FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

American Fuel Cell Bus Project: First Analysis Report

JUNE 2013

FTA Report No. 0047
Federal Transit Administration

PREPARED BY

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U.S. Department of Transportation
Federal Transit Administration

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U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

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Metric Conversion Table

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

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This report summarizes the experience and early results from the American Fuel Cell Bus Project, a fuel cell electric bus demonstration funded by the Federal Transit Administration (FTA) under the National Fuel Cell Bus Program. A team led by CALSTART and SunLine Transit Agency developed a next-generation fuel cell electric bus for demonstration. The 40-foot ElDorado National transit bus features a BAE Systems series hybrid propulsion system powered by a Ballard Power Systems fuel cell and lithium iron phosphate batteries. The National Renewable Energy Laboratory (NREL) has been tasked by FTA to evaluate the buses in service. This report documents the early development and implementation of the buses and summarizes the performance results through February 2013.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

This report summarizes the experience and early results from the American Fuel Cell Bus Project, a fuel cell electric bus demonstration funded by the Federal Transit Administration (FTA) under the National Fuel Cell Bus Program. A team led by CALSTART and SunLine Transit Agency developed a next-generation fuel cell electric bus for demonstration. The 40-foot ElDorado National transit bus features a BAE Systems series hybrid propulsion system powered by a Ballard Power Systems fuel cell and lithium iron phosphate batteries. The National Renewable Energy Laboratory (NREL) has been tasked by FTA to evaluate the buses in service. This report documents the early development and implementation of the buses and summarizes the performance results through February 2013.

EXECUTIVE SUMMARY

This report presents results of the American Fuel Cell Bus (AFCB) Project, a demonstration of a new fuel cell electric bus (FCEB) operating in the Coachella Valley area of California as part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP). Through the non-profit consortia CALSTART, a team led by SunLine Transit Agency and BAE Systems developed a new FCEB for demonstration. The report summarizes the performance results for the bus through February 2013.

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 has been evaluating 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 AFCB has a fuel-cell-dominant hybrid electric propulsion system in a series configuration. This next-generation design builds on a commercial hybrid electric propulsion system developed by BAE Systems. For the AFCB, BAE Systems served as the lead vehicle integrator and supplied the hybrid propulsion system, power converters, and electric accessories. Ballard Power Systems provided the fuel cell system, and ElDorado National produced the bus glider and served as the final stage manufacturer. The AFCB was delivered to SunLine in November 2011 and was put into revenue service in mid-December. From December 2011 through February 2013, the bus has traveled more than 48,000 miles and accumulated more than 3,000 hours on the fuel cell system.

This report focuses on the AFCB's performance for a one-year data period from March 2012 through February 2013. Table ES-1 provides a summary of results for several categories of data presented in this report. Data are included on the AFCB and on five compressed natural gas (CNG) buses used as a baseline.

Table ES-1

Summary of Evaluation Results

Data Item	AFCB	CNG
Number of buses	1	5
Data period	March 2012–February 2013	March 2012–February 2013
Number of months	12	12
Total mileage in period	42,988	228,225
Average monthly mileage per bus	3,582	3,036
Total fuel cell operating hours	2,758	N/A
Average bus operating speed (mph)	15.6	15.5
Availability (85% is target)	85	77
Fuel economy (miles/kg or GGE)	6.54	2.80
Fuel economy (miles/DGE[a])	7.39	3.13
Miles between roadcalls (MBRC) – bus	3,908	8,151
MBRC – propulsion only	7,165	32,604
MBRC – FC system only	14,329	N/A
Total maintenance ($/mile)[b]	0.39	0.53
Maintenance – propulsion only ($/mile)	0.12	0.24

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

During the evaluation period, the AFCB has achieved exceptional availability, averaging 85 percent. The issues causing downtime were most often related to general bus system items rather than the advanced technologies that were the focus of the demonstration. These issues were generally of a "low tech" nature and consistent with the type of issues that would be expected when introducing a new configuration in a prototype bus model. Overall, the AFCB averaged 6.54 miles per kilogram of hydrogen, which equates to 7.39 miles per diesel gallon equivalent (DGE). Using the gasoline gallon equivalent (GGE) fuel economy of the CNG buses as a baseline, the AFCB had a fuel economy 2.4 times higher than that of the CNG buses.

Each of the project team members report that the demonstration has gone well, and all are pleased with the performance of the AFCB. BAE Systems reports that the performance of the bus matched or exceeded their expectations. SunLine notes that the bus procurement and development process went well and the AFCB start-up issues were much fewer than with previous FCEBs.

