and 95% tank capacity.

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. Over the last year, manufacturers made significant progress toward meeting the target. At the end of the analysis period for this report (July 2014), NREL documented a single fuel cell power plant (FCPP) that had reached 17,200 hours. As of December 2014, this FCPP has surpassed 18,000 hours of

[1] Fuel Cell Technologies Program Record # 12012, September 12, 2012, http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf.

operation. Of the 36 FCPPs included in the data set, 75% (27) have surpassed 8,000 hours of operation. The average hours accumulated is 8,968.

Availability continues to vary from site to site with data from the last year ranging from a low of 45% up to a high of 72%, with the overall average at 70%. This is consistent with what was reported last year (69% average). The most common issue affecting the availability for the buses was general bus maintenance, followed by traction batteries and the hybrid propulsion system.

The targets for roadcall frequency include miles between roadcalls (MBRC) for the entire bus and MBRC for the fuel cell (FC) system only. The FC system MBRC includes any roadcalls due to issues with the FC stack or associated balance of plant. NREL tracks an additional metric of propulsion system MBRC. This category includes all roadcalls due to propulsion-related bus systems. Overall the MBRC for the last year was 2,235 for bus MBRC; 2,928 for propulsion MBRC; and 13,702 for FC system MBRC. The FC system MBRC shows a general upward trend and approaches the 2016 target toward the end of the data period.

The FCEBs continue to show higher fuel economy compared to the baseline buses in similar service. FTA's performance target for FCEB fuel economy is 8 miles per diesel gallon equivalent (mi/DGE), which is approximately 2 times higher than that of typical conventional diesel buses. Actual data from the FCEBs included in this report showed fuel economy ranging from 1.01 to 1.84 times higher than that of diesel baseline buses (AC Transit and BC Transit) and 2.17 times higher than that of compressed natural gas baseline buses (SunLine). Fuel economy for the FCEBs ranged from 4.3 mi/DGE up to 7.3 mi/DGE and averaged 6.25 mi/DGE. The FCEBs at BC Transit demonstrated lower fuel economy than that typically shown at other locations. Several factors contributed to the lower numbers including FCEB design strategy, an oversized heater, and a harsh duty cycle. The BC Transit demonstration concluded in March 2014 and the agency no longer has any FCEBs in operation.

At this point in the development, FCEBs are not commercial products. NREL considers each of the four FCEB designs included in the report to be around technology readiness level (TRL) 7, i.e., full-scale validation in a relevant environment. The manufacturers' goals for these demonstrations are to verify that the FCEB performance meets the technical targets and identify any issues that need to be resolved. The current costs for FCEB technology—both capital and operating costs—are still much higher than that of conventional diesel technology. This is expected considering diesel is a very mature technology (TRL 9).

FCEB performance continues to improve; however, there are still challenges to overcome to move the technology to a commercial product. The industry continues to have problems with companies leaving the market through restructuring or bankruptcy. This makes conducting long-term demonstrations a challenge when the partners no longer provide technical support or produce replacement parts. Other challenges include the following:

- **Integration and optimization of components.** Manufacturers continue to work on issues with systems integration and optimization, which remains one of the major challenges for FCEBs. Each FCEB development team has faced challenges similar to those experienced by hybrid bus developers, but with the added difficulty of optimizing communication and interfaces between advanced systems. The hybrid system, fuel cell, and batteries must all work together to propel the bus. Transit agencies need to continue working closely with the manufacturers to optimize and update hybrid systems to eliminate problems and increase performance.

- **Evolution of technology and components.** As technology development for FCEBs progresses, components and parts are being modified for new designs, which can result in parts obsolescence for current designs. Replacement parts (such as battery modules, air compressors, and motors) can be hard to locate because manufacturers have stopped producing the older designs or have gone out of business. BC Transit experienced these issues when the battery supplier discontinued the model used in its buses. The manufacturer's new design could not be used as a one-to-one replacement because it was not the same size as the original modules and had different operating characteristics.
- **Parts availability.** Finding replacement parts can be an issue for many FCEB projects because some advanced components are not common and can be costly. AC Transit has had issues with replacement parts that have a long lead time for delivery, in some cases because they come from outside the United States. These components were not typically stocked and were only ordered when needed. This has changed over time as the project partners have learned what should be kept on hand. While convenient, stocking these components can also be challenging—not only because the cost for advanced technologies can be high, but also because warranties on a component often begin when it is shipped, and the warranty can run out before it is installed.
- **Weight.** Newer FCEB designs incorporate modifications to reduce weight, but they are still heavier than conventional diesel buses. This has caused higher wear on suspension components. The AC Transit ZEBA buses are approximately 5,000 lb lighter than the early-generation buses, although the buses are still about 3,000 lb heavier than the comparable diesel model. Transit agencies need to be aware of this and plan to monitor affected components for wear and potentially replace them on a more frequent basis.
- **Transition of maintenance to transit staff.** The transition of knowledge from the manufacturers to the transit staff is essential to commercializing the technology. Transit agencies are making major progress toward this goal. Manufacturers are working to provide full maintenance manuals, troubleshooting guides, and tools to aid in the transfer of knowledge to transit staff. At AC Transit, agency staff has received training and taken on all preventive maintenance and repair work on the fuel cell buses. US Hybrid developed the service and maintenance manual, wireless diagnostic tools, and resources that the agency can use to help troubleshoot issues and perform the repairs on-site.
- **Integrating FCEB designs into the standard bus build process.** Manufacturers are making major strides to work FCEB designs into the production line along with conventional technology buses. The development team of BAE Systems, Ballard, and ElDorado National began to take this step with SunLine's order for two AFCBs under the FTA Transit Investments for Greenhouse Gas and Energy Reduction Program. The first bus glider was shipped to BAE Systems for integration of the propulsion system, and BAE Systems worked with ElDorado staff to complete the installation. The second bus was entirely built at the ElDorado factory with support from BAE Systems. Over the last year, more transit agencies have placed orders for this updated AFCB. These buses are being built at the ElDorado facility in the standard production line along with

conventional technology buses. More established original equipment manufacturers need to make this commitment before the industry can be sustained.

NREL plans to continue monitoring and evaluating the demonstrations at AC Transit and SunLine. The BC Transit demonstration has been completed. In the next year, several more FCEBs and operating sites are expected to begin demonstration; these will be included in next year's status report.

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Introduction

This report is the eighth in a series of annual status reports from the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL).[2] It summarizes status and progress from demonstrations of fuel cell transit buses in the United States and Canada. Since 2000, NREL has evaluated fuel cell electric bus (FCEB) demonstrations at transit agencies, looking at the buses, infrastructure, and each transit agency's implementation experience. These evaluations have been funded by DOE, the U.S. Department of Transportation's (DOT) Federal Transit Administration (FTA), and the California Air Resources Board (CARB). This work is described in a joint evaluation plan.[3]

Scope and Purpose

This annual status report discusses the achievements and challenges of fuel cell propulsion for transit and summarizes the introduction of fuel cell transit buses in the United States. It provides an analysis of the combined results from fuel cell transit bus demonstrations evaluated by NREL with a focus on the most recent data (through July 2014). NREL also evaluates the operating experience and costs of these demonstrations individually and posts reports at http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html. The "References" section of this report lists the most recent reports, each of which documents the performance and provides an unbiased assessment of a transit agency's experience implementing FCEBs into its operation.

This report combines results for FCEB demonstrations across North America and discusses the path forward for commercial viability of fuel cell technology for transit buses. Its intent is to inform FTA and DOE decision makers who direct research and funding; state and local government agencies that fund new propulsion technology transit buses; and interested transit agencies and industry manufacturers.

Organization

This report is organized into seven sections, beginning with this "Introduction." The section "Fuel Cell Electric Buses in Operation in North America" summarizes existing and upcoming demonstrations in the United States and Canada and includes an overview of FTA's National Fuel Cell Bus Program (NFCBP). The section "FCEB Development Process—Technology Readiness Levels" outlines the steps for developing and commercializing FCEBs and indicates where each of the current designs falls in the process. The section "Update of Evaluation Results Through July 2014" presents the results of the most recent NREL evaluations of fuel cell transit bus demonstrations with comparisons for availability, fuel economy, and roadcalls. The section "Current Status of Fuel Cell Bus Introductions: Summary of Achievements and Challenges" discusses the status and challenges of fuel cell propulsion for transit. The section "New Research to Facilitate Commercialization" outlines new areas of research funded by FTA to aid the industry in moving FCEB technology forward. The section "What's Expected for the 2015 Report" looks ahead to the results to be presented in next year's assessment report.

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[2] Previous reports are listed in the References section of this report.

[3] *Fuel Cell Transit Bus Evaluations, Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration,* 2010, NREL/TP-560-49342.

Additionally, the "References" section provides references for NREL's periodic evaluation reports for the individual fuel cell bus demonstrations, and the "Appendix" provides summary fuel cell bus data from each of the transit agencies.

What's New Since the Previous Report

Table 1 outlines which FCEB designs were included in the 2013 and 2014 (current) status reports. The 2013 report presented the results from five FCEB demonstration projects. Four projects represented three fuel cell dominant FCEB designs at three transit agencies and one project represented a battery dominant hybrid FCEB at another agency. For this report, results are updated for three of those demonstrations— the Alameda-Contra Costa Transit District (AC Transit) Zero Emission Bay Area (ZEBA) demonstration and the Advanced Technology (AT) FCEB and American Fuel Cell Bus (AFCB) demonstrations at SunLine.

Results for BC Transit's FCEB demonstration are also included in this report. NREL began working with BC Transit in July 2013 to conduct a third-party evaluation of the FCEB fleet in Whistler, British Columbia. Because the analysis was not yet complete in 2013, the results were not included in the previous report. The BC Transit demonstration concluded in March 2014 and the agency no longer has FCEBs in operation. The demonstrations in Texas and Connecticut concluded in 2013; therefore no data are available.

Table 1. Technologies Included in the 2013 or 2014 Status Reports

FCEB Demonstration	Included in 2013 Report	Included in Current Report	Status
AC Transit ZEBA	✓	✓	Active
CTTRANSIT Nutmeg	✓		Demonstration ended (3/2013)
SunLine AT FCEB	✓	✓	Active
SunLine AFCB	✓	✓	Active
Proterra, Austin, Texas	✓		Demonstration ended (3/2013)
BC Transit		✓	Demonstration ended (3/2014)

In July 2014, NREL began working with another demonstration team to evaluate the newest NFCBP bus in Birmingham, Alabama. The 30-foot battery dominant FCEB was developed by a new manufacturer team. Embedded Power provided the hybrid system and integrated the system using a Ballard fuel cell system and lithium titanate batteries. The bus was built by EV America. Figure 1 shows the bus at the fueling station in Birmingham. A summary of the results will be included in the 2015 status report.

Figure 1. New FCEB being demonstrated in Birmingham, Alabama

Fuel Cell Electric Buses in Operation in North America

In past reports, NREL documented the results from fleets specifically in the United States. This report also includes the results from the BC Transit demonstration in Canada. Table 2 lists current FCEB demonstrations in North America. These demonstrations focus on identifying improvements to optimize reliability and durability. As of August 2014, 19 FCEBs were active in demonstrations at several locations in North America.

Table 2. Current Fuel Cell Transit Bus Demonstrations in North America[a]

	Bus Operator	Location	Total Buses	Active Buses[b]	Technology Description
1	ZEBA (led by AC Transit)	San Francisco Bay Area, CA	13	12	Van Hool bus and hybrid system integration, US Hybrid fuel cell
2	SunLine Transit Agency, AT FCEB	Thousand Palms, CA	1	1	New Flyer bus with Bluways hybrid system and Ballard fuel cell
3	SunLine Transit Agency, AFCB	Thousand Palms, CA	1	1	ElDorado/BAE Systems/Ballard next-generation advanced design to meet 'Buy America' requirements
4	SunLine Transit Agency, AFCB TIGGER	Thousand Palms, CA	2	1	ElDorado/BAE Systems/Ballard updated AFCB design
5	BC Transit, FCEB	Whistler, BC, Canada	20	0	New Flyer bus with Bluways hybrid system and Ballard fuel cell
6	Birmingham FCEB	Birmingham, AL	1	1	EVAmerica bus with Embedded Power hybrid system and Ballard fuel cell
7	Flint MTA	Flint, MI	1	0	Van Hool bus and hybrid system integration, US Hybrid fuel cell
8	University of Delaware (Phase 1 and 2)	Newark, DE	2	2	Ebus battery dominant plug-in hybrid using Ballard fuel cells (22-ft)
9	Greater New Haven Transit District	New Haven, CT	1	1	Ebus battery dominant plug-in hybrid using Ballard fuel cells (22-ft)
		Total	**42**	**19**	

[a] Blue shaded rows indicate the project received funding through the NFCBP.
[b] Total buses in actual service as of August 2014.

NREL is evaluating the first six demonstrations shown in Table 2. These demonstrations, along with the current status, are described in more detail below.

