American Fuel Cell Bus Project Evaluation: Third Report

Leslie Eudy, Matthew Post, and Matthew Jeffers

National Renewable Energy Laboratory

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Technical Report
NREL/TP-5400-67209
May 2017

Contract No. DE-AC36-08GO28308

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Prepared under Task No. HT12.8210

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Acknowledgments

This evaluation at SunLine would not have been possible without the support and cooperation of many people. The authors thank the following individuals:

U.S. Department of Energy (DOE)
Jason Marcinkoski

U.S. Department of Transportation Federal Transit Administration
Christina Gikakis
Sean Ricketson

DOE's National Renewable Energy Laboratory
Keith Wipke
Jen Kurtz

SunLine Transit Agency
Tommy Edwards
Mike Hayes
Bill Loper

BAE Systems
Robert Devine
Yeshwanth Premkumar

Ballard Power Systems
Byron Somerville
Steve Potvin
George Morales

ElDorado National-California
Khalil Subat

Unless otherwise noted, all photos and illustrations by L. Eudy, NREL

Acronyms and Abbreviations

AFCB	American Fuel Cell Bus
CNG	compressed natural gas
dge	diesel gallon equivalent
DOE	U.S. Department of Energy
ENC	ElDorado National-California
FCEB	fuel cell electric bus
ft	feet
FTA	Federal Transit Administration
gge	gasoline gallon equivalent
hp	horsepower
HVAC	heating, ventilation, and air conditioning
in.	inches
kg	kilograms
kW	kilowatts
kWh	kilowatt hours
lb	pounds
MBRC	miles between roadcalls
mpg	miles per gallon
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
SI	International System of Units
TRL	technology readiness level

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.

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

Miles between roadcalls (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 results in the report are categorized as follows:

- Bus MBRC: Includes all chargeable roadcalls. Includes propulsion-related issues as well as problems with bus-related systems such as brakes, suspension, steering, windows, doors, and tires.
- Propulsion-related MBRC: Includes roadcalls that are attributed to the propulsion system. Propulsion-related roadcalls can be caused by issues with the power system (fuel cell), batteries, and hybrid systems.
- Fuel-cell-system-related MBRC: 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. The National Transit Database definition of chargeable roadcalls includes issues with accessories such as fareboxes. Because of this, the NREL calculations will not usually match what the agency reports to the National Transit Database.

Executive Summary

This report presents results of the American Fuel Cell Bus (AFCB) Project, a demonstration of fuel cell electric buses (FCEB) operating in the Coachella Valley area of California. The AFCB, built on an ElDorado National-California 40-foot Axess bus platform, has a fuel-cell-dominant hybrid electric propulsion system in a series configuration. BAE Systems' hybrid electric propulsion system is powered with a 150-kW Ballard fuel cell system. The prototype AFCB, which was developed as part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program, was delivered to SunLine in November 2011 and was put in revenue service in mid-December 2011. Two new AFCBs with an upgraded design were delivered in June/July of 2014 and a third new AFCB was delivered in February 2015.

FTA and the AFCB project team are collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. NREL evaluates FCEBs under funding from FTA and DOE and uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations.

The goal of this evaluation is to compare the FCEB performance to that of conventional technology and to track progress over time toward meeting the technical targets set by DOE and FTA. NREL collects data on five compressed natural gas (CNG) buses as a baseline comparison at SunLine.

This report covers the performance of the AFCBs from July 2015 through December 2016. Table ES-1 provides a summary of results for several categories of data presented in this report. Data are included on the four AFCBs and on the five CNG baseline buses. The table provides the data analysis for the entire demonstration as well as for the evaluation period that is the focus of the report. From the start of the demonstration through December 2016, the AFCBs have traveled more than 330,500 miles and accumulated more than 23,600 hours on the fuel cell systems.

Table ES-1. Summary of Evaluation Results

Data Item	AFCB All Data	AFCB Evaluation Period Data	CNG All Data	CNG Evaluation Period Data
Number of buses	4	4	5	5
Data period	3/12–12/16	7/15–12/16	3/12–12/16	7/15–12/16
Number of months	58	18	58	18
Total mileage in period	330,513	178,578	1,369,822	471,152
Average monthly mileage per bus	2,485	2,480	4,724	5,235
Total fuel cell operating hours	23,612	13,315	—	—
Availability (85% is target)	73	75	87	91
Fuel economy (miles per kg or gge[a])	5.72	5.42	2.88	2.90
Fuel economy (miles per dge[b])	6.46	6.13	3.21	3.24
Miles between roadcalls (MBRC) – all	4,722	5,761	9,012	10,025
MBRC – propulsion only	7,345	8,117	23,217	19,631
MBRC – fuel cell system only	17,395	16,234	—	—
Total maintenance,[c] $/mile	0.46	0.42	0.51	0.48
Maintenance – propulsion only, $/mile	0.24	0.21	0.23	0.21

[a] Gasoline gallon equivalent.
[b] Diesel gallon equivalent.
[c] Work order maintenance cost.

During the evaluation period, the AFCBs had an average fuel economy of 5.42 miles per kilogram of hydrogen, which equates to 6.13 miles per diesel gallon equivalent (dge). Using the gasoline gallon equivalent (gge) fuel economy of the CNG buses as a baseline, the AFCB fuel economy was 1.9 times higher than that of the CNG buses.

The average availability for the AFCBs was 76% compared to 91% for the CNG baseline buses. This has improved from what was documented in the last report (66%). The low points in availability were primarily driven by issues with the prototype bus. Those issues involved troubleshooting the accessory power system and an isolation fault that proved difficult to diagnose. The overall availability for the fuel cell system was 94%.

Reliability, measured as miles between roadcalls (MBRC), continues to show improvement. The overall bus MBRC for the AFCBs shows a steady increase over time, surpassing the ultimate target of 4,000 miles by the end of 2015. The fuel cell MBRC showed a steady increase over the evaluation period and has surpassed the DOE/FTA 2016 target of 15,000 miles.

In addition to analyzing the FCEB performance, NREL provides a cost analysis and comparison. The current maintenance costs for FCEB technology are slightly lower than the costs of conventional technology. The parts costs continue to be low for the AFCBs because these costs for the propulsion system are typically covered by the manufacturer under warranty; however, SunLine's mechanics do nearly all of the work. SunLine's CNG buses were manufactured in 2008 and are out of the warranty period. Each of these buses has accumulated more than 400,000 miles and has reached the mid-life point where costs tend to increase. This is evident by the increased costs for engine and other propulsion system maintenance.

Total maintenance costs per mile for the AFCBs during the data period were 12% lower than that of the CNG buses. Propulsion-related system costs per mile accounted for 50% of the total costs for the AFCBs and 45% of the total costs for the CNG buses.

The agency will continue working with NREL to collect data on the buses in service. The current CNG baseline buses have reached an advanced age and are experiencing issues that have increased maintenance costs. Because of this, they are no longer the best comparison. SunLine received new CNG buses in 2016. Beginning in January 2017, NREL will switch to collecting data on a selection of the new CNG buses for a baseline comparison. SunLine has received funding for several new projects that will add FCEBs to its fleet. These new projects will eventually increase the fleet to 17 FCEBs.

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Introduction

In December 2011, SunLine Transit Agency began operating its first "American Fuel Cell Bus" (AFCB), developed as part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP). SunLine received two additional AFCBs in 2014 and a third in 2015. SunLine is collaborating with the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. NREL has published two reports documenting the performance and SunLine's early experience with the AFCBs.[1,2] The previous reports included detailed descriptions of the project, technology, and facilities. The focus of this report is to provide an analysis of the new data and fleet experience from July 2015 through December 2016.

SunLine Transit Agency Profile

SunLine Transit Agency provides public transit services to Southern California's Coachella Valley. Headquartered in Thousand Palms, California, SunLine's service area covers more than 1,100 square miles including nine member cities and a portion of Riverside County. SunLine's service area is shown in Figure 1.

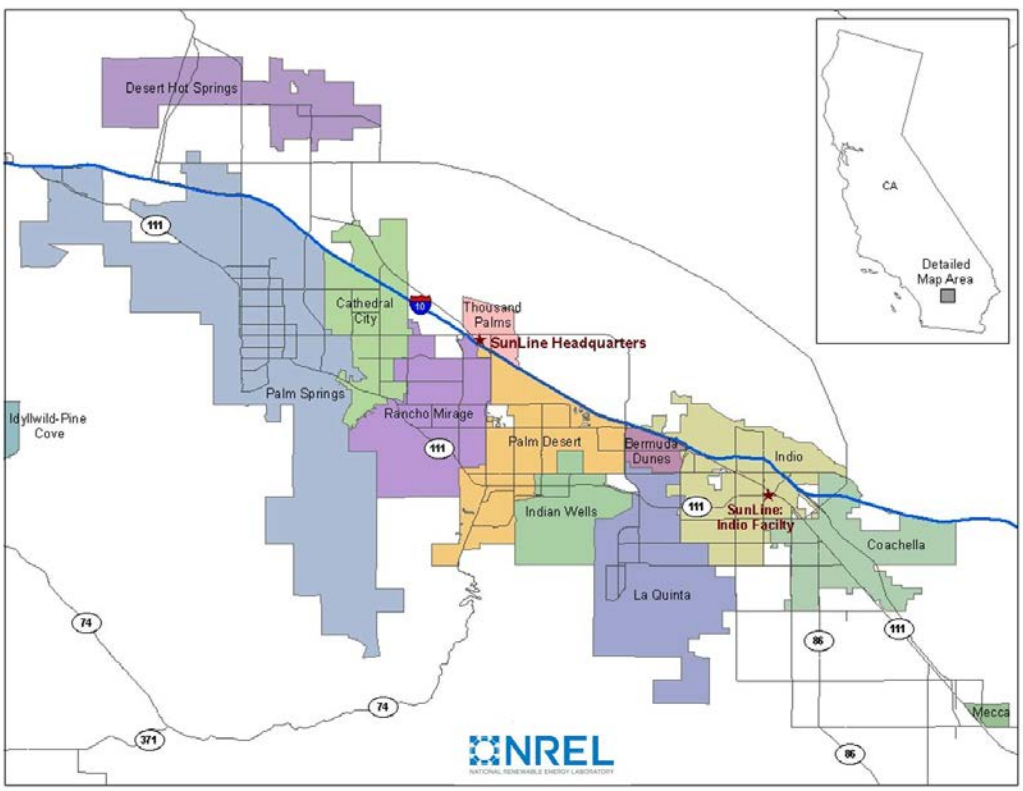

Figure 1. SunLine service area

[1] *American Fuel Cell Bus Project: First Analysis Report*, FTA Report No. 0047, June 2013, http://www.fta.dot.gov/documents/FTA_Report_No._0047.pdf.
[2] *American Fuel Cell Bus Project Evaluation: Second Report*, NREL/TP-5400-64344, September 2015, http://www.nrel.gov/docs/fy15osti/64344.pdf.

SunLine is committed to operating clean fuel technologies in its fleet. Over the last 10 years, SunLine has operated seven different generations of buses powered by hydrogen, including FCEBs, a hydrogen-fueled internal combustion engine bus, and buses operating on a blend of CNG and hydrogen.