The team credits the success of the demonstration to several factors, including:

- Use of an integrated project team approach to set common objectives and well-defined roles for each member
- Leveraging an existing, proven commercial technology hybrid propulsion system

- Extensive testing of the integrated fuel cell/series hybrid electric propulsion system in the systems integration laboratory to optimize the performance and work out potential issues prior to integration into the bus
- An experienced transit staff familiar with advanced technology buses

In early 2014, SunLine will add two AFCBs to its fleet through another FTA program (Transit Investments for Greenhouse Gas and Energy Reduction—TIGGER). BAE Systems, Ballard, and ElDorado are also building three AFCBs for demonstration at Chicago Transit Authority (NFCBP funding), Massachusetts Bay Transportation Authority (NFCBP Funding), and Connecticut Transit (federal grant funding). These demonstrations will provide the team with data on AFCB performance in colder climates and allow the technology to be optimized to meet the needs of any U.S. transit agency. The integrated project team is interested in advancing the commercialization of fuel cell buses. BAE Systems plans to include fully-integrated components that support fuel cell and all electric-powered buses in its hybrid product line.

For FCEBs to be fully commercialized, the fuel cell hybrid propulsion system needs to be an option offered by the bus original equipment manufacturer (OEM), as is the case with current diesel hybrid systems. With the SunLine TIGGER order for two AFCBs, the team is taking steps to make this transition. The first bus glider will be shipped to BAE Systems for integration of the propulsion system, and BAE Systems will work with ElDorado staff to complete the installation. The second bus will be built entirely at the ElDorado factory with support from BAE Systems.

In September 2012, DOE and FTA 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 ES-2 summarizes the current performance results of the AFCB compared to these targets. This table will be included in future NFCBP reports.

Table ES-2

Summary of AFCB Performance Compared to DOE/FTA Targets[1]

	Units	This Report[1]	2012 Status[a]	2016 Target[a]	Ultimate Target[a]
Bus lifetime	years/miles	1/48,760[b]	5/100,000	12/500,000	12/500,000
Power plant lifetime[c]	Hours	3,152[d]	12,000	18,000	25,000
Bus availability	%	85	60	85	90
Fuel fills[e]	per day	1	1	1 (< 10 min)	1 (< 10 min)
Bus cost[f]	$	[g]	2,000,000	1,000,000	600,000
Power plant cost[c,f]	$	N/A[h]	700,000	450,000	200,000
Hydrogen storage cost	$	N/A[h]	100,000	75,000	50,000
Roadcall frequency (bus/fuel cell system)	miles between roadcalls	3,908/14,329	2,500/ 10,000	3,500/15,000	4,000/20,000
Operation time	hours per day/ days per week	7–19/			
5–7	19/7	20/7	20/7		
Scheduled and unscheduled maintenance cost[i]	$/mile	0.39	1.20	0.75	0.40
Range	miles	323[j]	270	300	300
Fuel economy	miles per DGE	7.39	7	8	8

[a] Summary of results for AFCB in this report: data from March 2012–February 2013.
[b] Accumulated totals for AFCB through February 2013; this bus has not reached end of life.
[c] For DOE/FTA targets, power plant is defined as fuel cell system and battery system. fuel cell system includes supporting subsystems such as air, fuel,coolant, and control subsystems. Power electronics, electric drive, and hydrogen storage tanks are excluded.
[d] Status for power plant hours is for 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.
[g] Purchase price.
[h] Capital costs for subsystems are not currently reported by the manufacturers.
[i] Excludes mid-life overhaul of power plant.
[j] Based on fuel economy and tank capacity.

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

SECTION 1

Introduction

As part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP), a team led by CALSTART and SunLine Transit Agency developed a next-generation fuel cell electric bus (FCEB) for demonstration. This next-generation design builds on a commercial series hybrid electric propulsion system developed by BAE Systems. For the American Fuel Cell Bus (AFCB), BAE Systems served as the lead vehicle integrator and supplied the hybrid propulsion system, power converters, and electric accessories. Ballard Power Systems provided the fuel cell system, and ElDorado National produced the bus glider and served as the final stage manufacturer. The National Renewable Energy Laboratory (NREL), one of the U.S. Department of Energy's (DOE) national laboratories, is evaluating this technology for FTA as part of the NFCBP. This report documents the early development and implementation of the bus and summarizes performance results at SunLine Transit Agency in the Coachella Valley, California, area.