- **ZEBA Demonstration Group led by AC Transit—**Demonstration of 12 next-generation Van Hool fuel cell hybrid buses with a fuel cell system by US Hybrid. This program received funding through the NFCBP to perform accelerated testing of the first-generation buses and to purchase eight of the fuel cell systems for these new buses. The first bus was delivered in May 2010 and all 12 were in service by the end of November 2011. NREL completed three reports on the demonstration (in August 2011, July 2012, and May 2014). Four additional buses of this design were demonstrated in Connecticut as part of the NFCBP Nutmeg project. That project has concluded and one of those four buses was transferred to AC Transit, bringing the fleet to 13 FCEBs. AC Transit was awarded additional NFCBP funds to provide continued manufacturer support for another 2 years of in-service demonstration.
- **SunLine Transit Agency: AT FCEB—**Demonstration of one New Flyer bus with a Bluways hybrid system and a Ballard fuel cell. This bus went into service in May 2010. NREL completed four reports on this bus (in March 2011, October 2011, May 2012, and January 2013). This bus was the pilot bus for the BC Transit fleet described below. NREL has completed the evaluation on this bus and does not plan additional reports.
- **SunLine Transit Agency: AFCB Project—**Demonstration of one ElDorado National bus with a BAE Systems hybrid propulsion system and a Ballard fuel cell power system. This project is part of the NFCBP. NREL began data collection in December 2011 and the first report was completed in June 2013. NREL plans to publish a second report in fall 2014.
- **SunLine Transit Agency: AFCB TIGGER Project—**Demonstration of two AFCBs (ElDorado National bus, BAE Systems hybrid propulsion system, Ballard fuel cell) with an upgraded design. This project was funded under the FTA's Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) Program. The first bus was put into service in June 2014. The second bus was delivered in August 2014. NREL began data collection and will include results on these two buses along with the first AFCB in future reports.
- **BC Transit: Fuel Cell Bus Project—**BC Transit demonstrated a fleet of 20 FCEBs in the Whistler Resort area of British Columbia, Canada, beginning in February 2010 during the Winter Olympic Games. The program was a 5-year demonstration of the technology and included operation and maintenance of the FCEB fleet through March 2014. These New Flyer buses featured a Ballard fuel cell in a Bluways hybrid system. Under funding from CARB, NREL collected data on this fleet covering a 3-year data period from April 2011 through March 2014. The first report was published in February 2014, and the second and final report was published in September 2014.
- **Birmingham-Jefferson County Transit Authority: Birmingham Fuel Cell Bus Project**—Demonstration of one 30-foot EVAmerica bus with an Embedded Power battery dominant hybrid propulsion system using lithium titanate batteries and a Ballard fuel cell. The bus was delivered in early 2014 and was placed in service in June. NREL has begun data collection and will complete a report after a year of operation.

The University of Delaware and Greater New Haven Transit District FCEB projects were funded through FTA outside of the NFCBP. Flint Mass Transportation Agency's (MTA) FCEB was one of the four buses originally developed for the Connecticut Nutmeg FCEB project under NFCBP funding. The four buses were operated by Connecticut Transit in Hartford. One bus was transferred to Flint MTA in April 2012. At the conclusion of the Nutmeg demonstration, one of the three remaining buses was transferred to AC Transit, one was sent to South Carolina, and one was transferred to US Hybrid (Torrance, California) to aid in testing a new fuel cell power plant being developed.

During the last year, NREL collected data on the FCEBs demonstrated in the first three projects in Table 2 and the BC Transit project. The section "Update of Evaluation Results Through July 2014" provides the most recent results for these four demonstrations.

National Fuel Cell Bus Program

The NFCBP is a multi-year, cost-shared research program established by FTA in 2006, with an overall goal of developing and demonstrating commercially viable fuel cell technology for transit buses. Additional funding was added to the program over the following 4 years, bringing the total funds to nearly $90 million. Projects were competitively selected and included fuel cell bus demonstrations, component development projects, and outreach projects. Three non-profit consortia—CALSTART (Pasadena, California), the Center for Transportation and the Environment (CTE, Atlanta, Georgia), and the Northeast Advanced Vehicle Consortium (NAVC, Boston, Massachusetts)—are responsible for managing the projects. NREL was funded as a third-party evaluator to assess the viability of the buses demonstrated under the program.

The demonstration projects that are currently underway are included in Table 2 (blue shaded rows). Table 3 lists the remaining demonstration projects that are expected to field eight more fuel cell buses over the next few years.

Table 3. New Fuel Cell Transit Buses Planned for the FTA NFCBP

Project	Location	Total Buses	Technology Description
Massachusetts FCEB Demo (NAVC)	Boston, MA	1	ElDorado/BAE Systems/Ballard next-generation AFCB
Advanced Composite FCEB (CTE)	Austin, TX; Washington, DC	1	Proterra composite body with a next-generation battery dominant hybrid system and a Hydrogenics fuel cell
Advanced Generation FCEB (CALSTART)	Hartford, CT	1	New Flyer bus with next-generation fuel cell and BAE Systems hybrid propulsion
Next-Generation Compound Bus (CALSTART)	San Francisco, CA	1	BAE Systems diesel hybrid bus with fuel cell auxiliary power unit for auxiliary loads (next-generation system to the original Compound bus)
AFCB (CALSTART)	Canton, OH	2	ElDorado/BAE Systems/Ballard next-generation AFCB
Battery Dominant FCEB (CALSTART)	Palm Springs, CA	1	ElDorado bus with a battery dominant fuel cell system from BAE Systems and a Hydrogenics fuel cell
Central New York Fuel Cell Transportation Program (CTE)	Ithaca, NY	1	ElDorado/BAE Systems/Ballard next-generation AFCB

Beyond the NFCBP, FTA has funded fuel cell bus research at several universities and transit agencies around the country. The TIGGER Program funded a number of zero-emission buses at transit agencies in the United States. The majority of those buses are battery-electric buses; however, two agencies received funding for FCEBs. SunLine's TIGGER project, listed in Table 2, includes an upgraded AFCB design based on lessons learned from the first bus demonstrated there. Flint MTA also received TIGGER funding to add one AFCB with the upgraded design. Another AFCB will be delivered to the University of California in Irvine under funding from the state. NREL plans to collect data and report on all of these buses.

FCEB Development Process—Technology Readiness Levels

In the 2012 status report report, NREL introduced a guideline for assessing the technology readiness level (TRL) for FCEBs. This guideline was developed using a Technology Readiness Assessment Guide[4] published by DOE in September 2011. NREL presented a TRL guide tailored for the commercialization of FCEBs. Figure 2 provides a graphic representation of this process. A table outlining the TRLs and definitions is included in the Appendix.

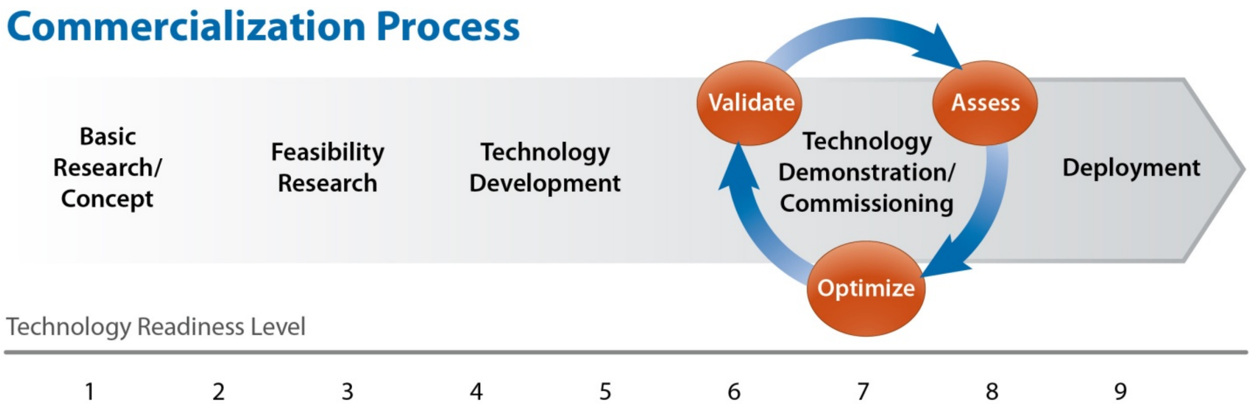

Figure 2. Graphic representation of the commercialization process developed for FCEBs

The technology demonstration/commissioning phase that includes TRLs 6 through 8 is the start of an 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.

New manufacturer teams introducing designs of FCEBs in smaller numbers are placed in the first step of the technology demonstration/commissioning phase. As with previous reports, a designation of first-generation is given to the prototype designs from new manufacturer teams that fall in TRL 6; a second-generation system is typically a follow-on design from an existing team that falls in TRL 7. These designations are used in this report for simplicity and do not necessarily coincide with any version or designation made by the manufacturers.

At this point in the development process, FCEBs are not commercial products. The manufacturers' goals for the demonstration phase are to verify that the FCEB performance meets the technical targets and identify any issues that need to be resolved. The current costs for FCEB technology—both capital and operating costs—are still much higher than that of conventional diesel technology. This is expected considering diesel is a very mature technology (TRL 9) and

[4] DOE Technology Readiness Assessment Guide, G 143.3-4a, https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view.

FCEBs are still in the development stage. Once an advanced technology, such as FCEBs, meets the performance targets, the industry can work to reduce costs. This was the case with both compressed natural gas (CNG) and diesel-hybrid bus technologies when they were first developed.

Table 4 lists the four manufacturer teams with FCEB designs that NREL is currently evaluating. This section, organized by bus original equipment manufacturer (OEM), describes each of these FCEBs and where they fall in the commercialization process outlined in Figure 2. The TRL determination for each FCEB type was made by NREL based on the descriptions in the FCEB TRL guide table (see Appendix). The designations are for each bus design as a whole package; individual components within the design might be commercially available products or prototypes. The first three manufacturer teams were described in the 2013 report. The TRL designations have not changed, but this section includes updates to the development status for each. The report was reviewed by the demonstration teams involved in the evaluations.

Table 4. Manufacturer Teams for FCEBs Currently Operating in North America

Bus OEM	Length (ft)	Fuel Cell System	Hybrid System	Design Strategy	TRL	Energy Storage
Van Hool	40	US Hybrid	Siemens ELFA integrated by Van Hool	Fuel cell dominant	7	Lithium-based batteries
New Flyer	40	Ballard	Siemens ELFA integrated by Bluways	Fuel cell dominant	7	Lithium-based batteries
ElDorado	40	Ballard	BAE Systems	Fuel cell dominant	7	Lithium-based batteries
EVAmerica	30	Ballard	Embedded Power	Battery dominant	6	Lithium titanate batteries

Van Hool—The design for this bus was originally a collaboration between UTC Power (a division of United Technologies Corporation) and Van Hool. The ZEBA buses at AC Transit and the buses previously operating at Connecticut Transit are this design. In 2012, United Technologies sold its fuel cell technology and business. At that time, US Hybrid assumed responsibility for the NFCBP projects originally awarded to UTC Power. As reported previously, this design is considered a second-generation product at TRL 7 because it involves 16 buses and the design includes upgrades based on the lessons learned from the previous FCEB.

New Flyer—This bus design is considered a second-generation product at TRL 7 because the design of the bus was led by manufacturers experienced with FCEB development and the deployment includes the 20-bus FCEB fleet in Whistler, Canada. The AT bus in operation at SunLine, which was the pilot bus for the Whistler fleet, was upgraded to match the final design of the rest of the Whistler fleet before it was eventually purchased by SunLine. The BC Transit buses were removed from service after the planned demonstration ended. New Flyer is working on a next-generation FCEB product for demonstration and has announced the purchase of a Ballard fuel cell system.

ElDorado—The development of this NFCBP-funded FCEB design was led by the hybrid manufacturer/integrator BAE Systems in partnership with Ballard Power Systems and ElDorado.

The system is based on BAE Systems' proven hybrid electric propulsion system that is commercially available for transit buses. The prototype bus has operated at SunLine for more than 2 years. Under TIGGER Program funding, the team has delivered two additional buses to SunLine that feature upgrades based on lessons learned with the prototype. The team is currently building seven additional AFCBs that will incorporate the upgrades. This bus is considered a second-generation product at TRL 7.

EVAmerica—This bus design effort is led by Embedded Power and uses a Ballard fuel cell system with lithium titanate batteries. The 30-foot bus body was built by EVAmerica. The design of this bus was originally funded as an FTA university research project, but teaming issues caused delays in completing the bus build and demonstration phase. The project received additional funds through the NFCBP to complete the bus and support the demonstration in Birmingham, Alabama. This bus is considered an early prototype design at TRL 6.

Both New Flyer and ElDorado produce transit buses for the U.S. market. Any future commercial FCEB product from these OEMs could be built to meet FTA's 'Buy America' requirements. The potential for a future U.S. FCEB product from the other two manufacturers is unclear. EVAmerica is currently insolvent and Van Hool is based in Belgium. However, the hybrid system providers could elect to move the FCEB design forward with another bus OEM.

Update of Evaluation Results Through July 2014

The data presented in this section represent the most recent results that have not been presented in a previous status report. These data come from four different FCEB demonstrations at three agencies. To simplify the presentation of the data, each FCEB is assigned an identifier that includes a site abbreviation followed by a manufacturer or project designation. All of the FCEBs presented in this section have hybrid systems that are fuel cell dominant. Table 5 provides some specifications for each FCEB by the unique identifier. The four fuel cell dominant FCEBs are pictured in Figure 3.