Bus Technology Descriptions

The AFCB is a 40-foot ElDorado National-California (ENC) bus with a BAE Systems hybrid electric propulsion system powered by Ballard's FCvelocity-HD6 150-kW fuel cell. Table 1 provides bus system descriptions for the AFCBs (one of which is shown in Figure 2) and the CNG buses studied in this evaluation. SunLine has assigned a designation of FC3 to its first AFCB. This bus was the original prototype bus developed under the NFCBP. The three next-generation AFCBs are designated FC4, FC5, and FC6. NREL is evaluating five CNG buses operating from the same SunLine location as a baseline comparison. Figure 3 is a picture of one of the CNG buses. These buses are 2008 model year New Flyer CNG buses with Cummins Westport ISL G natural gas engines designed to meet 2010 emission regulations.

Table 1. Fuel Cell and CNG Bus System Descriptions

Vehicle System	AFCB (Prototype)	AFCB (Next Generation)	CNG Bus
Number of buses	1	3	5
Bus designations	FC3	FC4, FC5, FC6	603, 604, 605, 606, 608
Bus manufacturer and model	ENC National, Axess	ENC National, Axess	New Flyer
Model year	2011	2014	2008
Length/width/height	40 ft/102 in./140 in.	40 ft/102 in./140 in.	40 ft/102 in./130.8 in.
Gross vehicle weight	43,420 lb	43,420 lb	42,540 lb
Passenger capacity	37 seated or 31 seated with two wheelchairs; 19 standees	37 seated or 31 seated with two wheelchairs; 19 standees	39 seated with no wheelchairs
Hybrid system	BAE Systems, series hybrid propulsion system, HDS 200, 200 kW peak	BAE Systems, series hybrid propulsion system, HDS 200 Series E, 200 kW peak	N/A
Fuel cell or engine	Ballard FCvelocity[3]-HD6, 150 kW	Ballard FCvelocity-HD6, 150 kW	Cummins Westport ISL G 280 hp @ 2,200 rpm
Energy storage	A123, Nanophosphate Li-ion; 200 kW, 11 kWh	A123, Nanophosphate Li-ion; 200 kW, 11 kWh	N/A
Accessories	Electric	Electric (APS3)	Mechanical
Fuel capacity	Gaseous hydrogen, 8 Luxfer-Dynetek cylinders, 50 kg at 350 bar	Gaseous hydrogen, 8 Luxfer-Dynetek cylinders, 50 kg at 350 bar	125 diesel gallon equivalent
Bus purchase cost	$2.4 million[4]	$2.1 million–$2.4 million[5]	$402,900

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

Additional orders for AFCBs have lowered the capital costs. SunLine has purchased five more AFCBs through a grant under the FTA's Low or No Emission Vehicle Deployment Program. Another agency has purchased five AFCBs under the program. Those buses have an average cost of $1.8 million each.

Figure 2. SunLine American Fuel Cell Bus

Figure 3. SunLine CNG bus

FCEB Development Process—Technology Readiness Levels

NREL has developed a guideline for assessing the technology readiness level (TRL) for FCEBs.[6] Figure 4 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 subsystems. Some

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[4] Approximate cost of the prototype AFCB based on a very low quantity as a non-production, prototype vehicle (not including non-recurring engineering for the initial design).
[5] Range of costs for the AFCBs produced during the same timeframe as FC4, FC5, and FC6.
[6] *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.

subsystems may include commercial, off-the-shelf components, while other subsystems may feature newly designed components at an earlier TRL.

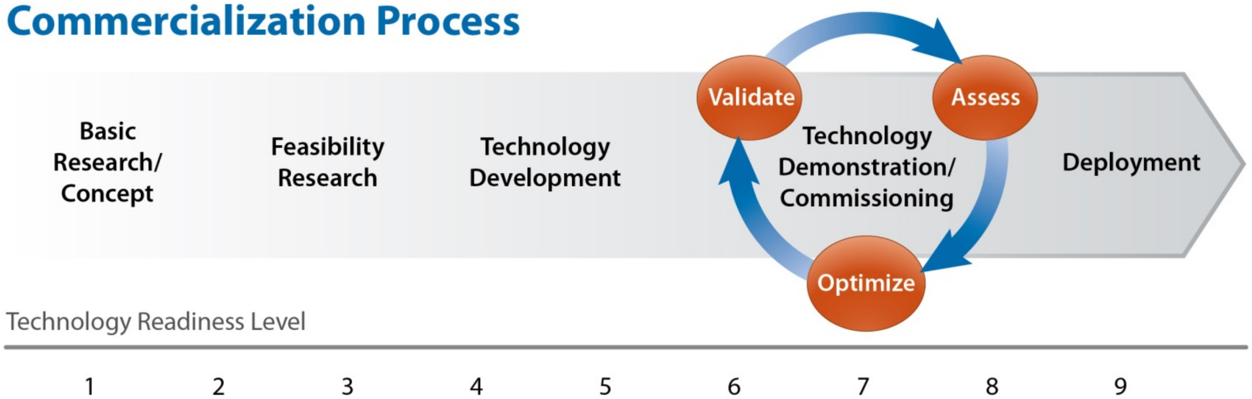

Figure 4. Graphic representation of the commercialization process developed for FCEBs

NREL considers the AFCB to be at TRL 7 because manufacturers, which were experienced with FCEB and hybrid technology development, led the design of the bus, and the deployment includes more than 20 buses in various locations. These buses represent a full-scale validation in a relevant environment. NREL's goal in evaluating FCEBs is to document the performance and track progress over time toward meeting the technical targets. NREL collects data on conventional buses at each demonstration site for a baseline comparison. This is important primarily because fuel economy is highly dependent on duty cycle, but also because maintenance practices can be different from site to site. The best comparisons need to include buses operated in similar service at the same operating division. For the evaluation at SunLine, NREL collects data on CNG buses for a baseline comparison to the FCEBs. SunLine does not operate any diesel buses.

Evaluation Results

The results presented in this section focus on the evaluation period from July 2015 through December 2016. (Unless otherwise noted, the term "evaluation period" refers to the data results during this period.) During that 18-month evaluation period, the FCEBs operated 178,578 miles over 13,315 hours of fuel cell operation. This section begins with a summary of fueling data followed by the summary of bus performance results and operational costs.

Summary of Fueling Data

During the evaluation period, SunLine operated all four fuel cell buses in its service area. Figure 5 shows the average daily hydrogen dispensed into SunLine's fuel cell buses during the evaluation period. The station was used at least once per day to fill at least one hydrogen bus for 94% of the calendar days during the period. The overall average daily use was 64.2 kg per day. During this period, SunLine dispensed a total of 33,138 kg of hydrogen. The months with the lowest hydrogen dispensed had downtime for one bus or another during that month. During June, July, and August 2016, SunLine limited use of the buses due to an issue with the hydrogen reformer.

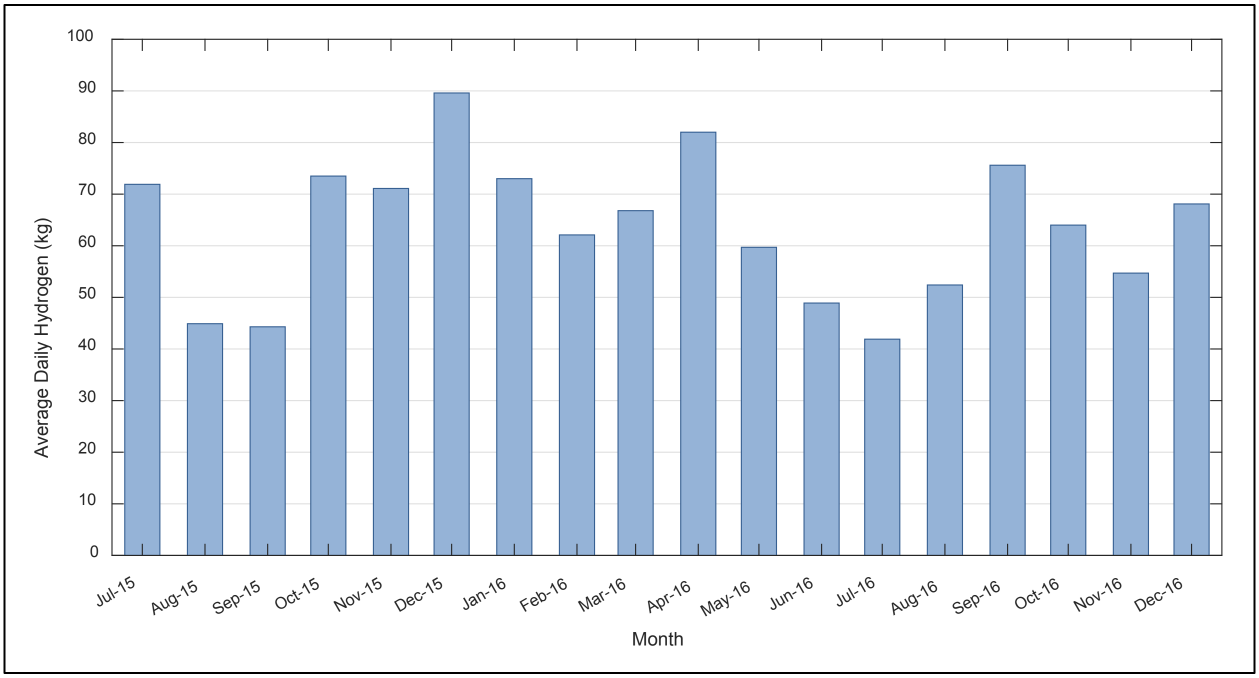

Figure 5. Average hydrogen dispensed per day (excluding 0 kg days)

Hydrogen fuel costs at SunLine consist of the cost of natural gas for the reformer, the cost for maintenance of the station equipment, and capital cost amortization. SunLine performs the maintenance of the station equipment, including parts and labor. The average monthly cost for hydrogen at SunLine varies based on total hydrogen dispensed and station maintenance costs. During the data period for the report, the agency has seen costs from as low as $3.10/kg to more than $23/kg. The average cost of hydrogen during the evaluation period was $7.68/kg. This cost is used in the calculations for the data results in the next section.

The average CNG price at the dispenser for SunLine (not the public price) during the data period was $0.96 per gasoline gallon equivalent (gge). This price includes all costs—natural gas, maintenance, and station amortization. SunLine supplies CNG fuel to users in its area, and the fueling station is accessible to the public. The high volume of natural gas use has allowed SunLine to command a low cost as a commodity user.

Summary of Bus Performance Data

This section focuses on the most recent operating data collected on the fuel cell and CNG buses from July 2015 through December 2016. Appendix B provides a summary of all data. Appendix C provides a data summary in SI (metric) units.