National Fuel Cell Bus Program

In 2006, FTA initiated the NFCBP,[2] which supplied $49 million over 4 years in competitive, 50–50 government-industry cost-share grants to facilitate the development of commercially-viable FCEB technologies. This FTA program was funded as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU).[3] The objectives of the program include:

- Developing improved components and technologies for FCEBs, including fuel cell, energy storage, and power electronics technologies
- Demonstrating FCEBs equipped with these improved components and technologies
- Understanding the requirements of market introduction, including fuel supply, fueling infrastructure, supplier networks, maintenance, education, safety, and insurance
- Collaborating in development of design standards for FCEB technologies

In October 2006, FTA awarded grants to three nonprofit consortia—CALSTART (Pasadena, California), the Center for Transportation and the Environment (CTE, Atlanta, Georgia), and the Northeast Advanced Vehicle Consortium (NAVC, Boston, Massachusetts). These consortia were funded to lead teams to develop

[2]FTA Bus Research and Testing website: http://www.fta.dot.gov/assistance/technology/research_4578.html.
[3]www.fhwa.dot.gov/safetealu/.

and test components, conduct outreach, and demonstrate FCEBs in a variety of geographic locations and climates across the United States.

A portfolio of 14 projects (managed by the 3 consortia), including 8 planned demonstration projects, was competitively selected by FTA to best advance FCEB commercialization.

For fiscal year 2010 and 2011, additional funding was appropriated for the NFCBP. To expand the original effort with this new funding, FTA solicited project proposals from the three selected consortia covering three areas:

1. Extensions or enhancements to existing projects with existing teams
2. New development and demonstration projects
3. Outreach, education, or coordination projects

For the 2010 funding, a total of eight new projects were selected, including four new development/demonstration projects, two component development projects, one outreach/education project, and one enhancement project for an existing demonstration. Eleven projects were selected for 2011 funding.

For fiscal year 2012, FTA again appropriated funding for projects under the NFCBP and has solicited another round of proposals for fuel cell bus projects. The proposals are currently in review. Table 1-1 outlines the NFCBP funding by year. To date, the NFCBP has secured more than $89 million in local and private commitments, which exceeds the federal contribution. A report outlining the overall status of FTA's FCEB-related research through 2011 is also available.[4]

Table 1-1

Funding for NFCBP

Funding Year	Total Funding (millions)	Number of Projects
2006–2009	49	14
2010	13.5	8
2011	13.4	11
2012	13.5	TBD
Total	**89.4**	**33**

Evaluation Activities

FTA is collaborating with DOE and funding NREL to ensure that data are collected on all FCEB demonstrations in a complete and consistent manner. FTA tasked NREL to be a third-party evaluator for the FCEBs developed and demonstrated under the NFCBP. Data collection, analysis, and reporting are a high priority for FTA to assess the success of the individual projects and the overall progress of fuel cell technology toward commercialization.

[4]FTA Fuel Cell Bus Program: Research Accomplishments through 2011, DOT/FTA Report No. 0014.

Under separate funding from DOE, NREL has been evaluating FCEBs to help determine the status of hydrogen and fuel cell systems in transit applications. NREL uses a standard data collection and analysis protocol that was established for DOE heavy-duty vehicle evaluations more than 10 years ago. In November 2010, NREL published *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration,* which outlines the methodology and plans for both the FTA and DOE FCEB evaluations[5] to be performed by NREL.

NREL has worked with SunLine to evaluate several early-generation FCEBs in service, including:

- ElDorado 30-foot FCEB with an ISE hybrid system and UTC Power fuel cell
- Van Hool 40-foot FCEB with an ISE hybrid system and UTC Power fuel cell
- New Flyer 40-foot FCEB with a Bluways hybrid system and Ballard fuel cell

This report is focused on the results for the AFCB bus from March 2012 through February 2013.

[5]Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/TP-5600-49342, Nov. 2010, http://www.nrel.gov/hydrogen/pdfs/49342-1.pdf.