Table 5. FCEB Identifiers and Selected Specifications

	ACT ZEBA	BCT AT	SL AT	SL AFCB
Transit agency	AC Transit	BC Transit	SunLine	SunLine
Number of buses	12	20	1	1
Bus OEM	Van Hool	New Flyer	New Flyer	ElDorado
Model/year	A300L/2010	H40LFR/2010	H40LFR/2010	Axcess/2011
Bus length	40 ft	40 ft	40 ft	40 ft
Gross vehicle weight	39,350 lb	44,530 lb	44,530 lb	43,420 lb
Fuel cell OEM	US Hybrid	Ballard	Ballard	Ballard
Fuel cell model	Puremotion 120	FCvelocity[5] HD6	FCvelocity HD6	FCvelocity HD6
Fuel cell power (kW)	120	150	150	150
Hybrid system integrator	Van Hool	Bluways	Bluways	BAE Systems
Design strategy	FC dominant	FC dominant	FC dominant	FC dominant
Energy storage OEM	EnerDel	Valence	Valence	A123
Energy storage type	Li-ion	Li-ion	Li-ion	Li-ion
Energy storage capacity	21 kWh	47 kWh	47 kWh	11 kWh
Hydrogen storage pressure (psi)	5,000	5,000	5,000	5,000
Hydrogen cylinders	8	8	6	8
Hydrogen capacity (kg)	40	56	43	50
TRL	7	7	7	7

Baseline buses—Conventional baseline bus data are provided for comparison with FCEB data when comparable buses are available. Data on baseline buses were included for all sites. For AC Transit, the primary comparison is with diesel buses. The BC Transit FCEBs were operated in Whistler, BC, and made up the majority of the fleet (20 of 23 total buses). The diesel buses in the Whistler fleet were used in a different service from the FCEBs. As a result, BC Transit provided the diesel baseline numbers based on an average for diesel buses operated in similar service at another of the agency's locations. The baseline buses at SunLine are CNG because the agency does not operate diesel buses. The Appendix summarizes the data results by demonstration location and provides additional charts that detail some of the results by agency.

Data periods included in the report—Although the report is focused on data from August 2013 through July 2014, the data period for each demonstration varies depending on the project status. The ZEBA buses and the two buses at SunLine were in service for the entire 12-month period;

[5] FCvelocity is a registered trademark of Ballard Power Systems.

however, at the time of publication, NREL only had the data on the ZEBA buses through June 2014. The BC Transit demonstration ended as scheduled at the end of March 2014. For this reason, NREL used the final year of data from April 2013 through March 2014 in this report.

Figure 3. FCEBs included in the data summary: AC Transit ZEBA FCEB (top left), BC TRANSIT FCEB (top right), SunLine AFCB (bottom left), SunLine AT FCEB (bottom right)

Total miles and hours—Table 6 shows miles, hours, average speed, and average monthly miles per bus for the FCEBs. The AFCB at SunLine has the highest average speed at 15.6 mph, followed by the BC Transit buses at 14.2 mph. SunLine's AT bus operates primarily on one specific route, while the AFCB has operated on several routes within the service area. The ZEBA buses in service at AC Transit have the lowest average speed at 8.5 mph. The average monthly bus use by demonstration ranges from a low of approximately 1,339 miles up to 2,927 miles per month. The average for the group is 2,189 miles per month. This is slightly higher than the average reported last year (1,534 miles per month), although the monthly miles for both the SunLine AFCB and the ZEBA buses are lower than in the last reporting period.

Table 6. Miles and Hours for the FCEBs

ID	Period	Months	No. of Buses	Miles	Hours	Avg. Speed (mph)	Avg. Monthly Miles
ACT ZEBA	8/13–6/14	11	12	337,237	39,717	8.5	2,555
BC Transit	4/13–3/14	12	20	561,923	42,749	14.2	2,927
SL AT	8/13–7/14	12	1	16,066	1,109	11.6	1,339
SL AFCB	8/13–7/14	12	1	23,218	1,486	15.6	1,935

Bus use—Figure 4 shows the average monthly bus use for the fuel cell buses and their respective baseline buses. The target of 3,000 miles is included on the chart. Most transit agencies continue to operate their fuel cell buses for fewer miles than they operate their baseline buses. This was not the case for BC Transit because the FCEBs made up the majority of the fleet (20 out of 23 buses).

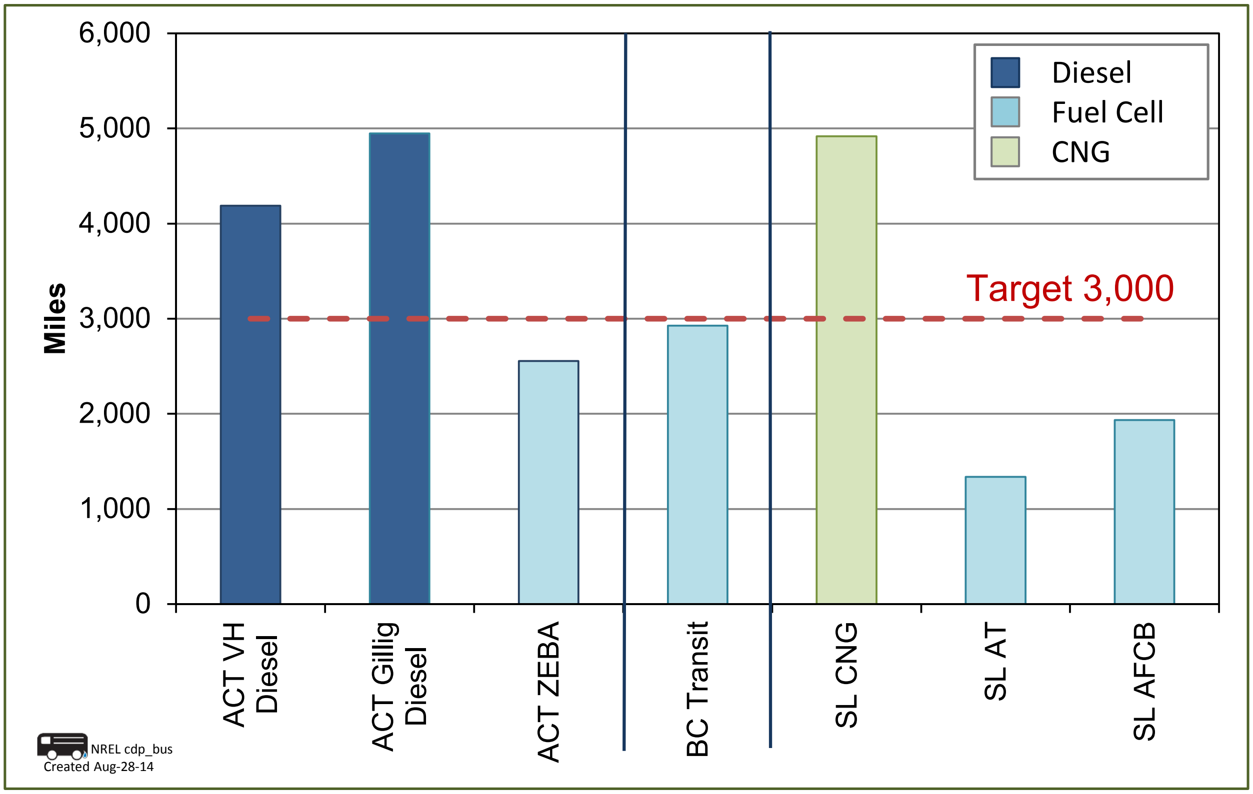

Figure 4. Average monthly mileage for the FCEBs and baseline buses

Availability—Availability is the percentage of days the buses are actually available out of days that buses are planned for operation. For AC Transit and BC Transit, the buses are planned to operate every day. For SunLine, the buses are typically planned to operate on weekdays; however, they often operate on weekends as well. Table 7 summarizes the availability of the fuel cell buses at each transit agency. Availability varies from site to site with a low of 45% up to a high of 72%. The average availability for the group is 70%. Figure 5 tracks the monthly availability for the FCEBs by project. The percent availability is shown as a separate colored line for each of the projects with the combined overall average for all of the FCEBs in orange.

Table 7. Availability for the FCEBs

ID	Period	Months	No. of Buses	Planned Days	Days Avail.	% Avail.
ACT ZEBA	8/13–6/14	11	12	1,479	1,197	72%
BC Transit	4/13–3/14	12	20	4,649	3,286	71%
SL AT	8/13–7/14	12	1	282	126	45%
SL AFCB	8/13–7/14	12	1	310	188	61%

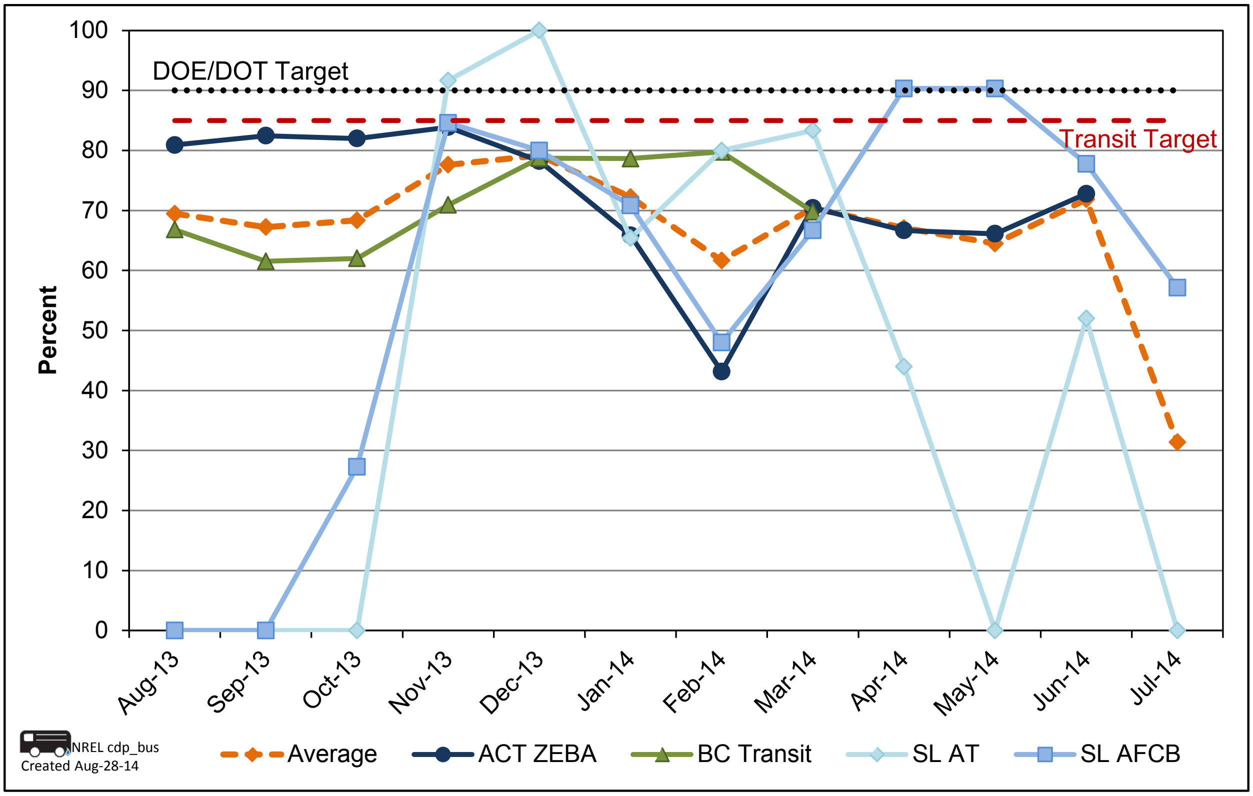

Figure 5. Monthly availability for the FCEBs

The ACT ZEBA FCEBs (dark blue line) were in service the entire data period. Availability dipped in February because an issue at the hydrogen station resulted in fuel unavailability. Drive system problems with two buses caused lower availability for the later months in the period.

The monthly availability for the BC Transit buses (green line) ranged between 60 and 80 percent. In the final year of the demonstration, several buses developed issues with one of the systems. 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, and the adjusted numbers are presented in this report.

The SL AFCB (medium blue line) was out of service at the beginning of the data period due to a coolant leak eventually traced to the radiator. Troubleshooting the problem proved to be difficult and contractual issues further extended the downtime of the bus. The leak was repaired in October 2013 and the availability increased. Issues with the fuel cell reduced the availability in February, and a hydrogen tank valve replacement resulted in lower availability in July.

The availability of the SunLine AT bus (light blue line) was much lower than what has been reported previously. The bus continues to have issues with the traction batteries and the hybrid system.

Figure 6 presents individual pie charts that show the reasons for unavailability by category for each of the four demonstrations. The data provided for the demonstrations at SunLine and AC Transit included the specific reason for each day the bus was not available. BC Transit tracks the availability of the buses but does not record the specific reason why a bus is not available. Because of this, a categorization of unavailability reasons is not possible. The pie chart for BC Transit instead includes a breakdown of labor hours by category to indicate the systems that are causing downtime. For the AFCB, the majority of problems have been related to bus-related components. For the other three demonstrations, problems with batteries and hybrid propulsion systems have been the dominant factors causing downtime.