Route Assignments

SunLine's service consists of 15 fixed routes and one commuter route to Riverside. In general, SunLine's buses are randomly dispatched on its local routes. The overall system average speed is 17.7 mph (not including the commuter route). Table 2 summarizes the route use for the AFCBs and the CNG baseline buses during the evaluation period. SunLine operated the AFCBs primarily on Line 111 (39%), Line 32 (24%), and Line 30 (22%) with some additional service on

Line 53 (8%). The overall average speed for the AFCBs was 17.0 mph. SunLine randomly dispatched the five CNG buses with the majority of time (81%) split between Line 111, Line 14, and Line 30. Based on the dispatching information, the CNG buses operated at a slightly lower average speed (16.5 mph) than the fuel cell buses did during the evaluation period.

Table 2. Summary of Route Use for the AFCBs and CNG Buses (Evaluation Period)

Route	Percent of Time	Average Speed (mph)
AFCB		
111	39	17.5
53	8	17.5
30	22	12.9
32	24	19.7
Average	—	17.0
CNG		
111	45	17.5
14	19	18.4
30	16	12.9
Average	—	16.5

Bus Use and Availability

This section summarizes bus usage and availability for the AFCBs and CNG buses. 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.

Table 3 and Figure 6 summarize average monthly mileage for the buses during the evaluation period. The AFCBs had an average monthly mileage that was about half that of the CNG buses. During the evaluation period, several issues with FC3 resulted in extended downtime. Also, the buses were used in limited service in mid-2016 while the hydrogen station reformer was out of service. The AFCBs averaged about 8 hours in service each day but achieved as many as 20 hours in a single day.

Table 3. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average
FC3	102,583	121,600	19,017	18	1,057
FC4	33,918	87,593	53,675	18	2,982
FC5	16,892	72,600	55,708	18	3,095
FC6	6,666	56,844	50,178	18	2,788
Total AFCB			**178,578**	**72**	**2,480**
603 CNG	376,259	471,689	95,430	18	5,302
604 CNG	373,069	466,824	93,755	18	5,209
605 CNG	353,637	451,671	98,034	18	5,446
606 CNG	366,283	465,335	99,052	18	5,503
608 CNG	376,760	461,641	84,881	18	4,716
Total CNG			**471,152**	**90**	**5,235**

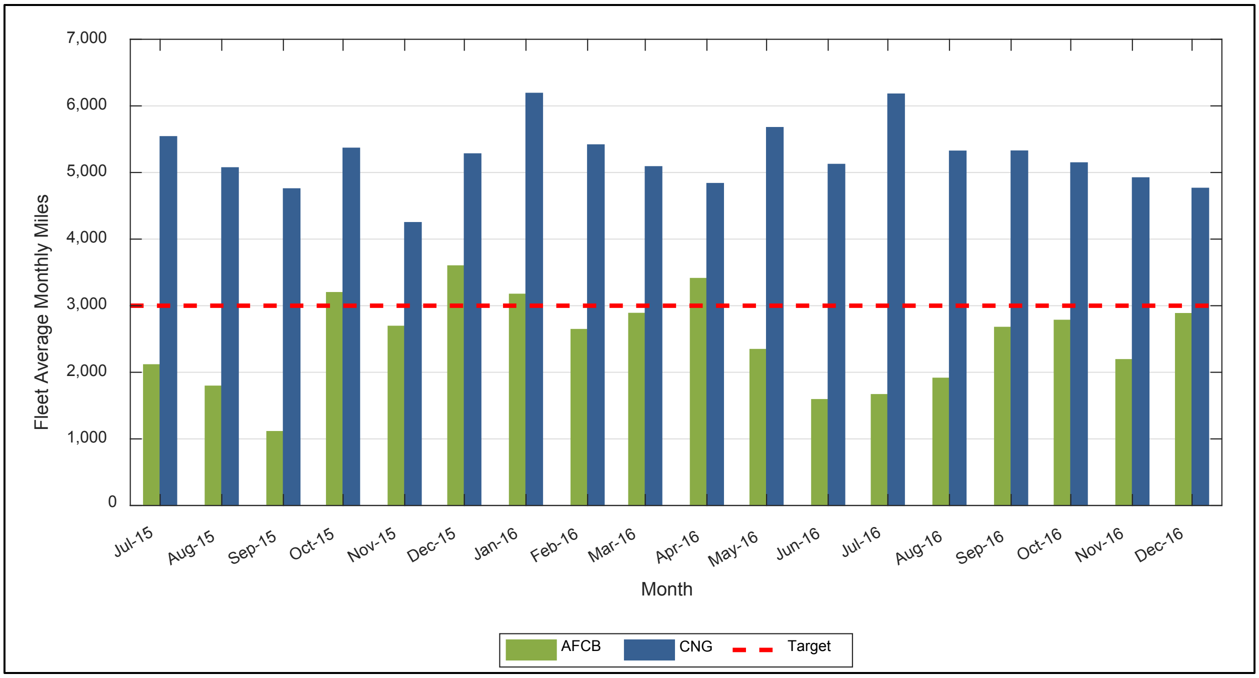

Figure 6. Monthly mileage for the AFCBs and CNG buses

Availability is the percentage of days that the buses are available for operation out of the days the buses are planned for operation. For SunLine, NREL calculates availability based on the planned service days, which are typically every weekday. Weekends and holidays are included in the calculation only if the bus operated in service on those days. If a bus does not operate on the weekend or on a holiday, it is not counted as unavailable. This strategy applies to both the AFCBs and the CNG buses. Figure 7 presents the monthly availability for the AFCBs and the CNG buses. The stacked bars show the total number of days the AFCBs were unavailable each month by primary system category. As shown in the chart, the availability goal is 85 percent for all buses. The chart also shows the availability for the fuel cell system as a separate line.

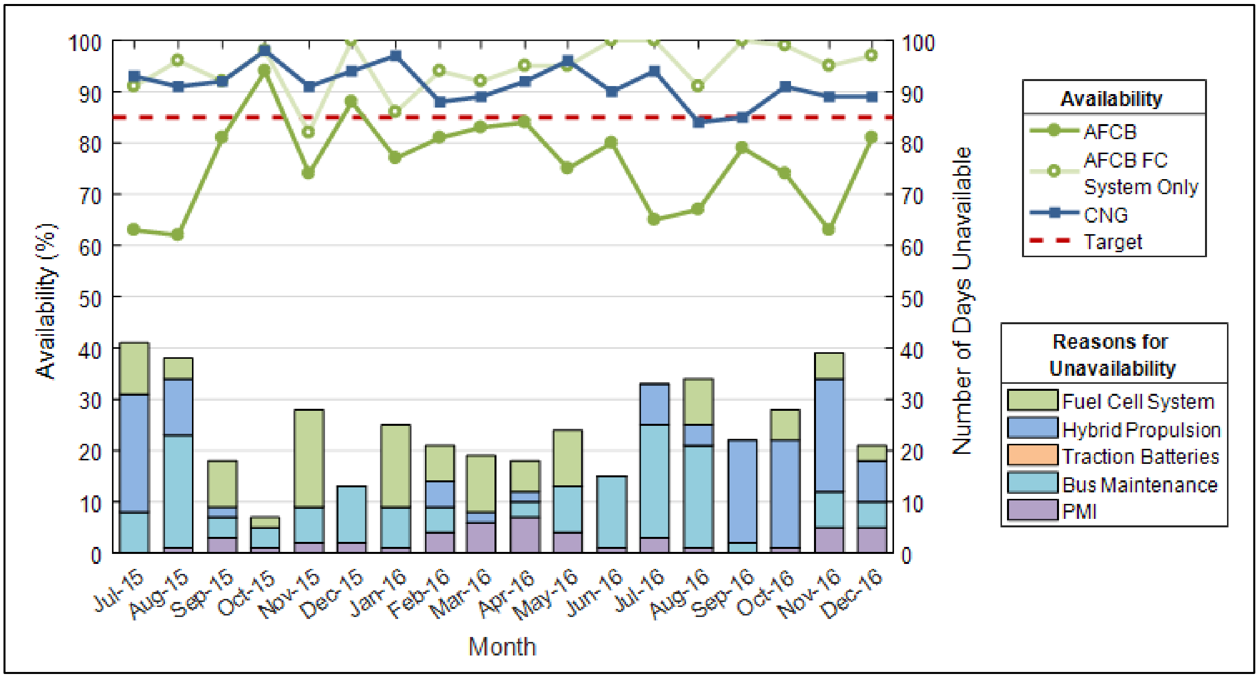

Figure 7. Monthly availability for the AFCBs and CNG buses

During the evaluation period, the lowest availability occurred during three periods: July through August of 2015, July through August of 2016, and November 2016. Issues with the accessory power system in FC3 and communication errors in FC6 were the primary drivers for the lower availability in July and August 2015. An issue with the fuel cell in FC3 and accessory power system issues in FC4 caused the low availability in July and August 2016. An isolation fault in FC3 resulted in lower availability in November 2016. The overall availability for the fuel cell system was 94%. The availability for the CNG buses was generally higher than the target of 85%.

Table 4 provides a summary of the reasons for unavailability for the AFCBs and CNG buses during the evaluation period. Figure 8 and Figure 9 present the results graphically. Overall, during the evaluation period the average availability for the AFCBs was 76%, which is an improvement over what was documented in the previous report (66%). The average availability for the CNG buses was 91%.

Table 4. Summary of Reasons for Availability and Unavailability of Buses for Service (Evaluation Period)

Category	AFCB		CNG Buses	
	Number	Percent	Number	Percent
Planned work days	1,884		2,492	
Days available	1,440	76	2,278	91
Available	**1,440**	**76**	**2,278**	**91**
On route	1,346	71.4	2,232	89.6
Event/demonstration	17	0.9	5	0.2
Training	0	0.0	0	0.0
Not used	77	4.1	20	0.8
Unavailable	**444**	**24**	**214**	**9**
Fuel cell propulsion	118	6.3	—	—
CNG engine	—	—	59	2.4
Hybrid propulsion	128	6.8	—	—
Traction batteries	0	0	—	—
Preventive maintenance	47	2.5	103	4.1
General bus maintenance	151	8.0	52	2.1

The primary issues that kept the AFCBs out of service were general bus issues (8.0%), the hybrid propulsion system (6.8%), and the fuel cell system (6.3%). The CNG baseline buses were down for engine issues only 2.4% of the time. The majority of the unavailable time was for preventive maintenance inspections (PMIs) or general bus issues such as air conditioning and brake repairs. Bus 604 had the most days out of service for an engine rebuild and accident repair, accounting for 56% of the total downtime. Bus 608 accounted for 36% of the downtime for engine issues.