SECTION
2

American Fuel Cell Bus Project

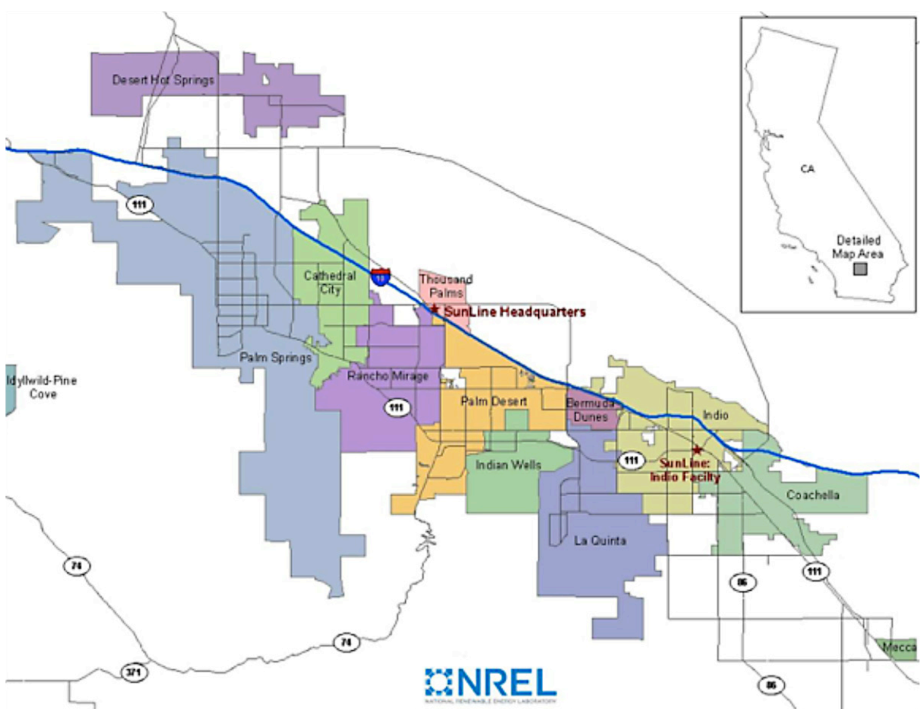
The AFCB Project is one of the demonstration projects awarded in 2006 when the NFCBP was initiated. The project is managed through CALSTART, a member organization focused on commercialization of clean transportation technologies. CALSTART is working with SunLine Transit Agency and a team of manufacturers to develop and demonstrate an FCEB that will advance the technology while addressing the challenge of "Buy America" compliance. The manufacturer team includes BAE Systems, Ballard Power Systems, and ElDorado National.

SunLine Transit Agency

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 is committed to operating clean fuel technologies in its fleet, beginning with complete fleet implementation of compressed natural gas (CNG) buses in 1994. Since then, the agency has tested many advanced technologies, including buses that run on a blend of hydrogen and CNG, battery electric power, and fuel cells. Over the last 10 years, SunLine has operated six different generations of buses powered by hydrogen. This experience makes the agency an excellent demonstration partner. SunLine's service area is shown in Figure 2-1.

Figure 2-1

Service Area for SunLine



BAE Systems

The development team is led by BAE Systems, a global defense, aerospace, and security company. BAE Systems' North American headquarters is located in Endicott, New York. The company has been manufacturing hybrid drive propulsion systems for more than a decade, with approximately 4,000 hybrid transit buses operating around the world. For the AFCB project, BAE Systems worked closely with Ballard and ElDorado to integrate the hybrid system and fuel cell powerplant into the bus. The hybrid system is based on the company's commercial system but uses a fuel cell powerplant in place of the diesel engine/generator.

Ballard Power Systems

Ballard Power Systems, based in British Columbia, Canada, provided the fuel cell power plant, which is the prime power source for the bus. For this project, Ballard provided its FCvelocity-HD6 fuel cell power system and worked with BAE Systems to integrate and test the system in the AFCB. Although the company is located in Canada, recent interest in fuel cell electric buses in the United States has led the company to establish U.S. manufacturing capabilities in Lowell, Massachusetts. The facility originally manufactured the gas diffusion layer for the fuel cells. In 2010, Ballard added the capability to manufacture the fuel cell systems for transit buses to meet future demand for Buy America-compliant buses. The fuel cell system for this bus was one of the first systems manufactured at the U.S. facility. In 2012, Ballard sold the Lowell facility to another company; however, it retains manufacturing capability.

ElDorado National

ElDorado National, a division of Thor Industries, Inc., has been building commercial buses for more than 30 years. The California division, located in Riverside, manufactures five lines of commercial vehicles, including the Axess model transit bus, a 40-foot, low-floor bus that was used as a base for the AFCB. ElDorado National worked with BAE Systems and Ballard to modify the bus as needed to enable integration of the hybrid system and fuel cell into the bus.

SECTION 3

Bus Technology Descriptions

The AFCB is a 40-foot ElDorado National bus with a BAE Systems hybrid electric propulsion system powered by Ballard's FCvelocity-HD6 150-kW fuel cell. Table 3-1 provides bus system descriptions for the AFCB (Figure 3-1) and the CNG buses studied in this evaluation. Five CNG buses operating from the same SunLine location are being used as a baseline comparison. One of the CNG buses is pictured in Figure 3-2. These buses are 2008 model year New Flyer CNG buses with Cummins Westport ISL G natural gas engines that are designed to meet 2010 emission regulations.