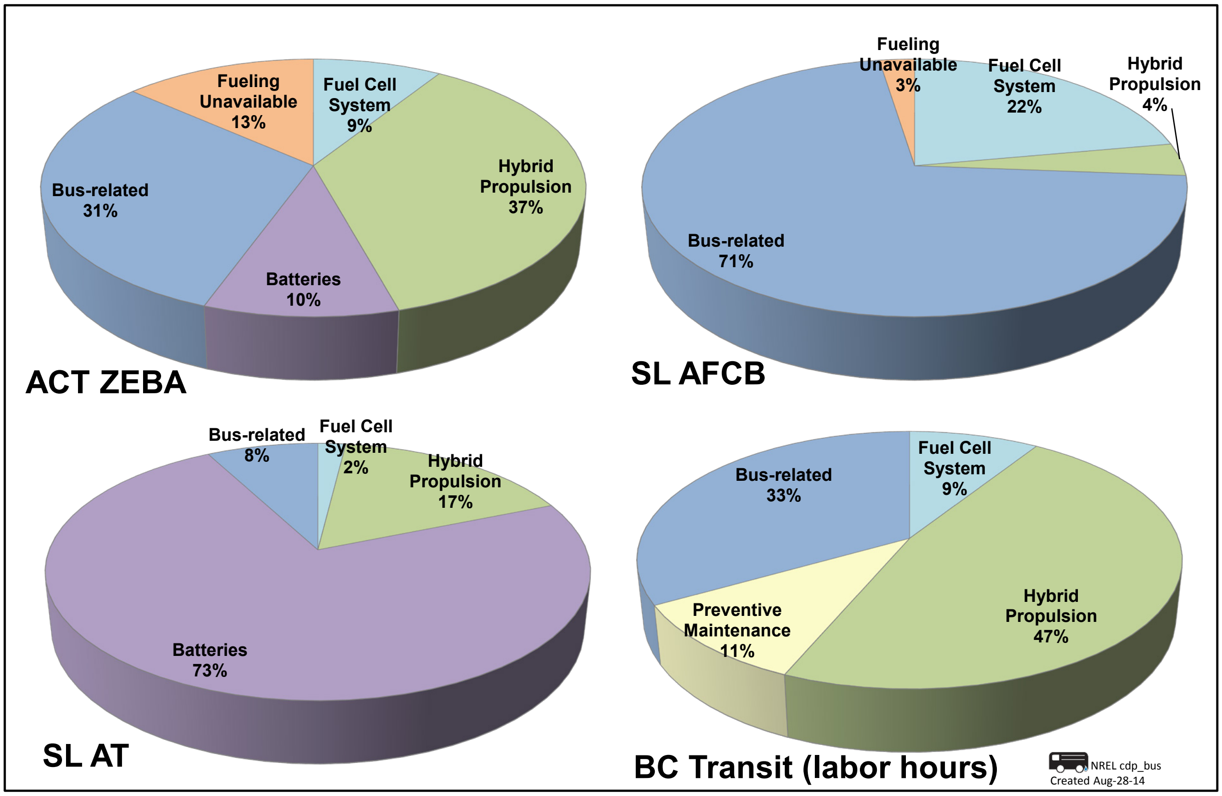

Figure 6. Reasons for unavailability for the FCEBs

Fuel economy—Table 8 shows the average fuel economy in miles per diesel gallon equivalent (mi/DGE) for each type of FCEB compared to the conventional baseline bus technology at the same site. The AC Transit ZEBA buses are compared to both Van Hool (VH) and Gillig diesel buses. The fuel economy for the ZEBA buses is 1.8 times higher than that of the Van Hool diesel buses and 1.6 times higher than that of the Gillig buses. The FCEBs at BC Transit demonstrate lower fuel economy than that typically shown at other locations and only slightly higher than that of the diesel buses. Several factors contribute to these lower numbers including FCEB design strategy, an oversized heater, and a harsh duty cycle (extreme grades, seasonal high passenger loadings, cold temperatures, and wet conditions). The FCEBs at SunLine both show improved fuel economy that is about 2 times higher than that of the CNG baseline buses.

Table 8. Average Fuel Economy Comparisons Between the FCEBs and Baseline Buses

ID	Miles per kg or GGE[a]	Miles per DGE	Difference from Baseline
ACT ZEBA	6.43	7.26	1.84x / 1.65x
ACT VH diesel	–	3.95	–
ACT Gillig diesel	–	4.39	–
BC Transit	3.83	4.32	1.01x
BC Transit diesel	–	4.28	–
SL AT	5.67	6.40	1.99x
SL AFCB	6.19	6.99	2.17x
SL CNG	2.88	3.22	–

[a] GGE: Gasoline gallon equivalent.

Figure 7 shows the fuel economy by month over the last year. In order to show the last full year of the BC Transit data, the chart begins with April 2013. The FCEBs continue to show improved fuel economy compared to the baseline buses in similar service. The fuel economy for hybrid fuel cell systems tends to vary from site to site depending on the duty cycle.

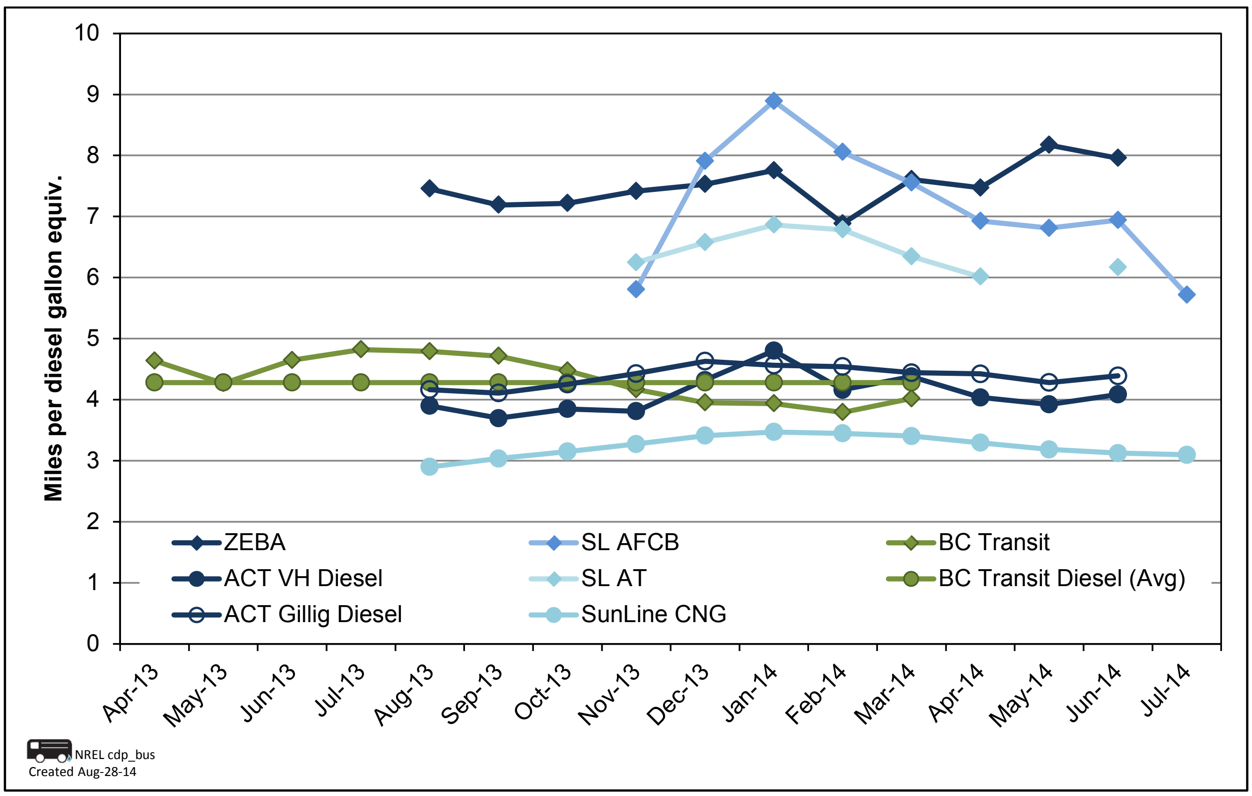

Figure 7. Fuel economy for FCEBs and baseline buses

Roadcalls—A roadcall or revenue vehicle system failure (see the National Transit Database[6]) is a failure of an in-service bus that causes the bus to be replaced on route or causes a significant

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

delay in schedule. If the bus is repaired during a layover and the schedule is maintained, then no roadcall is recorded. Figure 8 shows miles between roadcalls (MBRC) for bus roadcalls,[7] for propulsion-related-only roadcalls,[8] and for fuel-cell-system-only roadcalls[9] for the FCEBs during the data period. The black hashed line marks the DOE/FTA target for bus MBRC (4,000), and the orange hashed line is the target for fuel-cell-system-related MBRC (20,000). A secondary target of 10,000 MBRC for propulsion systems is marked with a red hashed line. This is not one of the DOE/FTA targets; however, it is a general target for the transit industry. While the MBRC rates are still lower than the targets, the MBRC for fuel-cell-system-only roadcalls shows that the reasons are not typically due to the fuel cell.

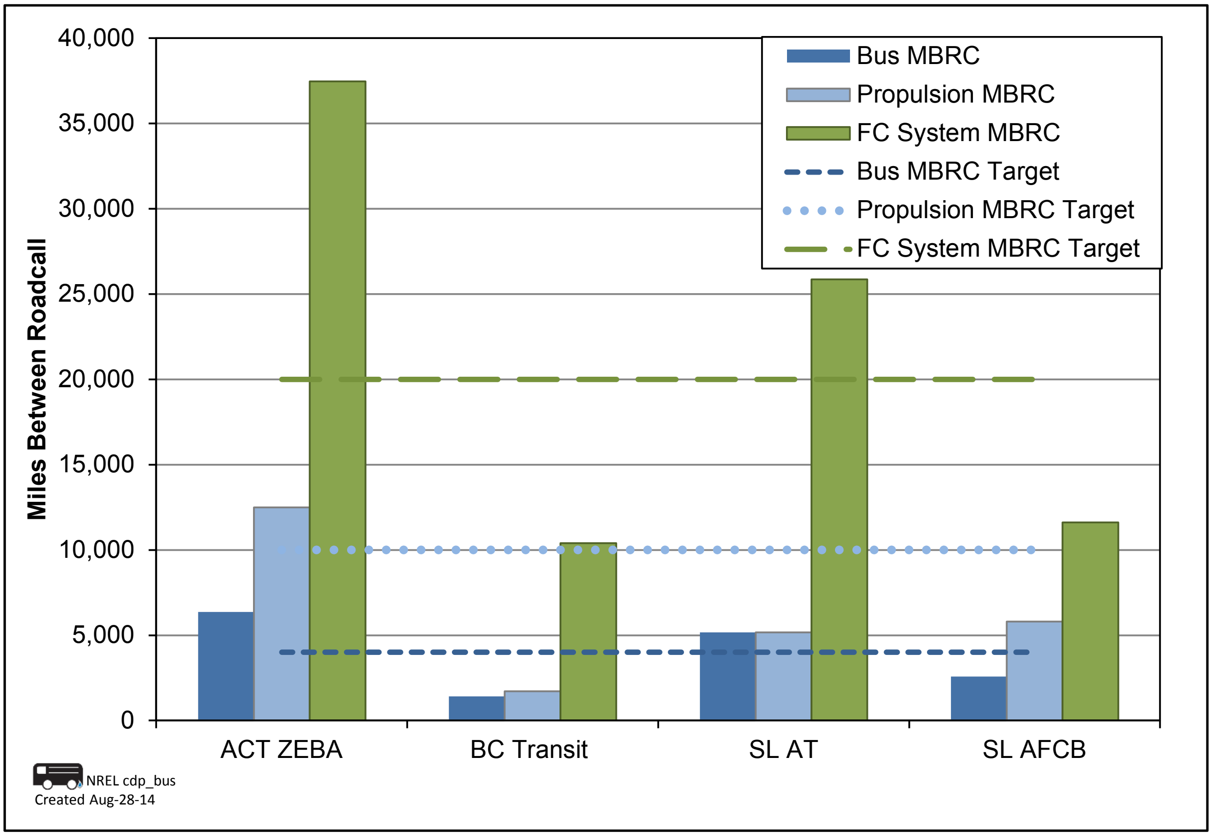

Figure 8. MBRC rates for FCEBs compared to the targets

Hydrogen fueling—NREL tracks total hydrogen use for FCEBs at all of the sites. Figure 9 shows the total hydrogen dispensed over time for the three primary sites since the current buses went into service through July 2014. Since that time, these FCEBs were fueled with more than 568,000 kg of hydrogen. During the past year at the three transit sites, the FCEBs were fueled 7,252 times with a total of 186,376 kg of hydrogen. The average fill amount for these fuel cell dominant FCEBs was 25.7 kg per fill.

[7] Bus MBRC is all chargeable roadcalls including propulsion-related issues as well as problems with bus-related systems such as brakes, suspension, steering, windows, doors, and tires.
[8] Propulsion-related MBRC 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.
[9] Fuel-cell-related MBRC includes roadcalls attributed to the fuel cell power plant and balance of plant only.