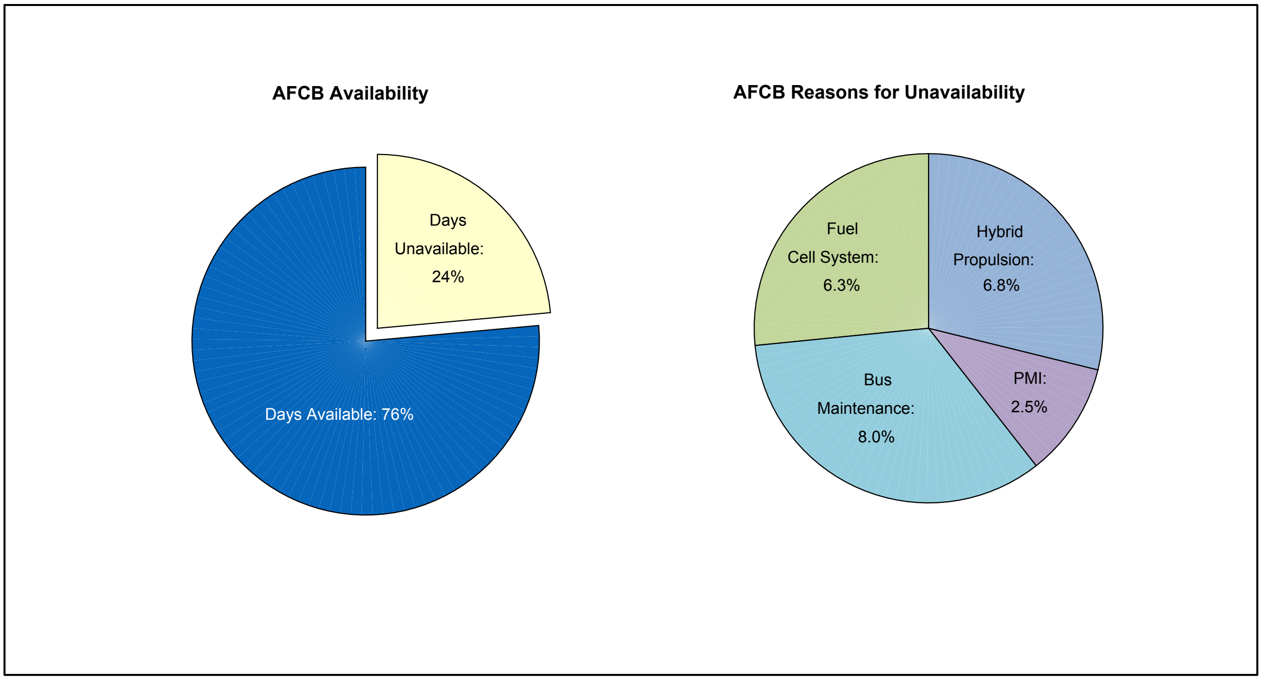

Figure 8. Overall AFCB availability and unavailability by category

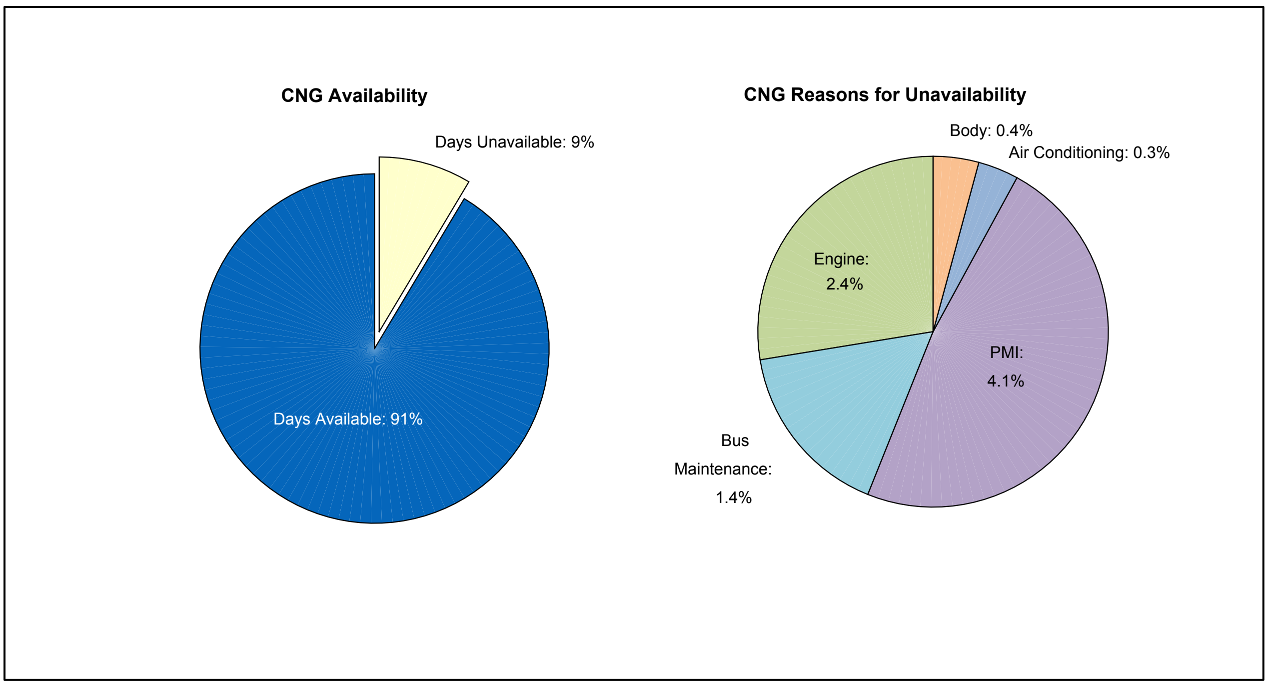

Figure 9. Overall CNG bus availability and unavailability by category

Fuel Economy and Cost

Table 5 shows hydrogen and CNG fuel economy for buses during the evaluation period. Using the gge fuel economy of the CNG buses as a baseline, the AFCBs had a fuel economy 1.9 times higher than that of the CNG buses. Figure 10 shows the average monthly fuel economy for each of the AFCBs and for the CNG buses as a group. The monthly average high temperature is included on the graph as a grey, dashed line. Both groups of buses show a slight decrease in fuel economy during the summer months when the air conditioning is used more frequently.

Table 5. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg) or CNG (gge)	Miles per kg or Miles per gge	Diesel Equivalent Amount (Gallon)	Miles per Gallon (dge[a])
FC3	18,900	3,058.8	6.18	2,706.9	6.98
FC4	53,261	9,566.7	5.57	8,466.1	6.29
FC5	53,863	10,277.1	5.24	9,094.8	5.92
FC6	49,015	9,372.0	5.23	8,293.8	5.91
Total AFCB	**175,039**	**32,274.6**	**5.42**	**28,561.6**	**6.13**
603 CNG	93,797	32,854.5	2.85	29,404.8	3.19
604 CNG	92,917	31,475.9	2.95	28,170.9	3.30
605 CNG	97,296	33,694.6	2.89	30,156.7	3.23
606 CNG	98,431	33,171.6	2.97	29,688.6	3.32
608 CNG	84,090	29,751.4	2.83	26,627.5	3.16
Total CNG	**466,531**	**160,948.0**	**2.90**	**144,048.5**	**3.24**

[a] Diesel gallon equivalent.

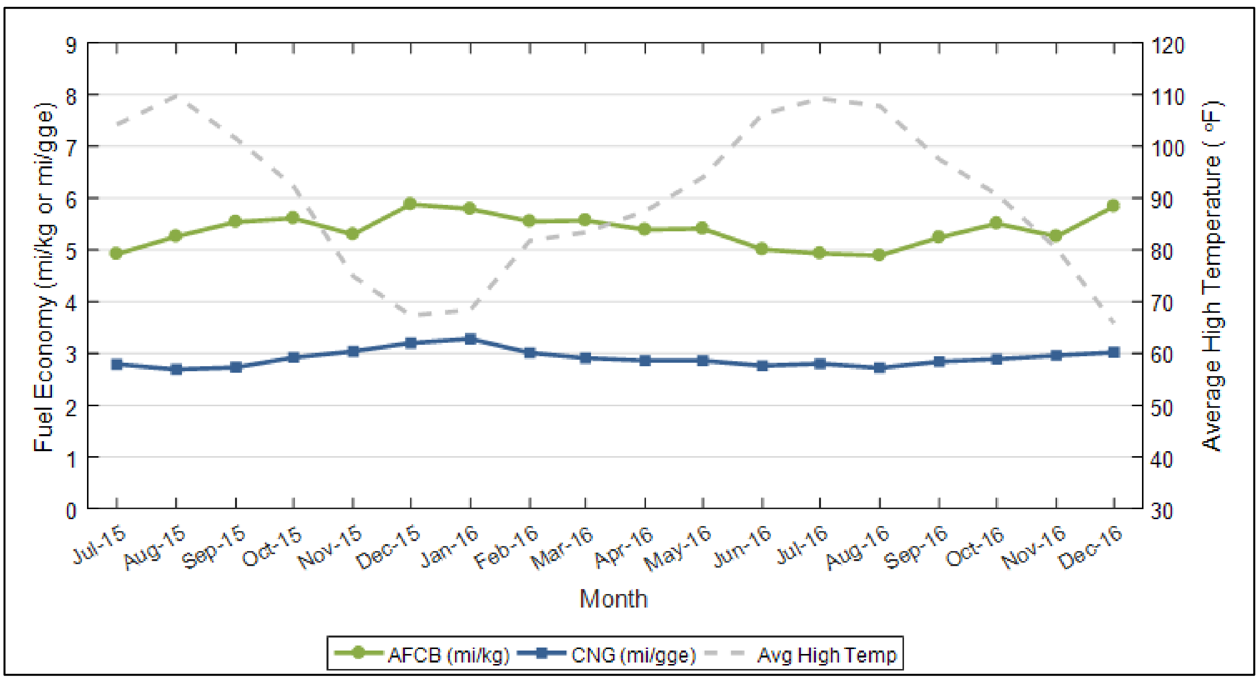

Figure 10. Monthly fuel economy for the AFCBs and CNG buses

SunLine tracks all of its fueling events in gasoline gallon equivalent (gge) units to comply with state fuel-sale regulations. For hydrogen, the unit used is typically kilograms—one kg of hydrogen contains essentially the same energy as one gge for fuel economy calculations. This report presents results in both gge (kg for hydrogen) and diesel gallon equivalent (dge) for hydrogen and CNG fuel consumption. The end of Appendix B shows the energy-conversion calculations for gge and dge.

The fuel costs per mile for the evaluation period were $1.42 per mile for the AFCBs and $0.33 per mile for the CNG buses. The CNG fuel cost at $0.96 per gge is much lower than the typical average cost per gallon for diesel fuel. The cost to produce hydrogen is much higher and includes the cost of the CNG used for reforming. SunLine's average cost for hydrogen during the period was $7.68/kg.

Roadcall Analysis

A roadcall, or revenue vehicle system failure,[7] 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 bus remains on schedule, this is not considered a roadcall. The analysis provided here includes only roadcalls caused by "chargeable" failures. Chargeable roadcalls include systems that can physically disable the bus from operating on route, such as interlocks (doors, air system), the engine, or things that are deemed to be safety issues if operation of the bus continues. They do not include roadcalls for things such as problems with radios, fareboxes, or destination signs.

The transit industry measures reliability as mean distance between failures, also documented as miles between roadcalls (MBRC). Table 6 provides the MBRC for the AFCBs and CNG buses categorized by bus roadcalls and propulsion-related roadcalls. Propulsion-related roadcalls include all roadcalls due to propulsion-related systems including the fuel cell system (or engine for a conventional bus), electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, and transmission systems. The fuel-cell-system-related roadcalls and MBRC are included for the AFCBs. The fuel cell system MBRC includes any roadcalls due to issues with the fuel cell stack or associated balance of plant. A total of 45 roadcalls for the AFCBs were attributed to the propulsion system. Of these, 19 were fuel cell related, resulting in a fuel cell system MBRC of 17,395.