Vehicle System	AFCB	CNG
Number of buses	1	5
Bus manufacturer and model	ElDorado National, Axess	New Flyer
Model year	2011	2008
Length/width/height	40 ft/102 in./140 in.	40 ft/102 in./130.8 in.
Gross vehicle weight	43,420 lb	42,540 lb
Passenger capacity	37 seated or 31 seated with 2 wheelchairs; 19 standees	39 seated with no wheelchairs
Hybrid system	BAE Systems, series hybrid propulsion system, HDS 200, 200 kW peak	N/A
Fuel cell or engine	Ballard FCvelocity-HD6, 150 kW	Cummins Westport ISL G 280 hp @ 2,200 rpm
Energy storage	A123, Nanophosphate Li-ion; 200 kW, 11 kWh	N/A
Accessories	Electric	Mechanical
Fuel capacity	Gaseous hydrogen, 8 Luxfer-Dynetek[6] cylinders, 50 kg at 350 bar	125 diesel gallon equivalent
Bus purchase cost	$2,400,000*	$402,900

*Approximate cost of AFCB based on very low quantity as non-production, prototype vehicle. Does not include non-recurring engineering for initial design.

[6]In September 2012, the Luxfer Group announced the acquisition of Dynetek.

Figure 3-1
SunLine American Fuel Cell Bus

Figure 3-2
SunLine CNG Bus

BAE Systems based the AFCB propulsion system on its commercial hybrid electric transit bus product, which is operating in buses around the world. For the AFCB, the system was modified to provide power with the Ballard fuel cell system in place of a diesel engine/generator. Ballard's 150-kW fuel cell incorporates the latest advances for durability and efficiency based on numerous field demonstrations of Ballard fuel cell-powered buses. The AFCB also incorporates a suite of electric accessories powered by BAE Systems' Accessory Power System.

SECTION
4

Fueling and Maintenance Facilities

SunLine Hydrogen Station

SunLine owns and operates a fueling station that supplies fuel for its fleet as well as to the public. The station offers CNG, a blend of CNG and hydrogen, and pure hydrogen. CNG is brought to the SunLine property via a high-pressure natural gas line and then compressed to 3,600 psi for dispensing into the vehicles. SunLine produces hydrogen onsite using a HyRadix natural gas reformer. SunLine typically operates the reformer at 4.5 kg per hour to meet current hydrogen demand, although the unit is capable of producing up to 9 kg of hydrogen per hour. Onsite storage of hydrogen is approximately 180 kg of hydrogen compressed to 6,000 psi for dispensing into the buses at 5,000 psi. SunLine estimates that this hydrogen fueling infrastructure can produce enough hydrogen to comfortably operate five full-size transit buses without running out of fuel for the small hydrogen vehicles expected to be fueled at this station. Figure 4 1 shows the AFCB during fueling at SunLine's hydrogen station.

Figure 4-1

AFCB at SunLine hydrogen station

SunLine tracks all of its fueling events in gasoline gallon equivalent (GGE) units to comply with State fuel-sale regulations. In the case of hydrogen, the unit used is typically kilograms (kg)—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 A shows the energy-conversion calculations for GGE and DGE.

Maintenance Facilities

To support operation and maintenance of CNG buses, SunLine made some modifications and upgrades to its maintenance facility in 1995. These modifications included the addition of combustible gas detectors and the upgrade of some of the electrical conduit, lighting, and ventilation in the maintenance bays. When SunLine first began testing hydrogen-fueled buses, it built a special on-site facility for maintenance. Located behind the CNG bus maintenance building, the facility was essentially a tent designed to vent hydrogen through its roof. In 2010, SunLine was able to procure funding to upgrade the current facility by adding two maintenance bays. At that time, the agency upgraded the gas detection system to handle CNG- and hydrogen-fueled buses in the entire facility. This increased the efficiency for the maintenance staff by allowing the buses to be maintained using the same process as the rest of the fleet.

One of the goals for this project was to prove that the systems on the AFCB are maintainable by a transit agency. SunLine staff members are experienced with hydrogen and fuel cell buses and handle much of the maintenance on the AFCB. BAE Systems has the capability to remotely monitor the bus performance, which aids in troubleshooting and eliminates the need to have permanent on-site staff. If needed, SunLine can call on the local BAE Systems sales and service office for support with the hybrid system, and SunLine has requested this support successfully on a few occasions.

SunLine staff members do all of the preventive maintenance on the fuel cell system. Like BAE Systems, Ballard can remotely monitor the performance of the fuel cell system. SunLine's maintenance staff uses a diagnostic tool to aid in troubleshooting. Ballard also expects SunLine to be able to do most repairs, and SunLine would request a Ballard technician only if needed. SunLine staff members have completed an exercise to remove and replace the fuel cell and are comfortable with the process. The Ballard fuel cell has a 5-year, 12,000-hour warranty.