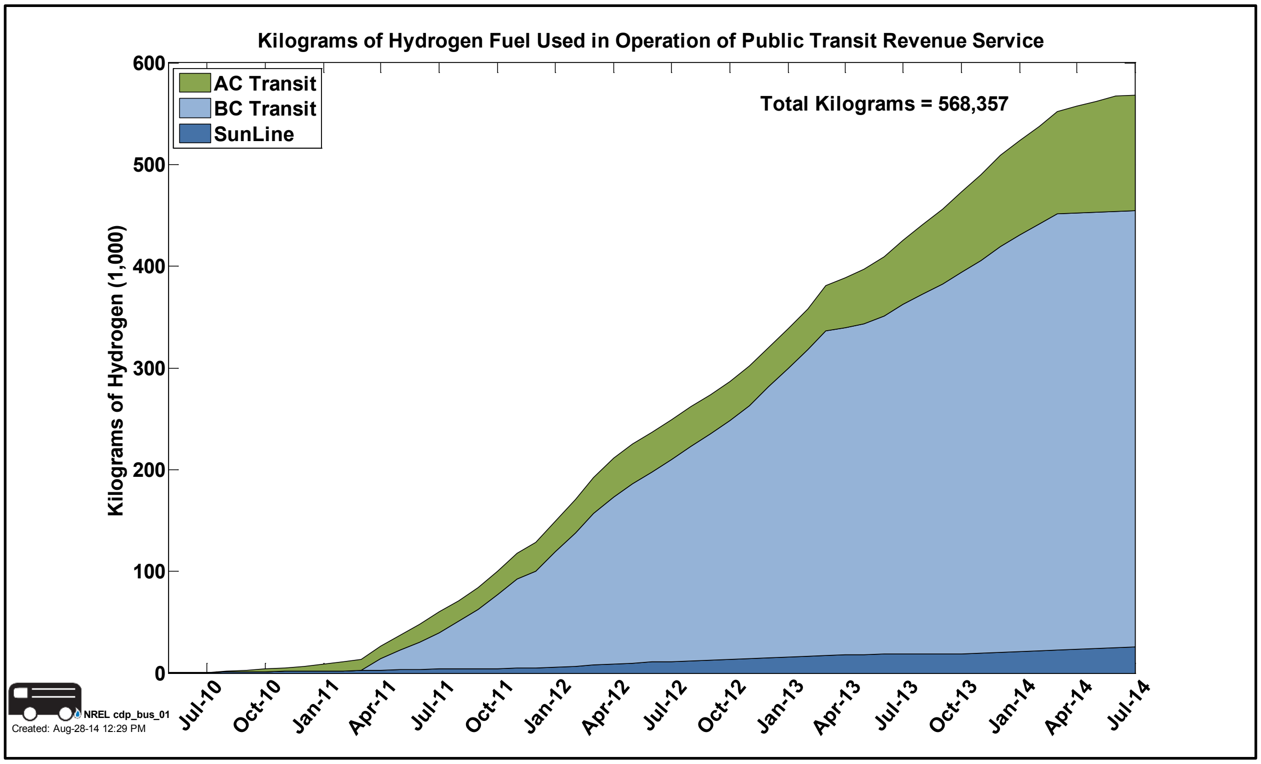

Figure 9. Hydrogen dispensed for the FCEBs through July 2014

Current Status of FCEB Introductions: Summary of Achievements and Challenges

FCEB technology continues to show progress toward meeting technical targets for increasing reliability and durability as well as reducing costs. This section discusses the progress being made and the challenges that remain to bring FCEBs to the market.

Progress Toward Meeting Technical Targets

In 2012, DOE and FTA established performance, and cost targets for FCEBs in a Fuel Cell Technologies Program Record.[10] Interim targets were set for 2016 along with ultimate targets that FCEBs would need to meet to compete with current commercial technology buses. Table 9 shows a selection of these technical targets for FCEBs.

Table 9. DOE/FTA Performance, Cost, and Durability Targets for FCEBs[a]

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

[a] The cost targets for subsystems (power plant and hydrogen storage) are not included.
[b] The power plant is defined as the fuel cell system and the battery system.
[c] Cost is projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only and does not represent an anticipated level of sales.
[d] Excludes mid-life overhaul of power plant.

Bus and power plant lifetime—The FTA minimum life cycle requirement for a full size bus is 12 years or 500,000 miles.[11] An FCPP needs to last about half of that time; this compares to a diesel engine that is often 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. In last year's report, NREL documented a single

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

FCPP surpassing 13,000 hours without repair or cell replacement. At the end of the analysis period for this report (July 2014), that FCPP had surpassed 17,200 hours, and as of December 2014 it has surpassed 18,000 hours. The addition of BC Transit to the analysis provides data on an additional 22 FCPPs (20 bus FCPPs plus 2 spares). Figure 10 shows the total hours accumulated on 36 FCPPs for the demonstrations at AC Transit (orange bars), BC Transit (blue bars), and SunLine (green bars). The DOE/FTA 2016 target for FCPPs of 18,000 hours is highlighted in the figure (orange hashed line), as is the group average of 8,968 hours (black hashed line). Of the 36 total FCPPs included in the graph, 75% (27) have surpassed 8,000 hours of operation. This shows significant improvement in durability toward meeting the 25,000 hour target.

It takes a significant amount of time to reach the higher hours shown in the figure. The BC Transit buses went into service in 2010 and were operated for more than 4 years. SunLine's AT FCEB and AC Transit's ZEBA buses also have been in service for more than 4 years. SunLine's AFCB has been operating for about 2.5 years. The FCPP with the highest hours was originally operated in the first-generation buses at AC Transit. At the end of that demonstration, the FCPP was transferred into a second-generation FCEB to continue to validate the system in service. Two additional FCPPs were transferred from early-generation buses into ZEBA buses. All three older FCPPs continue to accumulate hours. Although the BC Transit buses are no longer in service, Ballard reports that none of the 22 FCPPs had reached the end of life based on voltage degradation or leakage criteria.

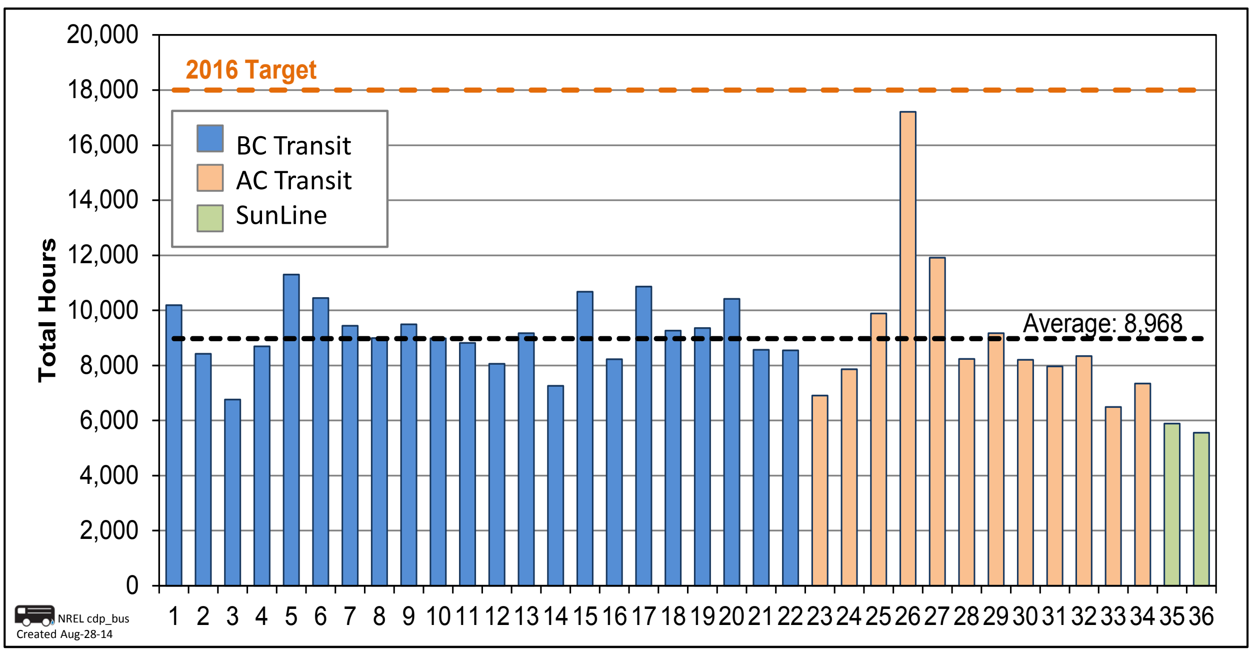

Figure 10. Total hours on the FCEBs through July 2014

Bus availability—As shown in the data summary section, the average bus availability for the four FCEB demonstrations ranges from a low of 45% to a high of 72%, with the overall average at 70%. Although this is much lower than the target, it is not unexpected for technology at this stage of development. Despite the lower availability numbers for one project, the average shows an increase over 2012 and 2013, when the overall average availability was 57% and 69%, respectively. The reasons for unavailability continue to be most often attributed to bus-related issues followed by hybrid system and battery issues. Downtime has been extended in some cases because intermittent issues are difficult to troubleshoot. For example, AC Transit experienced drive system faults with a couple of the ZEBA buses that have proved difficult to diagnose.

The manufacturers continue to work through issues with the integration and communication software between new systems and have shown progress in addressing the problems causing downtime. As the manufacturers identify and solve the issues, the availability is expected to increase.

Roadcall frequency—The transit industry measures reliability as mean distance between failure, also documented as MBRC. The DOE/FTA targets for roadcall frequency include MBRC for the entire bus and MBRC for the fuel cell system only. Bus MBRC includes all chargeable roadcalls, which means any issue that could physically disable the bus from operating on route. It does not include roadcalls for items such as fareboxes, radios, or destination signs. The fuel cell system MBRC includes any roadcalls due to issues with the fuel cell stack or associated balance of plant. NREL tracks an additional metric of propulsion system MBRC. This category includes all roadcalls due to propulsion-related bus systems. Propulsion-related systems include the fuel cell system (or engine for a conventional bus), electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, and transmission systems.

Each year, NREL presents summary data from the most recent evaluations. As demonstrations end, the data from those evaluations are removed from the combined calculations, while others are added. This makes it challenging to compare the current year's data to previous years because the data set can change significantly. Last year's report included four buses from the CTTRANSIT demonstration as well as a battery dominant prototype bus. Those demonstrations ended, and the 20-bus fleet at BC Transit was added to the data set. To better illustrate the trend over time of the FCEB designs included in this report, the following MBRC results include reliability data from these fleets back to the beginning of the evaluation periods. Figure 11 shows the monthly MBRC over time for all four bus demonstrations combined. The 2016 targets for bus MBRC and FC system MBRC are included as dashed lines on the chart. The black dotted line plots the trailing 12-month average for the FC system MBRC and shows a general upward trend, approaching the 2016 target toward the end of the data period.

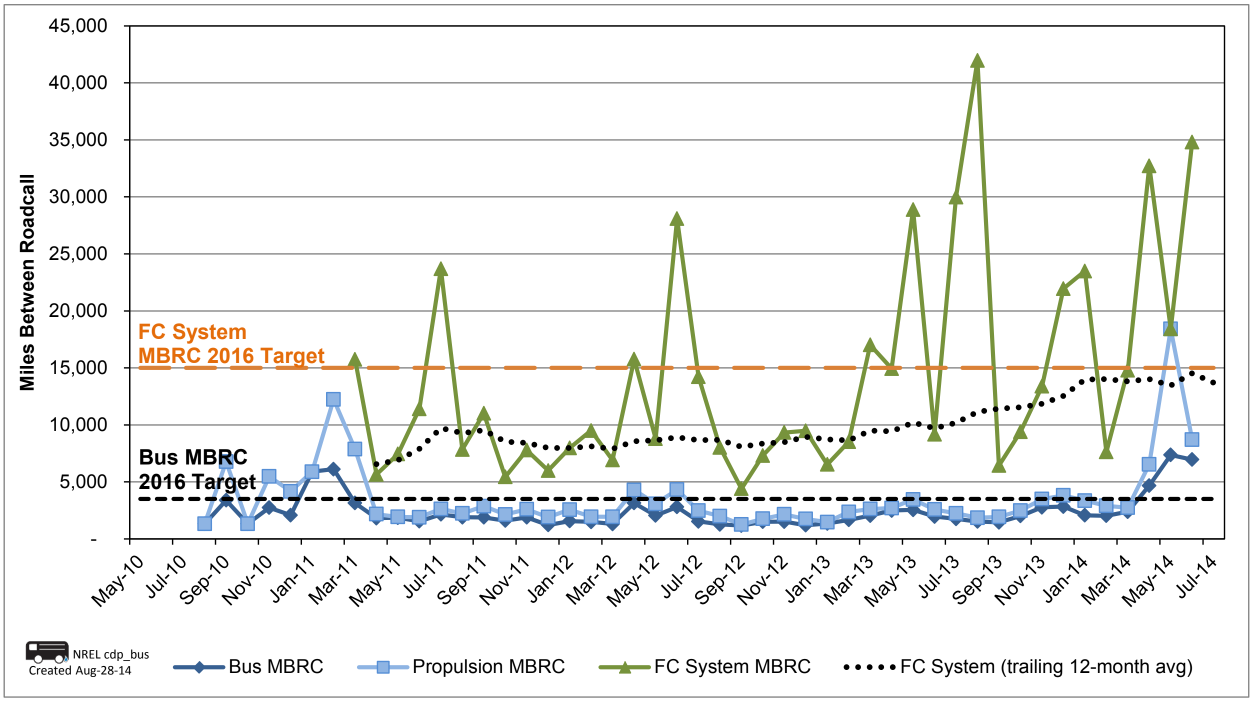

Figure 11. Monthly MBRC for the FCEBs

Table 10 provides the MBRC data for the four demonstrations over three separate data periods covering the last 3 years. The bus and propulsion system MBRCs decreased slightly from the first data period to the second and then increased by more than 25% during the third data period. The FC system MBRC shows an increase of approximately 15% from data period one to two and an increase of more than 25% from data period two to three.