Table 6. Roadcalls and MBRC (Cumulative from In-Service Date)

	AFCB Total	CNG Total
Data period	3/12–12/16	3/12–12/16
Total miles	330,513	1,369,822
Bus roadcalls	70	152
Bus MBRC	4,722	9,012
Propulsion roadcalls	45	59
Propulsion MBRC	7,345	23,217
Fuel cell system roadcalls	19	—
Fuel cell system MBRC	17,395	—

[7] Federal Transit Administration's National Transit Database website: www.ntdprogram.gov/ntdprogram/.

Figure 11 shows the cumulative monthly MBRC for the AFCBs and CNG buses through December 2016. The upper graph in the figure shows the overall bus MBRC trend over time. Toward the end of the data period, the AFCB fleet surpasses the DOE/FTA ultimate target of 4,000 MBRC. The lower graph in the figure tracks the propulsion-related MBRC for the AFCBs and CNG buses. The fuel-cell-system-related MBRC is also included for the AFCBs along with the DOE/FTA ultimate target. The fuel cell system MBRC for the AFCBs has shown a slow increase over time since the buses first went into service. Over the last year, the fuel cell system MBRC has been consistently above 15,000, which is the DOE/FTA target for 2016.

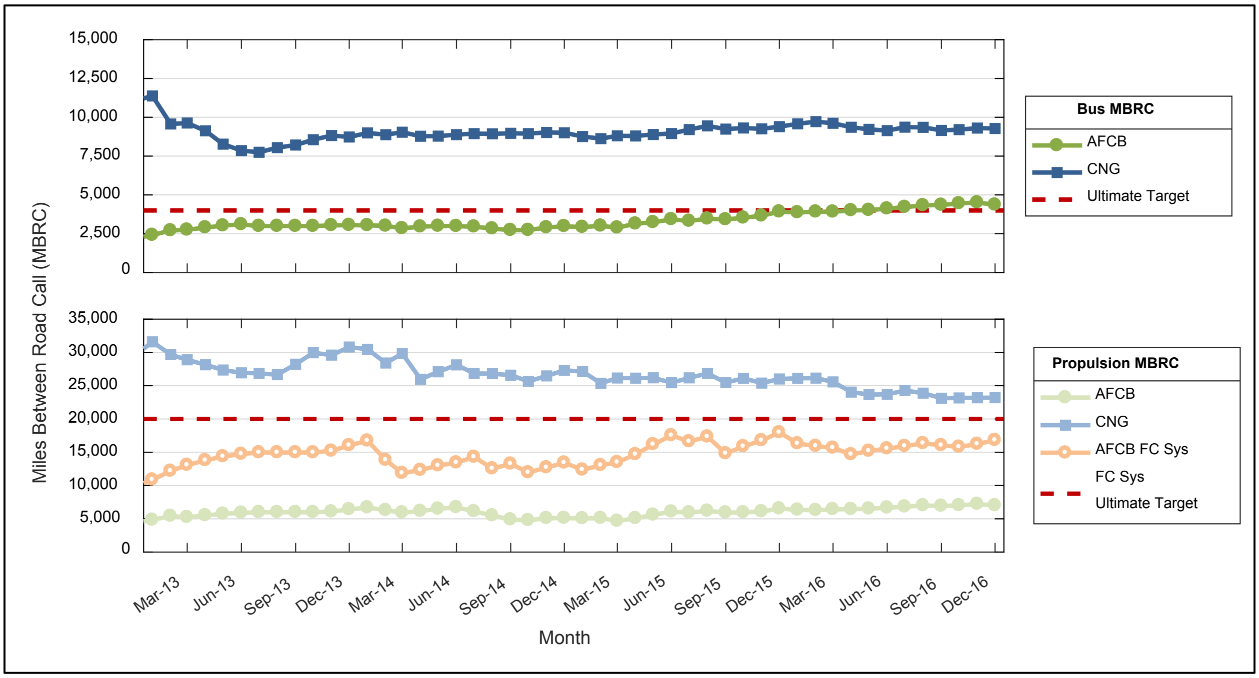

Figure 11. Cumulative monthly MBRC for the AFCBs and CNG buses

Maintenance Analysis

SunLine's maintenance facility is configured for maintaining both CNG- and hydrogen-fueled buses. SunLine staff members are experienced with hydrogen and fuel cell buses and handle most of the maintenance on the AFCBs. SunLine staff members do all of the preventive maintenance on the fuel cell systems and use a diagnostic tool to aid in troubleshooting any issues. SunLine can call on the local BAE Systems sales and service office for support with the hybrid system, if needed. Over the last year, Ballard hired a new technician that is stationed at SunLine. This technician is available to provide needed service to SunLine and other transit agencies in the area that operate AFCBs. This is similar to an engine manufacturer operating a regional service center. Although the technician is a Ballard employee, he is contracted to SunLine under a memorandum of understanding.

The maintenance cost analysis in this section is only for the evaluation period. Warranty costs are generally *not* included in the cost-per-mile calculations. NREL collected and analyzed all work orders for the study buses for this evaluation. For consistency with other evaluations, NREL set the maintenance labor rate at $50 per hour, which does not reflect an average rate for SunLine. The analysis eliminates costs for accident-related repair, which are extremely variable from bus to bus. SunLine's CNG buses, manufactured in 2008, are out of the warranty period. Each of these buses has accumulated more than 400,000 miles and has reached the mid-life point where costs tend to increase. This is evident by the increased costs for engine and other propulsion system maintenance. This section covers total maintenance costs first and then maintenance costs separated by bus system.

Total Maintenance Costs

Total maintenance costs include the price of parts and hourly labor rates of $50 per hour. Cost per mile is calculated as follows:

Cost per mile = [(labor hours * 50) + parts cost] / mileage

Table 7 shows total maintenance costs for the AFCBs and CNG buses. The table separates scheduled and unscheduled maintenance cost per mile by bus and by fleet. The AFCBs have total maintenance costs similar to those of the CNG buses. The parts costs continue to be low for the AFCBs because advanced technology parts are typically covered by the manufacturer under warranty; however, SunLine's mechanics do nearly all of the work.

Table 7. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Total Cost per Mile ($)	Scheduled Cost per Mile ($)	Unscheduled Cost per Mile ($)
FC3	19,017	3,253	435.0	1.31	0.06	1.25
FC4	53,675	1,500	320.0	0.33	0.07	0.25
FC5	55,708	1,177	304.3	0.29	0.09	0.21
FC6	50,178	1,597	300.5	0.33	0.07	0.26
Total AFCB	**178,578**	**7,527**	**1,359.8**	**0.42**	**0.08**	**0.35**
603 CNG	95,430	18,659	459.8	0.44	0.08	0.36
604 CNG	93,755	20,835	474.8	0.48	0.08	0.40
605 CNG	98,034	20,567	446.0	0.44	0.09	0.35
606 CNG	99,052	22,772	466.2	0.47	0.09	0.38
608 CNG	84,881	24,750	527.0	0.60	0.09	0.51
Total CNG	**471,152**	**107,582**	**2,373.7**	**0.48**	**0.08**	**0.40**

Figure 12 shows the monthly scheduled and unscheduled maintenance cost per mile for the AFCBs and CNG buses. The high cost per mile for the AFCBs in September 2015 was for labor associated with troubleshooting the cooling system issues on several buses and time to uninstall a fuel cell system on one bus.

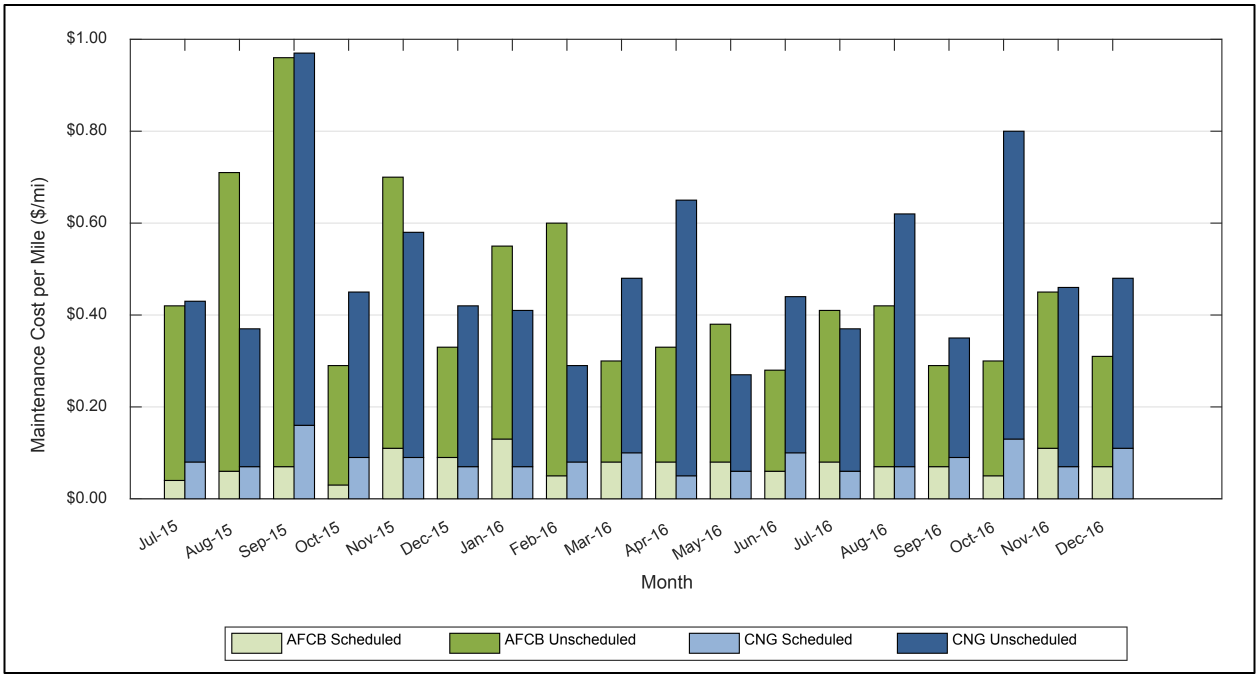

Figure 12. Monthly scheduled and unscheduled maintenance costs per mile for the AFCBs and CNG buses

Maintenance Costs Categorized by System

Table 8 shows maintenance costs by vehicle system[8] and bus fleet (without warranty costs). The vehicle systems shown in the table include the following:

- 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
- PMI—Labor for preventive maintenance
- Brakes
- Frame, steering, and suspension
- Heating, ventilation, and air conditioning (HVAC)
- Lighting
- Axles, wheels, and drive shaft
- Air system, general
- Tires.

[8] System categories are based on the Vehicle Maintenance Reporting Standards (VMRS) developed by the American Trucking Association.