Hydrogen Fueling Data Summary

During the data collection period, SunLine operated two fuel cell buses in its service area: the AFCB and a New Flyer fuel cell bus (AT FCEB). To show overall performance of the station, the fueling analysis figures include total hydrogen dispensed from the station into both of the buses. Figure 4-2 shows the total hydrogen dispensed per month into SunLine’s fuel cell buses from December 2011 through February 2013. The calculated average daily hydrogen dispensed for each month is marked with red lines. This calculation includes only the days on which the station dispensed hydrogen. The station was used at least once per day to fill at least one hydrogen bus for 88 percent of the calendar days during the period. The overall average daily use was 30.0 kg per day. During this period, SunLine dispensed a total of 12,059 kg of hydrogen. The months with the lowest hydrogen dispensed had downtime for one bus or the other during that month. The low point of July 2012 corresponds with downtime for both buses. The AT FCEB was also down for repair during August and September, resulting in lower hydrogen use for those months.

Figure 4-2

Total hydrogen dispensed per month and average hydrogen dispensed per day

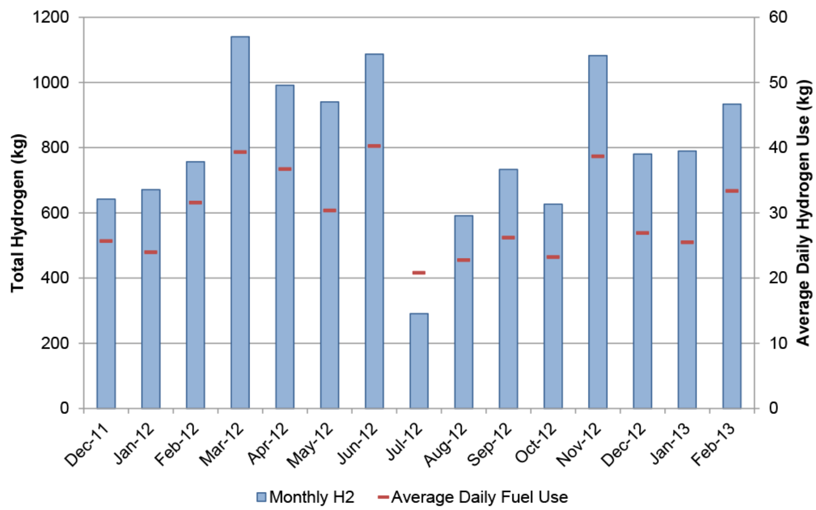
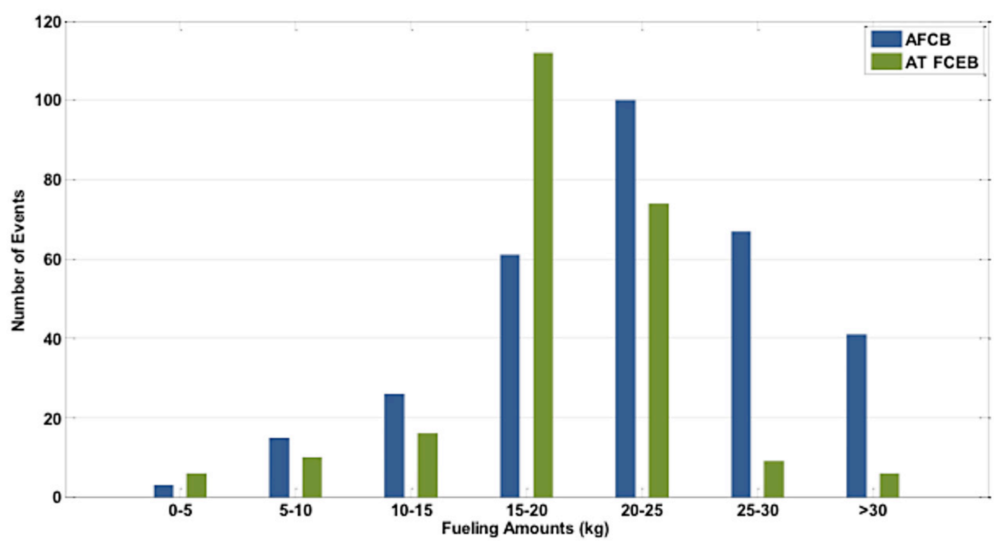


Figure 4-3 shows the distribution of hydrogen amounts dispensed per fill by bus. The buses were filled a total of 546 times during the evaluation period for a total of 11,334 kg hydrogen.[7] The average amount of hydrogen per fill was 20.8 kg per fill. Figure 4-4 shows a cumulative fueling rate histogram for the SunLine hydrogen station from December 2011 through February 2013. The overall average fueling rate was 0.97 kg per minute, and the average time for a fill was approximately 20 minutes.