Table 10. Summary of MBRC for the Last Three Years

	Data Period 1 8/11–7/12	Data Period 2 8/12–7/13	Data Period 3 8/13–7/14
Total miles	884,996	897,054	726,229
Bus roadcalls	517	537	325
Bus MBRC	1,712	1,670	2,235
Propulsion system roadcalls	358	421	248
Propulsion system MBRC	2,472	2,131	2,928
FC system roadcalls	102	88	53
FC system MBRC	8,676	10,194	13,702

Range and fuel economy—Table 11 lists the fuel economy and hydrogen capacity for the FCEBs in all four demonstrations as well as an overall average for 40-foot buses. Fuel economy for the FCEBs ranged from 3.83 mi/kg up to 6.43 mi/kg for an average of 5.53 mi/kg. The estimated range is calculated based on the fuel economy numbers and useful fuel amount (95% of the tank's capacity), resulting in an estimated average range for the group of 229 miles.

Table 11. Fuel Economy and Range for the FCEBs

ID	Period	Fuel Economy (mi/kg)	Hydrogen Capacity (kg)	Range (miles)
ACT ZEBA	8/13–6/14	6.43	40	244
BC Transit	4/13–3/14	3.83	40	145
SL AT	8/13–7/14	5.67	43	231
SL AFCB	8/13–7/14	6.19	50	294
Average for 40-ft FCEBs		**5.53**		**229**

Remaining Challenges

FCEB performance continues to improve, and new FCEB designs have incorporated the early lessons learned from the first-generation systems. However, there are still challenges to overcome to move FCEB technology to a commercial product. This section outlines the ongoing challenges as well as lessons learned from recent issues that occurred over the last year.

Changing market players—The FCEB industry continues to have issues with companies dropping out of the market through restructuring or bankruptcy. This makes conducting long-term demonstrations a challenge when the partners no longer provide technical support or produce replacement parts. The previous report noted the exit of UTC Power from the market when its parent company, United Technologies, made a business decision to sell its fuel cell division. This division included the PEM fuel cell production capability for transit bus (and other transportation applications) power plants as well as the phosphoric acid fuel cell production capability for the stationary power business. The PEM transportation portion was purchased by US Hybrid and the stationary fuel cell portion was purchased by ClearEdge Power, a relatively small company in the fuel cell market. This development had a ripple effect on the NFCBP because of several incomplete projects that were awarded to UTC Power. US Hybrid stepped in to take on the UTC Power projects, including one to develop a next-generation FCPP for buses. US Hybrid has been involved in several component development projects funded through the NFCBP and understands the program goals. The company has taken over the South Windsor, Connecticut, fuel cell development and production facility and established US Fuel Cell as a division of US Hybrid. The company has licensed the fuel cell technology and plans to produce FCPPs for the transit bus market as well as the medium, and heavy-duty specialty and delivery trucks market. ClearEdge Power declared bankruptcy in 2014.

The BC Transit project was also plagued by manufacturer problems. Early in the demonstration, the integrator of the bus design, ISE Corporation, declared bankruptcy. As the primary manufacturer for the BC Transit 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.

Integration/optimization of components—Manufacturers continue to work on issues with systems integration and optimization, which is still one of the major challenges for FCEBs. Transit agencies are working closely with the manufacturers to optimize and update hybrid systems to eliminate problems and increase performance. For the AC Transit ZEBA buses, software changes have helped address issues with the hybrid system and energy storage. Some of the early issues were intermittent, which made troubleshooting difficult. The modifications have helped; however, two buses have experienced extended downtime with drive system issues that have proved difficult to diagnose.

BC Transit's FCEB fleet developed issues with the air supply system for the fuel cell. This system is made up of three main components: air compressor, motor, and controller assembly. The components were sourced and integrated into the system by the original integrator (ISE Corporation). This 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. Retrofits eliminated this failure in the first year of operation. The compressors began to fail after that, followed by motor failures. 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.

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. Replacement parts can be hard to locate because manufacturers have stopped producing the older designs or have gone out of business. 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 as a one-to-one replacement because it was not the same size as the original modules and had different operating characteristics.

Parts availability—Finding replacement parts is also an issue for many FCEB projects because some advanced components are not common and can be costly. AC Transit has had issues with replacement parts that have a long lead time for delivery, in some cases because they come from outside the United States. These components were not typically stocked and were only ordered when needed. This has changed over time as the project partners have learned what should be kept on hand. While convenient, stocking these components can also be challenging—not only because the cost for advanced technologies can be high, but also because warranties on a component often begin when it is shipped, and the warranty can run out before it is installed. Although the parts supply issues have improved at AC Transit, they have not yet been completely resolved. After operating the buses for several years, the agency understands what parts need to be on-hand and has added these parts to its inventory. BC Transit also experienced similar issues with parts supplies. The air supply system issues that occurred toward the end of the planned demonstration resulted in the agency permanently removing several buses 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 planned demonstration.

Bus build process—The previous report outlined the progress made by the industry to integrate FCEB manufacturing into the standard process for conventional technology buses. For FCEBs to be fully commercialized, the fuel cell hybrid propulsion system needs to be an option offered by the bus OEM, as opposed to the current process for most projects where the hybrid system integrator has the lead role in developing and building the bus. The development team of BAE Systems, Ballard, and ElDorado National began to take that step with SunLine's order for two AFCBs under the FTA TIGGER Program. The first bus glider was shipped to BAE Systems for integration of the propulsion system. BAE Systems worked with ElDorado staff to complete the installation. The second bus was entirely built at the ElDorado factory with support from BAE Systems. Over the last year, more transit agencies have placed orders for this updated AFCB. These buses are being built at the ElDorado facility in the standard production line along with conventional technology buses. To date there have been orders for seven more AFCBs, bringing the total fleet to 10 (outlined in Table 12). This represents a major step toward commercialization for FCEBs; however, more OEMs need to make this commitment before the industry can be sustained.

Table 12. Current and Planned AFCBs in the United States

Operator	Location	Number of AFCBs	Status
SunLine	Thousand Palms, CA	1	Original prototype bus—in operation
SunLine	Thousand Palms, CA	2	TIGGER buses—both delivered, one in service
MBTA	Boston, MA	1	Expected delivery late 2014
CTTRANSIT	Hartford, CT	1	Expected delivery late 2014
UCI	Irvine, CA	1	Expected delivery early 2015
Flint MTA	Flint, MI	1	Expected delivery mid 2015
SARTA	Canton, OH	2	Expected delivery mid 2015
TCAT	Ithaca, NY	1	Expected delivery late 2015
Total fleet		10	

Weight—FCEBs are typically heavier than similar-sized conventional buses because of added systems such as hydrogen tanks and energy storage systems. In the past, FCEB demonstrations have been forced to reduce the number of allowable standing passengers to avoid being over acceptable weight requirements. The BC Transit buses had issues with the suspension because of the weight and the difficult duty cycle in Whistler. 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. Newer designs have incorporated technology to reduce the weight compared to previous models. The AC Transit ZEBA buses are approximately 5,000 lb lighter than the early-generation buses, although the buses are still about 3,000 lb heavier than the comparable diesel model.

Transition of maintenance to transit staff—The transition of knowledge from the manufacturers to the transit staff is essential to commercializing the technology. Much progress has been made over the last few years toward reaching this goal. Past demonstrations have included on-site manufacturer staff to handle preventive maintenance and repair of the more advanced components. This is rapidly changing. At AC Transit, agency staff has received training and taken on all preventive maintenance and repair work on the fuel cell buses. US Hybrid developed the service and maintenance manual, wireless diagnostic tools, and resources that the agency can use to help troubleshoot issues and perform the repairs on-site. Any manufacturer support needed will be provided mainly through remote diagnostics. A site visit for repair will only be necessary occasionally. The BC Transit project was very successful at transitioning the maintenance work to Whistler Transit staff. 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. SunLine's experience has been similar to the other two agencies, but the transition was faster because the agency has past FCEB experience dating back to 2000. SunLine staff members were already familiar with the general operation and maintenance of a FCEB—they only needed to learn the specifics of the components from a new manufacturer.

Costs for FCEBs—At this point in the development of FCEB technology, costs are still high. DOE/FTA has set a 2016 target for capital cost of $1 million per bus with an ultimate target of $600,000 per bus. Bus capital costs have dropped from that of early designs at more than $3 million, but they are still an order of magnitude higher than conventional diesel bus costs. This is expected to decrease with larger orders of buses. As far as operational costs, most FCEB demonstration project buses are still covered under some level of warranty support from the manufacturers. Although agencies have increased staff to begin transitioning to in-house maintenance, most parts costs are still covered under warranty. To help with future planning, transit agencies need to understand what future costs will be as the technology moves into early commercial deployment. With the help of government grants, transit agencies have been successful in negotiating extended warranties for the FCEBs.

New Research to Facilitate Commercialization

FTA has funded several areas of research to aid in commercializing FCEB technology. These projects, which are part of the NFCBP, are described below.

Altoona testing—FTA has funded a project under the NFCBP that will provide one FCEB for testing at Altoona. New bus models must be tested before they can be purchased with federal funds.[12] The testing is conducted at the Altoona Bus Research and Testing Center in Altoona, Pennsylvania. Because FCEBs are still in development, none have been submitted for this testing. In addition to conducting the comprehensive tests required for a commercial bus, the project will help develop consistent procedures and guidelines for testing all FCEBs. This is an important step in commercializing FCEBs for the transit industry.

Zero emission bus procurement risk management—Typical bus procurements involve commercially mature technologies that are a limited risk for agencies. For technologies such as FCEBs that are still in the early stage of development, procurement poses a higher level of risk than transit agencies can take on. With FTA oversight, CTE and the American Public Transportation Association are leading a committee to explore risk management for advanced technology bus procurements. The committee is composed of a select group of manufacturers, transit agencies, and subcomponent suppliers. The committee's goal is to provide guidance for adequate risk management of advanced technology bus and infrastructure procurements, allowing for open competition and growth of emerging technology suppliers. The committee has begun discussions with the key stakeholders to understand the concerns from each perspective and identify solutions to address the issues.

Market analysis for FCEBs in the United States—FTA has funded a project to provide a better understanding of the market for FCEBs in the United States. The project is being conducted by CALSTART with input from U.S. transit agencies. CALSTART is analyzing the market to determine FCEB demand, price sensitivity, consumer acceptance, energy efficiency benefits, and service and maintenance requirements. The study results will help FTA, DOE, and the transit industry better understand the future market for the technology and what transit agencies need for improved implementation.

Best practices for fueling and maintenance facilities—FTA has funded an effort by CALSTART to develop a best practices guide for fueling and maintenance facilities. This guide is being developed with input from transit agencies that have FCEB experience as well as key hydrogen infrastructure partners. The guide will be an important resource for agencies as they plan for future FCEB deployments.

[12] The Surface Transportation and Uniform Relocation Assistance Act of 1987, Section 317.

What's Expected for the 2015 Status Report

This report includes data from four different FCEB bus designs at three sites. In the next year, several new demonstrations should begin, and NREL expects to monitor and evaluate those demonstrations with funding from DOE and FTA. The addition of new FCEB designs and demonstration locations is expected to expand this annual assessment report's scope for determining the status of development. NREL plans to produce several new evaluation reports to present data and experiences from each of these sites.

In addition to the current FCEBs, the following demonstrations (with number of buses in parentheses) are expected to be included in next year's assessment report:

- EV America/Ballard bus in Birmingham, Alabama (1)
- Next-generation AFCB at SunLine in Thousand Palms, California (2)
- Next-generation AFCB at Massachusetts Bay Transportation Authority in Boston, Massachusetts (1)
- Next-generation AFCB at CTTRANSIT in Hartford, Connecticut (1)
- Proterra next-generation battery dominant FCEB at Capital Metro in Austin, Texas (1).

The following additional buses may begin operation and have data available for the next report:

- Additional AFCBs in four locations:
    - Tompkins Consolidated Area Transit in Ithaca, New York (1)
    - Stark Area Regional Transit Authority in Canton, Ohio (2)
    - Flint Mass Transportation Authority in Flint, Michigan (1)
    - University of California at Irvine (1).

These demonstrations may not have enough data available to be included in the next assessment report; however, a status update will be provided.

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. Some of the most recent reports are included here.

Eudy, L.; Post, M. (2014). *BC Transit Fuel Cell Bus Project Evaluation Results: Second Report*. NREL/TP-5400-62317. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Post, M. (2014). *Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: Third Results Report*. NREL/TP-5400-60527. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Post, M. (2014). *BC Transit Fuel Cell Bus Project: Evaluation Results Report*. NREL/TP-5400-60603. Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Gikakis, C. (2013). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2013*. NREL/TP-5400-60490. Golden, CO: National Renewable Energy Laboratory.

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

Eudy, L.; Chandler, K. (2013). *SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Fourth Results Report*. NREL/TP-5600-57560. Golden, CO: National Renewable Energy Laboratory.

Appendix: Summary Statistics

Table A-1. Technology Readiness Levels for FCEB Commercialization

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Deployment (Stage 6)	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 (Stage 5)	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 (Stage 3–4)	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 (Stage 2)	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 (Stage 1)	TRL 1	Basic principles observed and reported	Scientific research and early development of FCEB concepts.