Table 8. Vehicle System Maintenance Cost per Mile by System (Evaluation Period)

System	AFCB Cost per Mile ($)	AFCB Percent of Total (%)	CNG Cost per Mile ($)	CNG Percent of Total (%)
Propulsion-related	0.21	50	0.21	45
Cab, body, and accessories	0.07	17	0.11	22
PMI	0.08	18	0.06	12
Brakes	0.00	0	0.03	7
Frame, steering, and suspension	0.02	5	0.01	3
HVAC	0.01	2	0.03	6
Lighting	0.01	2	0.01	1
General air system repairs	0.00	0	0.00	0
Axles, wheels, and drive shaft	0.02	4	0.01	2
Tires	0.01	1	0.01	2
Total	***0.42***	*100*	***0.48***	*100*

For the AFCBs, the systems with the highest percentage of maintenance costs were propulsion-related; PMI; and cab, body, and accessories. The same categories made up the highest percentage of maintenance costs for the CNG buses, but in a slightly different order. The CNG buses continue to experience engine issues typical of buses at the mid-point of expected life. Figure 13 shows the monthly maintenance cost per mile by category for the AFCBs and Figure 14 provides the monthly maintenance cost by category for the CNG buses.

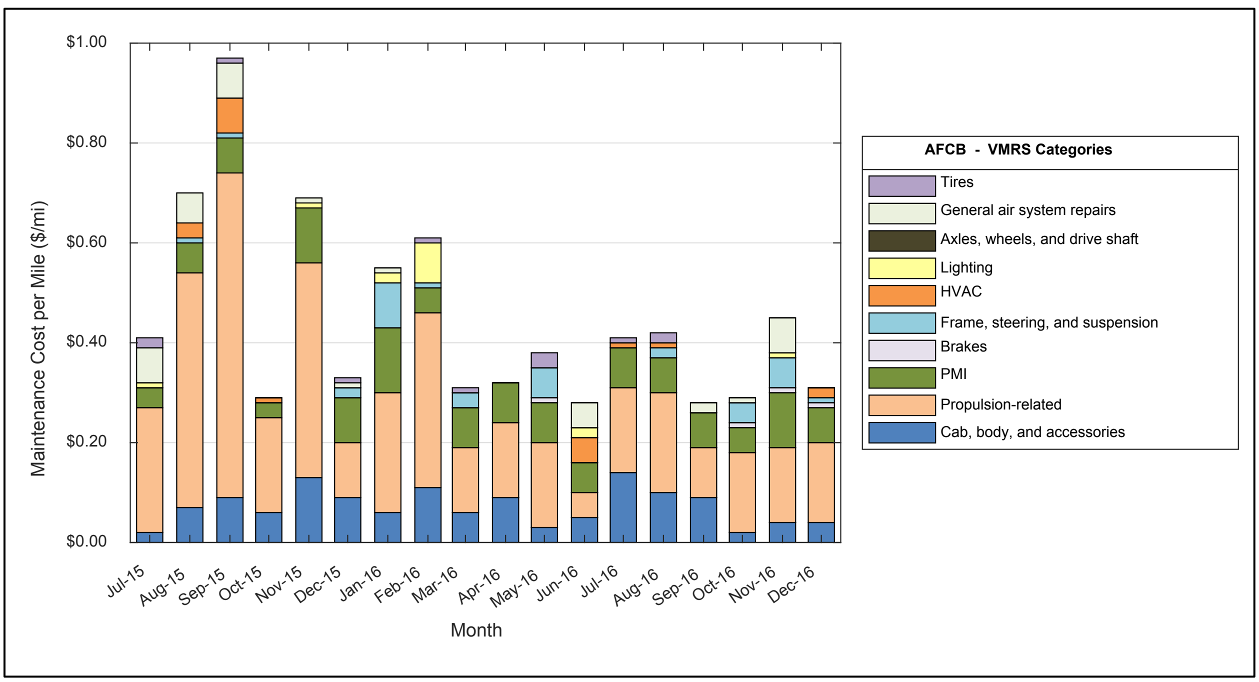

Figure 13. Monthly maintenance cost per mile by category for the AFCBs

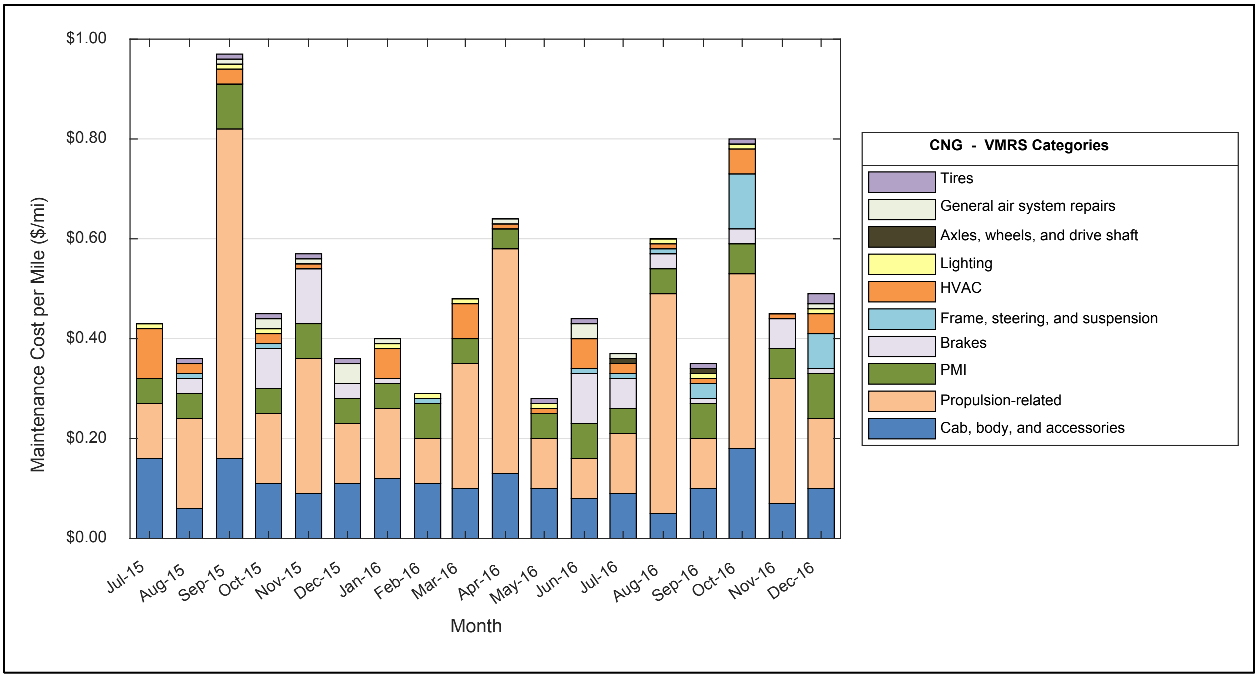

Figure 14. Monthly maintenance cost per mile by category for the CNG buses

Propulsion-Related Maintenance Costs

The propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. Table 9 categorizes the propulsion-related system repairs for the AFCBs and CNG buses during the evaluation period (not including warranty). The AFCBs were under warranty for most of the key systems during the entire evaluation period. The CNG buses are no longer under warranty. The SunLine mechanics continue to handle nearly all of the maintenance on the AFCBs, with support as needed by the manufacturers. However, the manufacturers generally supplied the parts under warranty for the propulsion system, so the costs for these parts are not included in the maintenance costs.

- **Total propulsion-related**—The propulsion-related maintenance cost was essentially the same for the AFCBs as for the CNG buses. The majority of this maintenance for the AFCBs has been labor.
- **Exhaust system**—Costs for this system were low or zero for both CNG buses and AFCBs.
- **Fuel system**—Costs for this system for the CNG buses and AFCBs were low.
- **Power plant and electric propulsion**—The power-plant-related maintenance cost per mile for the AFCBs was the similar to the cost per mile of the engine-related work for the CNG buses. The AFCB maintenance reported here was almost exclusively labor for SunLine mechanics—for troubleshooting and making the repairs on the bus or supporting manufacturer work on the bus. There are no electric propulsion costs for the CNG buses because they are not hybrids. The CNG buses continue to experience engine issues and

have required tune-ups during the data period. SunLine also rebuilt engines on two of the CNG buses. This is expected of buses that have surpassed 400,000 miles.

- **Non-lighting electrical (charging, cranking, and ignition)—**The AFCB costs in this category were primarily for replacing bus batteries and repairing general bus electrical problems. The CNG buses mostly had preventive maintenance repairs in this category, for spark plugs at the 30,000-mile preventive-maintenance cycle for each bus.
- **Air intake—**Costs for this system for the study bus groups were low.
- **Cooling—**The AFCBs had high costs, primarily for labor, for maintenance of the fuel cell and hybrid cooling systems. Costs for this system for the CNG bus group were low.
- **Transmission—**Costs for this system for the CNG buses were low. The AFCBs do not have a traditional transmission; costs are included in the electric propulsion category.

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

Maintenance System	Maintenance Costs	AFCB	CNG
Mileage		178,578	471,152
Total Propulsion-Related Systems (Roll-up)	Parts cost ($)	3,273	61,996
	Labor hours	694.3	783.0
	Total cost ($)	37,985	101,144
	Total cost ($) per mile	**0.21**	**0.21**
Exhaust System Repairs	Parts cost ($)	0	9,664
	Labor hours	0.0	27.3
	Total cost ($)	0	11,027
	Total cost ($) per mile	**0.00**	**0.02**
Fuel System Repairs	Parts cost ($)	0	2,899
	Labor hours	5.0	9.3
	Total cost ($)	250	3,361
	Total cost ($) per mile	**0.00**	**0.01**
Power Plant System Repairs	Parts cost ($)	77	28,850
	Labor hours	361.3	533.5
	Total cost ($)	18,139	55,525
	Total cost ($) per mile	**0.10**	**0.12**
Electric Propulsion System Repairs	Parts cost ($)	15	0
	Labor hours	73.5	0.0
	Total cost ($)	3,690	0
	Total cost ($) per mile	**0.02**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)	Parts cost ($)	3,121	11,598
	Labor hours	91.8	77.8
	Total cost ($)	7,709	15,485
	Total cost ($) per mile	**0.04**	**0.03**
Air Intake System Repairs	Parts cost ($)	16	1,468
	Labor hours	5.8	0.0
	Total cost ($)	303	1,468
	Total cost ($) per mile	**0.00**	**0.00**
Cooling System Repairs	Parts cost ($)	43	3,265
	Labor hours	157.0	106.5
	Total cost ($)	7,893	8,588
	Total cost ($) per mile	**0.04**	**0.02**
Transmission System Repairs	Parts cost ($)	0	1,748
	Labor hours	0.0	28.8
	Total cost ($)	0	3,186
	Total cost ($) per mile	**0.00**	**0.01**
Hydraulic System Repairs	Parts cost ($)	0	2,504
	Labor hours	0.0	0.0
	Total cost ($)	0	2,504
	Total cost ($) per mile	**0.00**	**0.01**

Summary of Achievements and Challenges

This section describes the most recent experience with the AFCBs at SunLine. All four buses were operating during the evaluation period. Since the last report, there have been multiple accomplishments.