Figure 4-3

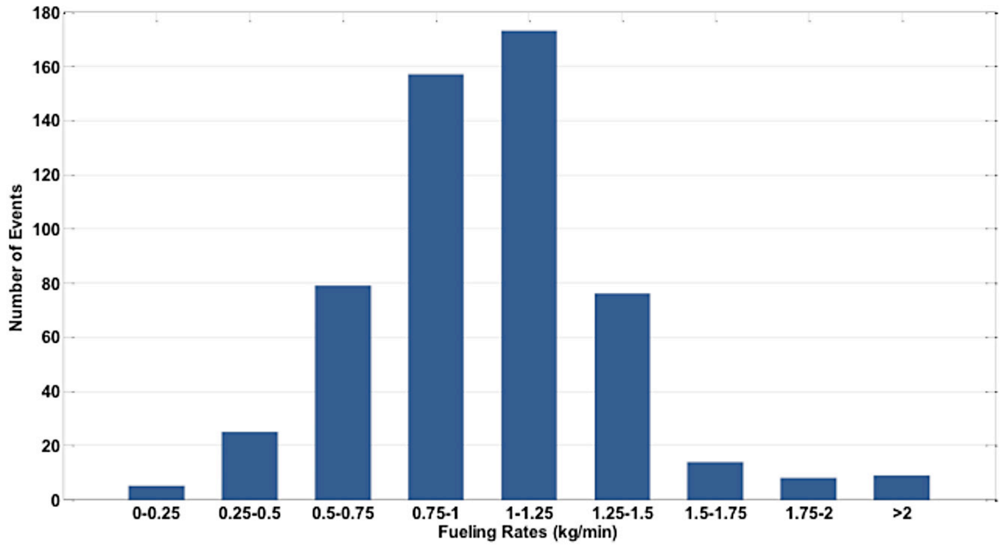
Histogram of fueling amounts by bus



[7]This total is slightly lower than discussed above. If the time for the fueling was not captured in data collection, that fueling data point was excluded for this calculation.

Figure 4-4

Histogram of fueling amounts by bus



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 maintenance cost differences. The agency has seen costs from as low as $4/kg to greater than $26/kg. SunLine indicates that the best steady-state operating point for the reformer system would bring the average cost of hydrogen to around $8/kg. This cost estimate is used in the cost calculations for the data results in the next section.

The CNG average price at the dispenser for SunLine (not the public price) during 2012 was $0.91 per 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.

SECTION 5

Implementation Experience

The AFCB project was selected in the first round of funding for the NFCBP, but early issues delayed the start-up. Between the time that the proposal was submitted to FTA and the selections were announced, the original manufacturer team pulled out of the project. This left SunLine and CALSTART with a major challenge of finding new partners to design and build a fuel cell electric bus that met the original intent of the project proposal. After discussions with several companies involved in the industry, BAE Systems, Ballard Power Systems, and ElDorado National joined the team and began work on the AFCB. Each of these organizations brought a wealth of experience and technology to the team. BAE Systems' experience in power management, platform integration and having a mature hybrid electric propulsion system made them a natural choice as the lead integrator. Ballard's fuel cell system has been tested and improved through extensive demonstrations in transit buses around the world. ElDorado National has been building buses for 30 years and offers a modern design, heavy-duty 40 foot urban transit bus.

The overall project goals were to:

- Achieve a commercially-viable, production-capable fuel cell bus product that is "Buy America"-compliant.
- Demonstrate significantly longer operating life for the fuel cell and battery system and reduce lifecycle cost.
- Provide an FCEB with attractive styling and reduced weight and noise to maximize passenger capacity and comfort.
- Extend operating temperature range of FCEBs and demonstrate durability for the high temperatures in the Coachella valley.
- Advance public acceptance of hydrogen powered transportation through safe and reliable operation.

Development Process

At the onset of the project, SunLine organized a meeting with all of the team members to discuss the overall project goals, the roles of each team member, and the integrated project team approach for developing and demonstrating the AFCB. This ensured that each member shared the common goals for the project and understood its respective tasks to meet those goals. BAE Systems took the lead integrator role, responsible for integrating the system into the bus and making sure the final product met the performance specifications. BAE Systems was also the primary coordinator between the other technology providers.

As mentioned previously, BAE Systems based the AFCB propulsion system on its fully commercial diesel hybrid platform. BAE Systems modified the design to incorporate a fuel cell in place of the diesel engine. Ballard provided its most current fuel cell model at that time, the FCvelocity-HD6, and the necessary DC/DC power converters to interface the fuel cell with the hybrid propulsion system. This fuel cell system was built at Ballard's manufacturing facility in Massachusetts. BAE Systems set up a systems integration laboratory at its business unit in New York to assemble all components and begin testing. This laboratory allowed BAE Systems to operate the propulsion system to optimize the performance and perform full hardware integration of the system prior to installing it on a bus. To aid in the process, BAE Systems outfitted one of SunLine's CNG buses to collect in-service duty cycle data on the actual routes on which the bus would be operated. These data were used to simulate the route and further optimize the system during testing in the systems integration laboratory.