AC Transit ZEBA Demonstration Summary

Table A-2. AC Transit Data Summary

	ACT ZEBA All Data	ACT ZEBA Past Year	ACT VH Diesel All Data	ACT VH Diesel Past Year	ACT Gillig Diesel All Data	ACT Gillig Diesel Past Year
Data period	9/11–6/14	8/13–6/14	9/11–6/14	8/13–6/14	7/13–6/14	8/13–6/14
Number of buses	12	12	3	3	13	11
Number of months	26	11	26	11	10	10
Total miles	611,235	337,237	154,921	154,921	588,123	544,169
Total FC hours	72,066	39,717	–	–	–	–
Average speed (mph)	8.5	8.5	–	–	–	–
Average miles per month	2,144	2,555	3,977	4,187	4,901	4,947
Number of scheduled days	7,706	4,007	2,268	1,032	3,650	3,340
Number of days available	5,343	2,896	1,757	778	3,131	2,870
Availability	69%	72%	77%	75%	86%	86%
Fuel economy (mi/kg)	6.46	6.43	–	–	–	–
Fuel economy (mi/DGE)	7.30	7.26	3.94	3.95	4.33	4.39
Bus MBRC	4,102	6,363	3,077	4,695	6,257	6,802
Propulsion-only MBRC	6,739	12,490	7,461	15,492	16,804	21,767
FC system-only MBRC	17,380	37,471	–	–	–	–
Total hydrogen used (kg)	89,006	50,672	–	–	–	–
SI Units						
Total kilometers	983,687	542,730	249,321	249,321	946,492	875,755
Average speed (kph)	13.6	13.7	–	–	–	–
Average km per month	3,153	4,112	3,196	7,555	7,281	7,961
Fuel consumption (kg/100 km)	9.62	9.67	–	–	–	–
Fuel consumption (L/100 km)	30.31	31.27	60.00	59.85	54.61	53.89
Bus km between roadcalls (KBRC)	6,602	10,240	4,952	7,555	10,069	10,947
Propulsion-only KBRC	10,846	20,101	12,008	24,932	27,043	35,030
FC system-only KBRC	27,971	60,303	–	–	–	–

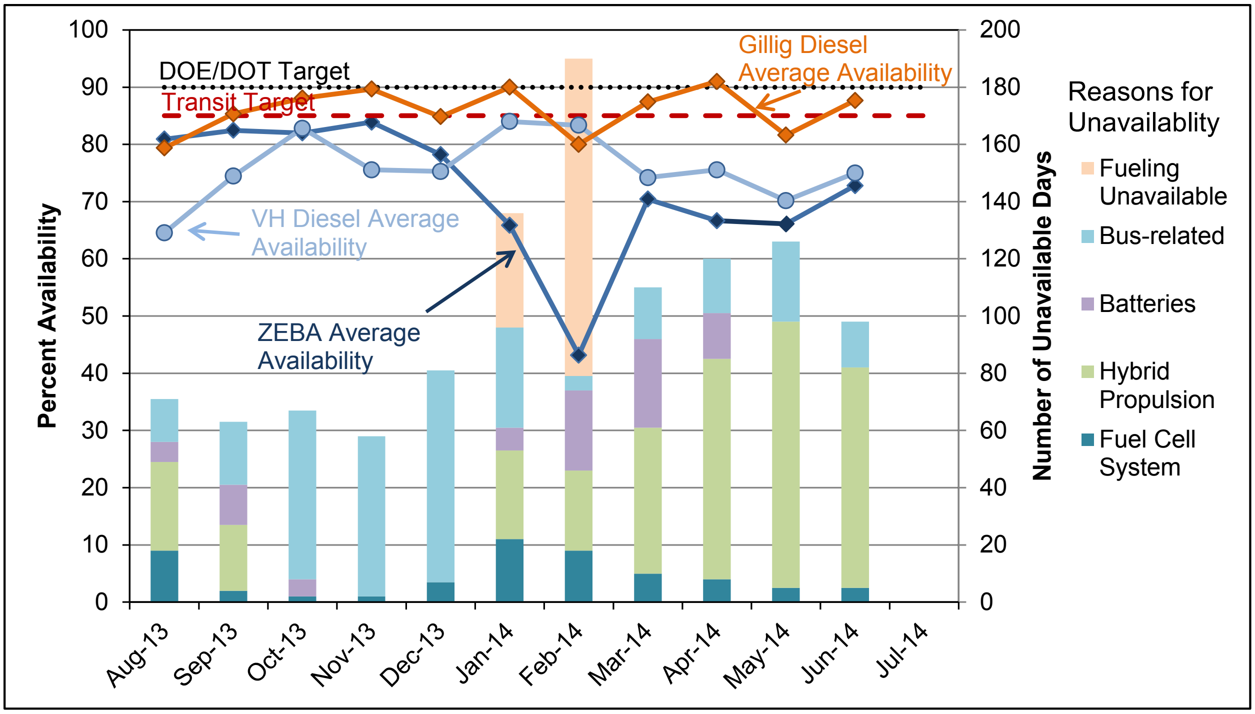

Figure A-1. Monthly availability and number of unavailability days for the ACT ZEBA buses

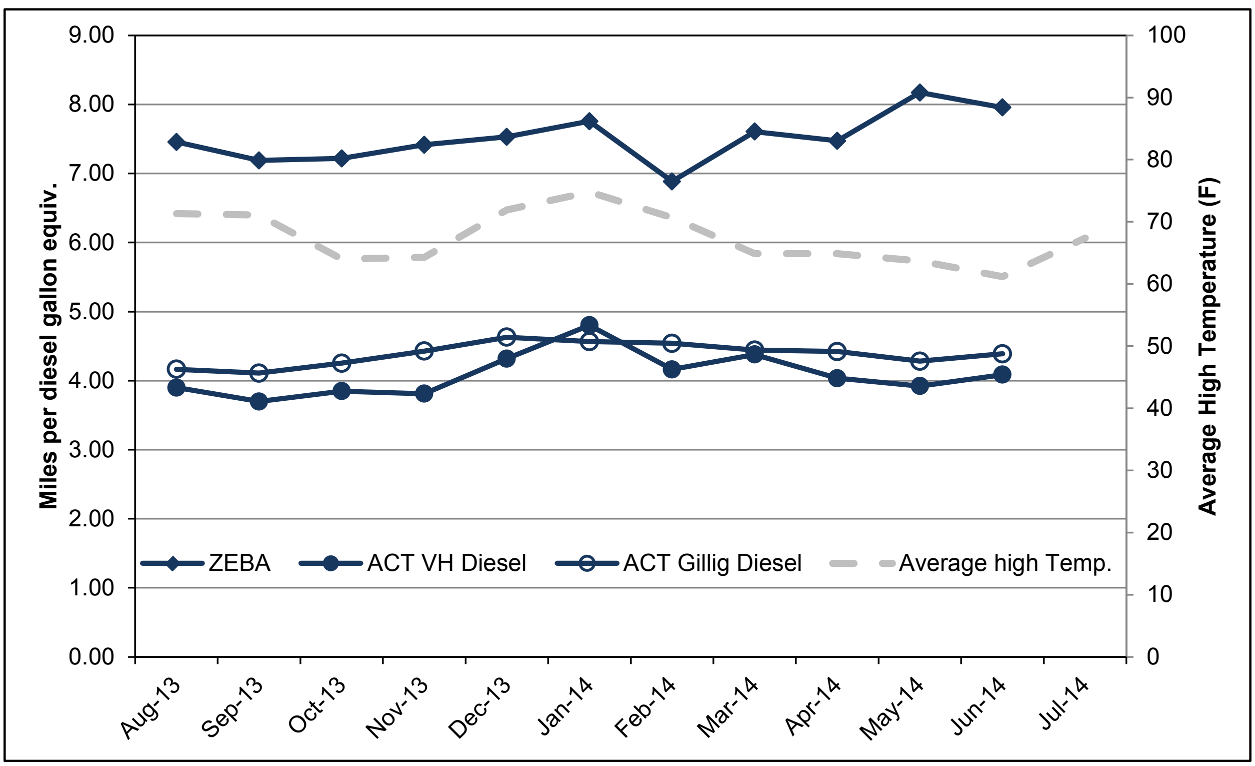

Figure A-2. Monthly fuel economy for the ACT ZEBA and diesel buses

BC Transit Demonstration Summary

Table A-3. BC Transit Data Summary

	BCT All Data	BCT Final Year	BCT Diesel Data
Data period	4/11–3/14	4/13–3/14	–
Number of buses	20	20	–
Number of months	36	12	–
Total miles	1,880,753	561,923	–
Total FC hours	201,911[a]	42,749	–
Average speed (mph)	14.2	14.2	–
Average miles per month	2,799	2,927	–
Availability	70%	55%	–
Fuel economy (mi/kg)	3.97	3.83	–
Fuel economy (mi/DGE)	4.48	4.32	4.28
Bus MBRC	1,487	1,408	–
Propulsion-only MBRC	1,915	1,718	–
FC system-only MBRC	8,871	10,406	–
Total hydrogen used (kg)	591,590[a]	129,228	–
SI Units			
Total kilometers	3,026,778	904,327	–
Average speed (kph)	22.9	22.9	–
Average km per month	4,504	4,710	–
Fuel consumption (kg/100 km)	16.67	16.24	–
Fuel consumption (L/100 km)	52.49	54.38	55.00
Bus km between roadcalls (KBRC)	2,393	2,266	–
Propulsion-only KBRC	3,081	2,766	–
FC system-only KBRC	14,277	16,747	–

[a] Total FC hours and total hydrogen used includes the entire demonstration period from Feb 2010 through March 2013