- The four AFCBs have operated 330,513 miles and accumulated 23,612 hours on the fuel cell power systems since being placed into service.
- SunLine has safely fueled its FCEBs 1,418 times with more than 33,100 kg of hydrogen during the data period.
- The prototype AFCB has surpassed 8,112 hours on the fuel cell power system.

DOE and FTA have published performance, cost, and durability targets for FCEBs. These targets, established with industry input, include interim targets for 2016 and ultimate targets for commercialization. Table 10 summarizes the current performance of the AFCBs compared to these targets. The results in the table cover the time period from when the buses first went into service through December 2016.

Table 10. Summary of AFCB Performance Compared to DOE/FTA Targets[9]

	Units	This Report[a]	2016 Target	Ultimate Target
Bus lifetime	years/miles	5/121,600[b]	12/500,000	12/500,000
Power plant lifetime[c]	hours	8,100[d]	18,000	25,000
Bus availability	%	74	85	90
Fuel fills[e]	per day	1	1 (<10 min)	1 (<10 min)
Bus cost[f]	$	2,400,000[g]	1,000,000	600,000
Roadcall frequency (bus/fuel cell system)	miles between roadcalls	4,700/ 17,400	3,500/ 15,000	4,000/ 20,000
Operation time	hours per day/days per week	7–20/ 5–7	20/7	20/7
Scheduled and unscheduled maintenance cost[h]	$/mile	0.46	0.75	0.40
Range	miles	270[i]	300	300
Fuel economy	miles per diesel gallon equivalent	6.46	8	8

[a] Summary of the results for the AFCBs from the start of service: data from March 2013 to December 2016.
[b] Accumulated totals for the oldest AFCB through December 2016; these buses have not reached end of life; targets are for lifetime.
[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] Multiple sequential fuel fills should be possible without an increase in fill time.
[f] 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.

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

[g] Approximate cost of the prototype AFCB based on a very low quantity as a non-production, prototype vehicle (not including non-recurring engineering for the initial design).
[h] Excludes mid-life overhaul of the power plant.
[i] Based on fuel economy and a useful fuel tank capacity of 95%.

Summary of Challenges

Advanced technology demonstrations typically experience challenges and issues that need to be resolved. A few of the recent issues and status of resolution are provided here.

Upgrade of prototype AFCB (FC3): Results from the early demonstration period of the prototype bus led to multiple design upgrades for the next buses produced. The manufacturers made several updates to the prototype bus to more closely match the new design. Over the last year, the bus developed issues related to some of the systems that had not been upgraded. One issue involved a bad resistor for the air conditioning compressor and motor. The problem component took some time to locate because data for the prototype bus are captured differently from that of the newer buses. Another issue occurred with a controller in the dash that was causing the fuel cell to turn off and the cooling fans to activate. The new replacement part did not fit in the old style dash and had to be modified. This resulted in the bus being down for a month. The bus also developed a problem with the accessory power system. The failed component also proved to be difficult to locate. In May 2016, the bus was removed from service to fully upgrade the bus to match the newer design. Upgrades included replacing the dash and the power electronics, and upgrading the software. The upgrade of the prototype will help the agency to maintain the bus by standardizing components and troubleshooting procedures. The upgrade was completed in July. SunLine did not schedule the bus to operate during this time and the data were removed from the availability analysis.

Fuel cell system issues: During the data period, the fuel cell system on one bus developed an internal stack leak. The system was shipped to Ballard for repair and was reinstalled in the bus. The majority of fuel cell system issues involved components in the balance of plant, which includes air and fuel management components. Issues included problems with a sensor, commutator, regulator, blower motor, and pump.

Coolant leaks: The AFCB has several coolant loops to control temperature for the different systems on the bus. During the data period, SunLine identified and repaired minor leaks in the bus, fuel cell, and hybrid cooling systems. In one instance, a leak inside the fuel cell module was causing an isolation fault. This issue proved difficult to diagnose and resulted in extended downtime for the bus.

Parts supply: SunLine has had difficulty getting parts for advanced components. The agency reports that this has improved over time. The manufacturers now have a local area parts warehouse that is expected to reduce downtime.

Hydrogen station: In early June 2016, SunLine's hydrogen station developed an issue during a power outage that caused the reformer controller to burn out. The situation resulted in damage to the pressure swing adsorption beds and rotary valve in the reformer. To repair the unit, SunLine replaced the pressure swing adsorption bed material and the valve. The actual repair took about four days; however, the agency had to wait several weeks for the parts to be shipped. After the repair, SunLine sent a sample of the hydrogen produced out for analysis. The reformer was out of service for approximately eight weeks. During that time, the agency had to have hydrogen trucked to the site. SunLine limited the service time for the buses because the cost for delivered hydrogen is higher than the agency's cost to produce it on-site.

Lessons Learned

As with all new technology development, lessons learned during this project could aid other agencies considering FCEB technology. Key lessons learned since the beginning of the project include the following:

- Treat the FCEBs as you would any other bus and not as a special fleet. An agency should depend on the buses to meet service regardless of the propulsion technology.

- Involve all mechanics in repair for the buses. An agency needs to get as many mechanics trained to service the advanced technology buses as possible. The maintenance staff will become more comfortable over time, and labor hours should drop as the learning curve improves.

- Be aware of the parts and components that have issues. Keep those parts in inventory to avoid unnecessary downtime, especially for those that require a long lead time.

- Be diligent with preventive maintenance and ensure all items are checked off as scheduled. General bus PMIs will be the same as that of the conventional technology; however, advanced components will require different tasks and safety precautions.

What's Next for SunLine

This report covers SunLine's operation of the AFCBs and CNG buses through December 2016. The agency will continue working with NREL to collect data on the buses in service. The current CNG baseline buses have reached an advanced age and are experiencing issues that have increased maintenance costs. Because of this, they are no longer the best comparison to the newer FCEBs. SunLine received new CNG buses in 2016. Beginning in January 2017, NREL will switch to collecting data on a selection of the new CNG buses for a baseline comparison.

SunLine has received funding for several new projects that will add FCEBs to its fleet. Table 11 summarizes the current and upcoming FCEB projects for SunLine. The blue shaded lines show which projects are included in the analysis for this report.

Table 11. Summary of Current and Planned FCEB Projects at SunLine

Project	Funding Program	# Buses	Description	In Service Start
Advanced Technology FCEB	N/A	1	New Flyer 40-foot bus, Siemens ELFA hybrid system, lithium phosphate batteries, Ballard fuel cell power system	May 2010
American Fuel Cell Bus Program	FTA—NFCBP	1	Prototype AFCB, ENC 40-foot bus, BAE Systems hybrid system, lithium ion batteries, Ballard fuel cell power system.	Dec 2011
American Fuel Cell Buses for SunLine	FTA—TIGGER	2	Upgraded AFCB design, ENC/BAE Systems/Ballard	June 2014
AFCB Addition	N/A	1	AFCB—ENC/BAE Systems/ Ballard (originally planned for another transit agency)	May 2015
SunLine AFCB Deployment	FTA—Low-No	5	AFCB—ENC/BAE Systems/ Ballard	Q4 2017
Battery Dominant Fuel Cell Hybrid Bus	FTA—NFCBP	1	Battery dominant FCEB based on AFCB platform with a smaller fuel cell	Q3 2017
New Flyer/ Hydrogenics FCEB	CEC[a]—Alternative and Renewable Fuel and Vehicle Technology Program	1	New Flyer Xcelsior bus, Siemens ELFA hybrid drive system with Hydrogenics fuel cell system	Q1 2018
SunLine FCEBs and Fueling Station Deployment	CARB[b]	5	New Flyer Xcelsior bus, Siemens ELFA hybrid drive system with Hydrogenics fuel cell system	Q4 2018
	Total FCEBs	**17**		

[a] California Energy Commission.
[b] California Air Resources Board.

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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.

Other SunLine Reports

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Appendix A: TRL Guideline Table

Technology Readiness Levels for FCEB Commercialization

Technology Readiness Level	TRL Definition	Description
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.
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.
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.
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.
TRL 1	Basic principles observed and reported	Scientific research and early development of FCEB concepts.

Appendix B: Fleet Summary Statistics

Fleet Summary Statistics: SunLine Transit Agency
AFCB and CNG Study Groups
Fleet Operations and Economics

	AFCB All Data	AFCB New Data	CNG All Data	CNG New Data
Number of vehicles	4	4	5	5
Period used for fuel and oil op analysis	3/12-12/16	7/15-12/16	3/12-12/16	7/15-12/16
Total number of months in period	58	18	58	18
Fuel and oil analysis base fleet mileage	322,109	175,039	1,362,268	466,531
Period used for maintenance op analysis	3/12-12/16	7/15-12/16	3/12-12/16	7/15-12/16
Total number of months in period	58	18	58	18
Maintenance analysis base fleet mileage	330,513	178,578	1,369,822	471,152
Average monthly mileage per vehicle	2,485	2,480	4,724	5,235
Availability	73	75	87	92
Fleet fuel usage in kg H_2 or gge CNG	56,359.8	32,274.6	473,649.9	160,947.9
Roadcalls	70	31	152	47
Total MBRC	4,722	5,761	9,012	10,025
Propulsion roadcalls	45	22	59	24
Propulsion MBRC	7,345	8,117	23,217	19,631
Fleet miles/kg hydrogen (1.13 kg H_2/gge CNG)	5.72	5.42	2.88	2.90
Representative fleet mpg (energy equiv.)	6.46	6.13	3.21	3.24
Hydrogen cost per kg	7.68	7.68		
CNG cost per gge			0.96	0.96
Fuel cost per mile	1.34	1.42	0.33	0.33
Total scheduled repair cost per mile	0.08	0.08	0.09	0.08
Total unscheduled repair cost per mile	0.38	0.35	0.42	0.40
Total maintenance cost per mile	0.46	0.42	0.51	0.48
Total operating cost per mile	***1.80***	***1.84***	***0.85***	***0.81***

Maintenance Costs

	AFCB All Data	AFCB New Data	CNG All Data	CNG New Data
Fleet mileage	330,513	178,578	1,369,822	471,152
Total parts cost	17,353.13	7,527.02	321,061.44	107,581.60
Total labor hours	2,683.0	1,359.8	7,668.5	2,373.7
Average labor cost (@ $50.00 per hour)	134,150.00	67,987.50	383,422.50	118,685.00
Total maintenance cost	151,503.13	75,514.52	704,483.94	226,266.60
Total maintenance cost per bus	2,612.12	1,301.97	39,138.00	12,570.37
Total maintenance cost per mile	***0.46***	***0.42***	***0.51***	***0.48***