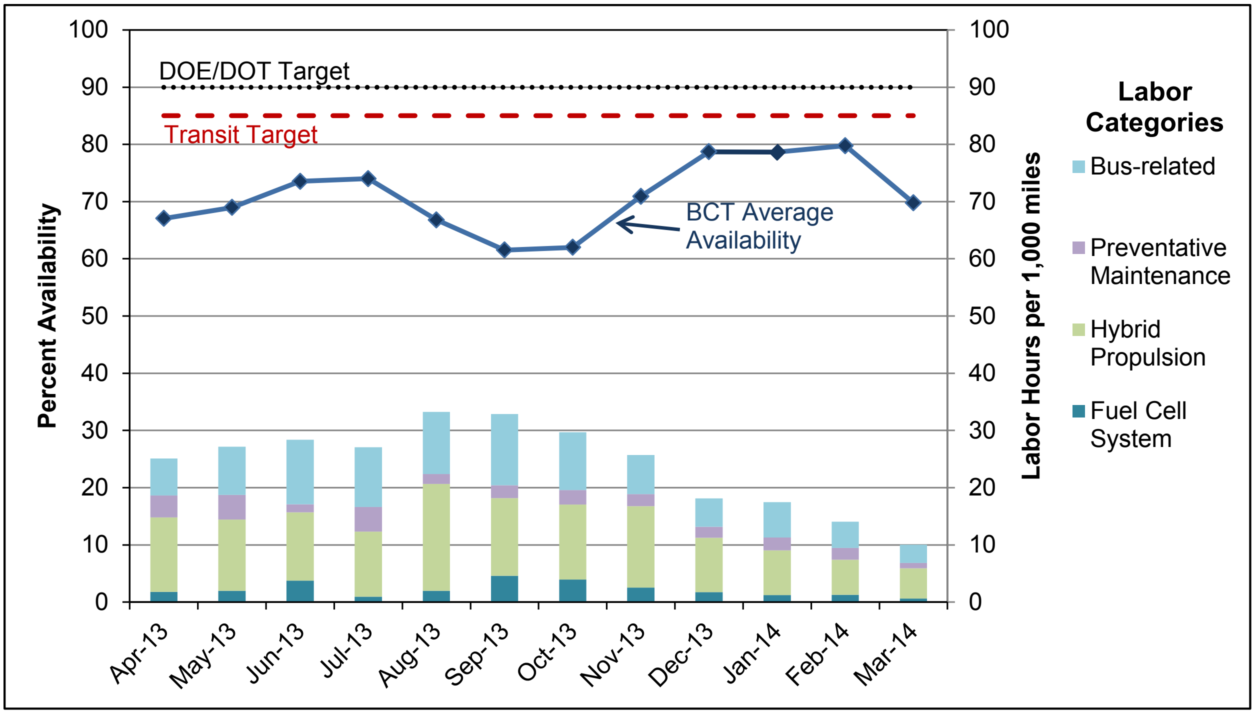

Figure A-3. Monthly availability and labor hours for the BCT FCEBs

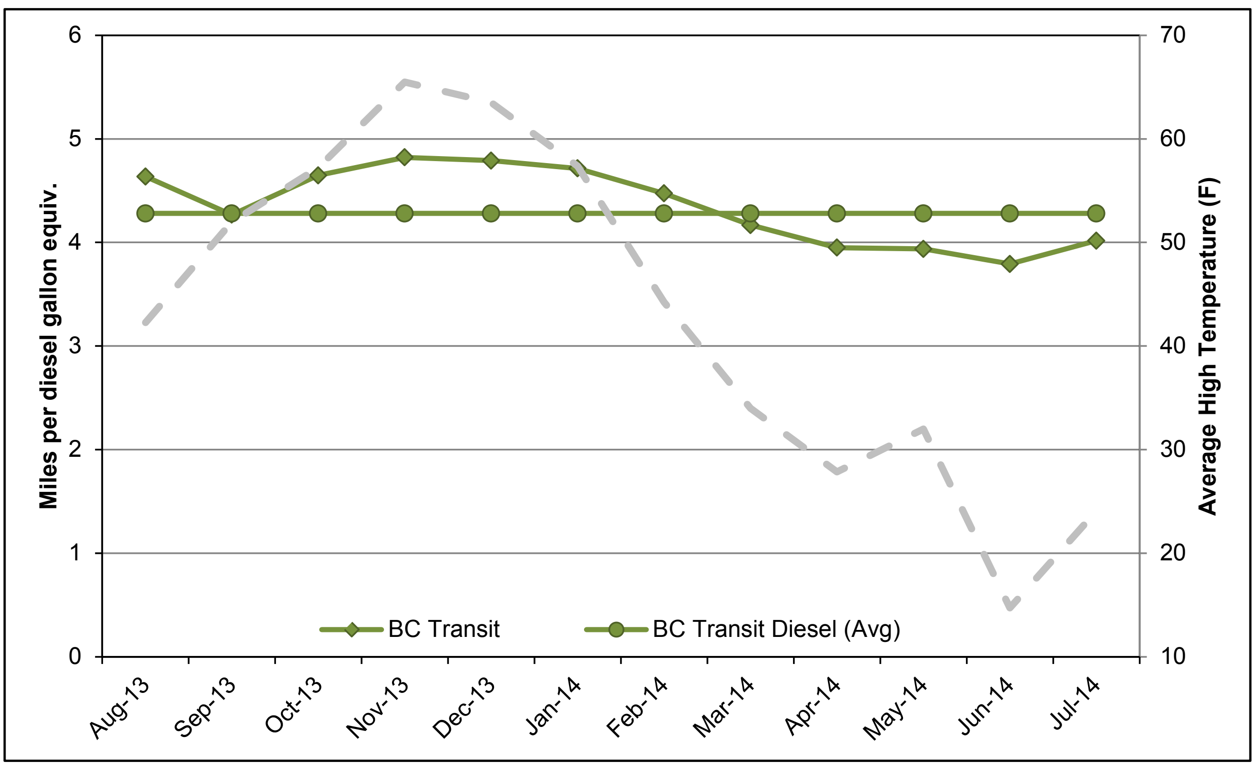

Figure A-4. Monthly fuel economy for the BCT FCEBs and the diesel bus average

SunLine AT and AFCB Demonstration Summary

Table A-4. SunLine Data Summary

	SL AFCB All Data	SL AFCB Past Year	SL CNG All Data	SL CNG Past Year	SL AT All Data	SL AT Past Year
Data period	3/12–7/14	8/13–7/14	3/12–7/14	8/13–7/14	5/10–7/14	8/13–7/14
Number of buses	1	1	5	5	1	1
Number of months	29	12	29	12	51	12
Total miles	77,284	23,218	1,136,399	295,049	68,815	16,066
Total FC hours	4,982	1,486	–	–	5,666	1,109
Average speed (mph)	15.5	15.6	–	–	12.1	14.5
Average miles per month	2,665	1,935	4,456	4,917	1,349	1,339
Number of scheduled days	769	310	3,878	1,676	1,235	282
Number of days available	514	188	3,217	1,500	645	126
Availability	67%	61%	85%	89%	52%	45%
Fuel economy (mi/kg or gge)	6.40	6.19	2.89	2.88	5.55	5.67
Fuel economy (mi/DGE)	7.24	6.99	3.23	3.22	6.27	6.40
Bus MBRC	3,513	2,580	10,928	11,356	2,640	3,213
Propulsion-only MBRC	7,026	5,805	27,061	24,605	2,860	3,213
FC system-only MBRC	15,457	11,609	–	–	6,865	16,066
Total hydrogen used (kg)	11,986	3,668	–	–	12,333	2,808
SI Units						
Total kilometers	124,377	37,366	1,828,857	474,835	110,747	25,856
Average speed (kph)	25.0	25.1	–	–	19.5	23.3
Average km per month	4,289	3,114	12,613	7,914	2,172	2,155
Fuel consumption (kg/100 km)	9.70	10.04	–	–	11.20	10.97
Fuel consumption (L/100 km)	32.28	32.88	73.20	73.56	37.30	36.37
Bus km between roadcalls (KBRC)	5,653	4,152	17,587	18,276	4,249	5,171
Propulsion-only KBRC	11,307	9,341	43,550	39,598	4,603	5,171
FC system-only KBRC	24,875	18,683	–	–	11,048	25,856

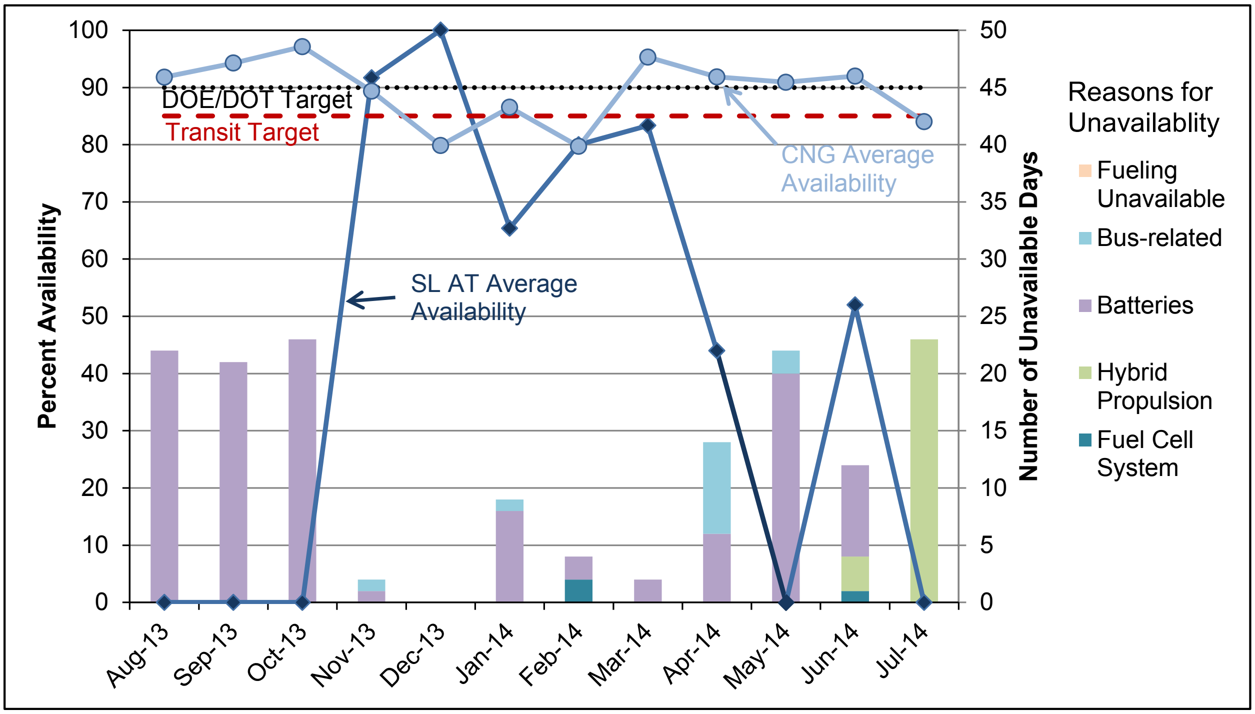

Figure A-5. Monthly availability and number of unavailable days for the SunLine AT FCEB

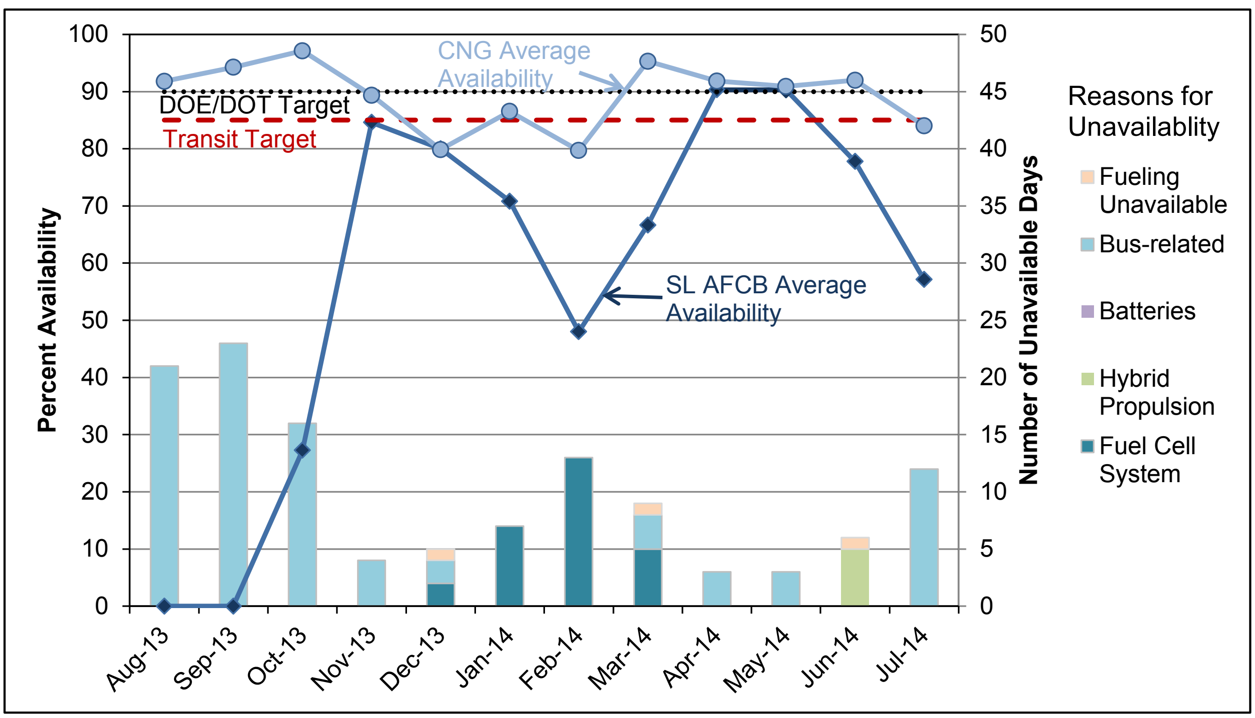

Figure A-6. Monthly availability and number of unavailable days for the SunLine AFCB

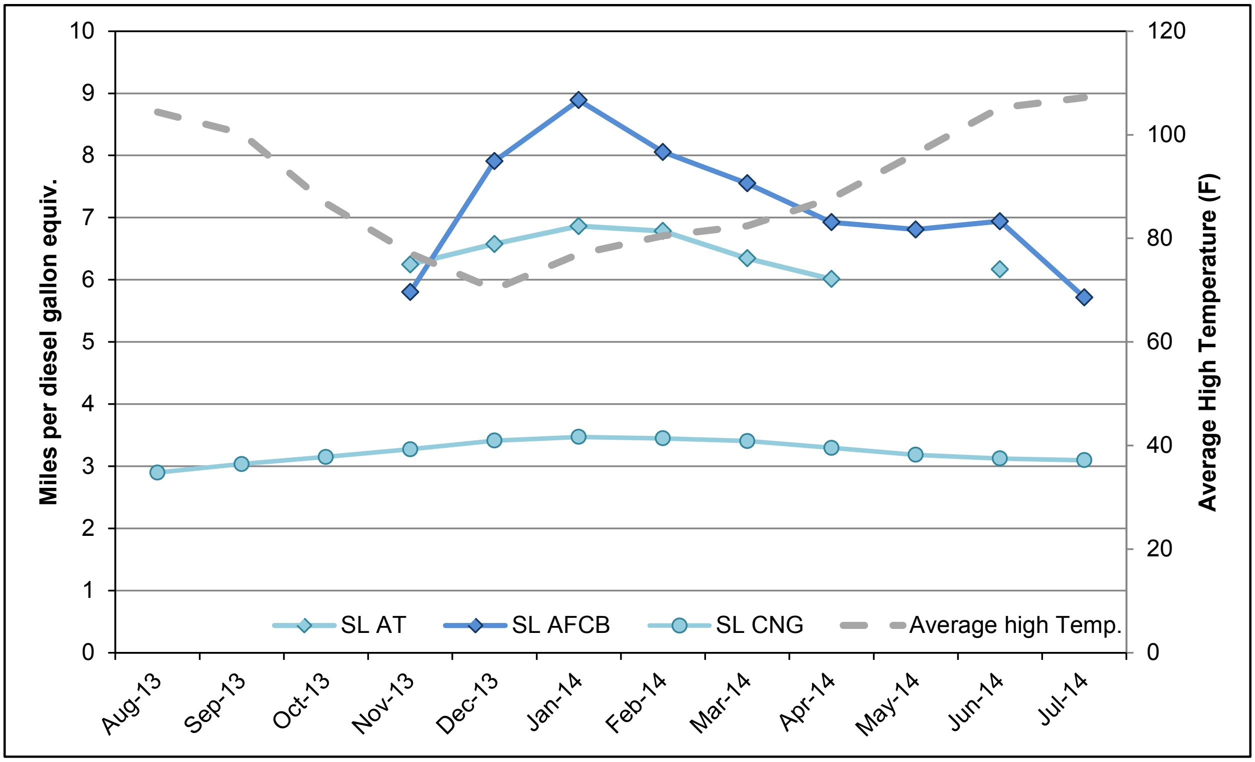

Figure A-7. Monthly fuel economy for the SunLine FCEBs and CNG buses