Maintenance Costs by Vehicle System

	AFCB All Data	AFCB New Data	CNG All Data	CNG New Data
Fleet mileage	330,513	178,578	1,369,822	471,152
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	6,997.78	3,272.51	177,532.51	61,996.17
Labor hours	1,464.25	694.25	2,726.70	782.95
Average labor cost	73,212.50	34,712.50	136,335.00	39,147.50
Total cost (for system)	80,210.28	37,985.01	313,867.51	101,143.67
Total cost (for system) per bus	1,382.94	654.91	17,437.08	5,619.09
Total cost (for system) per mile	**0.24**	**0.21**	**0.23**	**0.21**
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	17,206.13	9,664.06
Labor hours	0.0	0.0	65.3	27.3
Average labor cost	0.00	0.00	3,262.50	1,362.50
Total cost (for system)	0.00	0.00	20,468.63	11,026.56
Total cost (for system) per bus	0.00	0.00	1,137.15	612.59
Total cost (for system) per mile	**0.00**	**0.00**	**0.01**	**0.02**
Fuel System Repairs (ATA VMRS 44)				
Parts cost	0.00	0.00	6,997.72	2,898.72
Labor hours	81.3	5.0	16.8	9.3
Average labor cost	4,062.50	250.00	837.50	462.50
Total cost (for system)	4,062.50	250.00	7,835.22	3,361.22
Total cost (for system) per bus	70.04	4.31	435.29	186.73
Total cost (for system) per mile	**0.01**	**0.00**	**0.01**	**0.01**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	181.57	76.94	88,883.82	28,850.19
Labor hours	628.3	361.3	2,044.8	533.5
Average labor cost	31,412.50	18,062.50	102,237.50	26,675.00
Total cost (for system)	31,594.07	18,139.44	191,121.32	55,525.19
Total cost (for system) per bus	544.73	312.75	10,617.85	3,084.73
Total cost (for system) per mile	**0.10**	**0.10**	**0.14**	**0.12**
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	74.00	15.00	0.00	0.00
Labor hours	178.3	73.5	0.0	0.0
Average labor cost	8,912.50	3,675.00	0.00	0.00
Total cost (for system)	8,986.50	3,690.00	0.00	0.00
Total cost (for system) per bus	154.94	63.62	0.00	0.00
Total cost (for system) per mile	**0.03**	**0.02**	**0.00**	**0.00**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	6,653.76	3,121.35	42,577.84	11,597.65
Labor hours	177.3	91.8	184.0	77.8
Average labor cost	8,862.50	4,587.50	9,200.00	3,887.50
Total cost (for system)	15,516.26	7,708.85	51,777.84	15,485.15
Total cost (for system) per bus	267.52	132.91	2,876.55	860.29
Total cost (for system) per mile	**0.05**	**0.04**	**0.04**	**0.03**

Maintenance Costs by Vehicle System (continued)

	AFCB All Data	AFCB New Data	CNG All Data	CNG New Data
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	24.53	15.95	5,013.21	1,467.72
Labor hours	5.8	5.8	1.0	0.0
Average labor cost	287.50	287.50	50.00	0.00
Total cost (for system)	312.03	303.45	5,063.21	1,467.72
Total cost (for system) per bus	5.38	5.23	281.29	81.54
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Cooling System Repairs (ATA VMRS 42)				
Parts cost	63.92	43.27	7,468.97	3,265.48
Labor hours	393.5	157.0	337.5	106.5
Average labor cost	19,675.00	7,850.00	16,872.50	5,322.50
Total cost (for system)	19,738.92	7,893.27	24,341.47	8,587.98
Total cost (for system) per bus	340.33	136.09	1,352.30	477.11
Total cost (for system) per mile	**0.06**	**0.04**	**0.02**	**0.02**
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0.00	0.00	5,447.16	2,504.33
Labor hours	0.0	0.0	7.0	0.0
Average labor cost	0.00	0.00	350.00	0.00
Total cost (for system)	0.00	0.00	5,797.16	2,504.33
Total cost (for system) per bus	0.00	0.00	322.06	139.13
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.01**
General Air System Repairs (ATA VMRS 10)				
Parts cost	627.22	221.40	3,653.09	1,034.04
Labor hours	70.8	55.0	260.5	64.0
Average labor cost	3,537.50	2,750.00	13,025.00	3,200.00
Total cost (for system)	4,164.72	2,971.40	16,678.09	4,234.04
Total cost (for system) per bus	71.81	51.23	926.56	235.22
Total cost (for system) per mile	**0.01**	**0.02**	**0.01**	**0.01**
Brake System Repairs (ATA VMRS 13)				
Parts cost	669.13	49.57	28,412.69	10,284.00
Labor hours	20.3	5.0	223.0	89.8
Average labor cost	1,012.50	250.00	11,150.00	4,487.50
Total cost (for system)	1,681.63	299.57	39,562.69	14,771.50
Total cost (for system) per bus	28.99	5.17	2,197.93	820.64
Total cost (for system) per mile	**0.01**	**0.00**	**0.03**	**0.03**
Transmission Repairs (ATA VMRS 27)				
Parts cost	0.00	0.00	3,937.66	1,748.02
Labor hours	0.0	0.0	70.5	28.8
Average labor cost	0.00	0.00	3,525.00	1,437.50
Total cost (for system)	0.00	0.00	7,462.66	3,185.52
Total cost (for system) per bus	0.00	0.00	414.59	176.97
Total cost (for system) per mile	**0.00**	**0.00**	**0.01**	**0.01**

Maintenance Costs by Vehicle System (continued)

	AFCB All Data	AFCB New Data	CNG All Data	CNG New Data
Inspections Only - no parts replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	495.8	271.0	1733.8	548.5
Average labor cost	24,787.50	13,550.00	86,687.50	27,425.00
Total cost (for system)	24,787.50	13,550.00	86,687.50	27,425.00
Total cost (for system) per bus	427.37	233.62	4,815.97	1,523.61
Total cost (for system) per mile	**0.07**	**0.08**	**0.06**	**0.06**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	5,162.53	2,036.98	50,219.01	21,205.55
Labor hours	418.5	216.3	1,596.8	588.0
Average labor cost	20,925.00	10,812.50	79,837.50	29,400.00
Total cost (for system)	26,087.53	12,849.48	130,056.51	50,605.55
Total cost (for system) per bus	449.79	221.54	7,225.36	2,811.42
Total cost (for system) per mile	**0.08**	**0.07**	**0.09**	**0.11**
HVAC System Repairs (ATA VMRS 01)				
Parts cost	48.30	0.00	41,440.58	7,063.16
Labor hours	42.3	28.3	513.3	142.8
Average labor cost	2,112.50	1,412.50	25,662.50	7,137.50
Total cost (for system)	2,160.80	1,412.50	67,103.08	14,200.66
Total cost (for system) per bus	37.26	24.35	3,727.95	788.93
Total cost (for system) per mile	**0.01**	**0.01**	**0.05**	**0.03**
Lighting System Repairs (ATA VMRS 34)				
Parts cost	1,487.09	1,180.88	3,445.12	1,111.89
Labor hours	30.5	7.8	174.5	34.0
Average labor cost	1,525.00	387.50	8,725.00	1,700.00
Total cost (for system)	3,012.09	1,568.38	12,170.12	2,811.89
Total cost (for system) per bus	51.93	27.04	676.12	156.22
Total cost (for system) per mile	**0.01**	**0.01**	**0.01**	**0.01**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	2,361.08	765.68	9,277.95	4,379.37
Labor hours	101.0	60.0	155.8	53.0
Average labor cost	5,050.00	3,000.00	7,787.50	2,650.00
Total cost (for system)	7,411.08	3,765.68	17,065.45	7,029.37
Total cost (for system) per bus	127.78	64.93	948.08	390.52
Total cost (for system) per mile	**0.02**	**0.02**	**0.01**	**0.01**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	0.00	0.00	7,052.54	507.42
Labor hours	0.0	0.0	57.5	0.5
Average labor cost	0.00	0.00	2,875.00	25.00
Total cost (for system)	0.00	0.00	9,927.54	532.42
Total cost (for system) per bus	0.00	0.00	551.53	29.58
Total cost (for system) per mile	**0.00**	**0.00**	**0.01**	**0.00**

Maintenance Costs by Vehicle System (continued)

	AFCB All Data	AFCB New Data	CNG All Data	CNG New Data
Tire Repairs (ATA VMRS 17)				
Parts cost	0.00	0.00	27.95	0.00
Labor hours	39.8	22.3	226.8	70.3
Average labor cost	1,987.50	1,112.50	11,337.50	3,512.50
Total cost (for system)	1,987.50	1,112.50	11,365.45	3,512.50
Total cost (for system) per bus	34.27	19.18	631.41	195.14
Total cost (for system) per mile	**0.01**	**0.01**	**0.01**	**0.01**

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 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

The gasoline LHV or gge is 115,000 Btu/gal, which is approximately 1% higher than 113,628 Btu/kg for hydrogen; these have been called equivalent for this report.

Gasoline/diesel = 115,000 Btu/gallon / 128,400 Btu/gallon = 0.896

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. Average labor cost is assumed to be $50 per hour.

7. Warranty costs are not included.

Appendix C: Fleet Summary Statistics—SI Units

Fleet Summary Statistics: SunLine Transit Agency
AFCB and CNG Study Groups
Fleet Operations and Economics

	AFCB Total	AFCB Data Period	CNG Total	CNG Data Period
Number of vehicles	4	4	5	5
Period used for fuel and oil op analysis	3/12-12/16	7/15-12/16	3/12-12/16	7/15-12/16
Total number of months in period	58	18	58	18
Fuel and oil analysis base fleet kilometers	518,370	281,690	2,192,298	750,788
Period used for maintenance op analysis	3/12-12/16	7/15-12/16	3/12-12/16	7/15-12/16
Total number of months in period	58	18	58	18
Maintenance analysis base fleet kilometers	531,895	287,386	2,204,455	758,225
Average monthly kilometers per vehicle	3,999	3,991	7,602	8,425
Availability	73	75	87	92
Fleet fuel usage in kg H_2 or liter equiv. CNG	56,359.8	32,274.6	1,792,959.9	609,254.1
Roadcalls	70	31	152	47
Total KMBRC	7,598	9,271	14,503	16,132
Propulsion roadcalls	45	22	59	24
Propulsion KMBRC	11,820	13,063	37,364	31,593
Fleet kg hydrogen/100 km (1.13 kg H_2/gal diesel fuel)	10.87	11.46		
Rep. fleet fuel consumption (L/100 km)	36.42	38.38	73.20	72.63
Hydrogen cost per kg	7.68	7.68		
CNG cost per liter			0.25	0.25
Fuel cost per kilometer	**0.84**	**0.88**	**0.21**	**0.21**
Total scheduled repair cost per kilometer	0.05	0.05	0.06	0.05
Total unscheduled repair cost per kilometer	0.24	0.22	0.26	0.25
Total maintenance cost per kilometer	**0.28**	**0.26**	**0.32**	**0.30**
Total operating cost per kilometer	***1.12***	***1.14***	***0.53***	***0.50***

Maintenance Costs

	AFCB Total	AFCB Data Period	CNG Total	CNG Data Period
Fleet mileage	531,895	287,386	2,204,455	758,225
Total parts cost	17,353.13	7,527.02	321,061.44	107,581.60
Total labor hours	2,683.0	1,359.8	7,668.5	2,373.7
Average labor cost (@ $50.00 per hour)	134,150.00	67,987.50	383,422.50	118,685.00
Total maintenance cost	151,503.13	75,514.52	704,483.94	226,266.60
Total maintenance cost per bus	37,875.78	18,878.63	176,120.99	45,253.32
Total maintenance cost per kilometer	***0.28***	***0.26***	***0.32***	***0.30***