While BAE Systems was developing the propulsion system, ElDorado National was constructing the glider in its Riverside, California facility. The company made modifications to its Axess model platform to reduce weight and allow the installation of the propulsion system. ElDorado completed the glider, except for the interior, and delivered it to BAE Systems in New York. BAE Systems installed the propulsion system into the bus and conducted about 500 miles of road testing before returning the bus to ElDorado for the final finishing of the interior and exterior, final testing, and installation of SunLine's exterior graphics. The finished AFCB was delivered to SunLine in early November 2011 and placed into service in mid-December 2011.

Demonstration Experience

Because the project team wanted to prove the AFCB was able to perform as well as conventional technology buses, SunLine did not limit its service to selected routes or specific times of day. The bus was placed in service on the agency's most demanding route that operates across the entire service area and carries the highest passenger loads. The bus experienced several issues over the first few months, but most of these were bus issues that had nothing to do with the propulsion system.

BAE Systems and the team credit the success of the start-up to the extensive testing in the systems integration lab. This testing helped fine tune the system, and BAE Systems estimates that it saved three to six months of tweaking the software in the field at SunLine. The early failures were items that were not a part of this bench testing. Ballard reports that the early problems were mechanical and not related to control and software issues as was the case with many previous demonstrations. Issues encountered include the following:

- Hydrogen storage valve leak – a control valve in the hydrogen storage system failed. The valve was replaced.
- Door – the electrically-operated rear door developed issues that were traced to a failed sensor. The sensor was replaced and the door operation tested before putting the bus back in service.
- Fuel cell ventilation vent clogging – because the fuel cell system intake air vent was positioned low and at the rear of the bus, dust was pulled into the system and clogged the filter. The air intake was repositioned higher on the bus, and the air filter was upgraded to a better quality filter.
- Water separator – there were problems with water collecting in the exhaust and vent system on the bus. A new prototype design water separator was installed on the bus at the end of 2012 and placed in a lower part of the bus for better operation.
- Air conditioning – SunLine's service area can see temperatures as high as 120°F, which has resulted in issues for most of the previous FCEBs. The AFCB experienced high temperatures in the engine compartment that resulted in issues with circuit breakers for the air conditioner and air compressor.
- Batteries – during the hottest part of the summer, the traction batteries experienced temperature fold-back. This condition results in lower fuel economy because the batteries cannot take as much regenerative braking energy. The temperature range software was updated, adding a more conservative five degrees to the operating range.
- Air compressor motor – the original motor design had a problem with water getting onto the windings, which caused a ground fault in the electrical circuit at the distribution box. A totally enclosed fan-cooled motor replaced the existing open frame motor to eliminate the motor problem. The team also worked to determine what type of upgraded circuit breaker was adequate to take into account the higher-than-expected heat in the compartment.

Early Lessons Learned

Each of the project team members reports that the demonstration has gone well and all are pleased with the performance of the AFCB. BAE Systems reports that the performance of the bus matched or exceeded its expectations. SunLine notes that the bus procurement and development process went well and that the AFCB start-up issues were much fewer than with previous FCEBs. The agency feels that of all of the FCEBs it has demonstrated, this bus is the closest to being ready for commercialization.

Some of the lessons learned include the following:

- When developing a new prototype bus, try to limit the number of advanced technology components that are not part of the primary area of focus. This will minimize down time and distraction associated with maturing non-essential advanced technology components.
- Leveraging production components as much as possible aids in developing an advanced system. BAE Systems' hybrid propulsion system is a proven product that is commercially available. Using this as the base for the AFCB reduced the development time and allowed the team to focus on integrating the added components—the fuel cell and hydrogen storage system. Parts availability for the majority of the system is not an issue because there is a ready supply for the hybrid bus market.
- Special tools may be required for repair and troubleshooting. Early in the demonstration, a valve in the hydrogen storage system failed. This was extremely difficult to fix because no tools were planned for this type of repair. The team had issues de-pressurizing the fuel system to make the repair. There was a need for electrical control of the system to allow an override for this type of activity. BAE Systems plans to design a new system for future models and will retrofit it on this bus. Basic tools and replacement parts for the fuel system would have been helpful.
- Cooperative teams are extremely important for success. The integrated team approach, with common objectives and well-defined roles for each member, worked well for the project. This approach should be the pattern for all future bus development projects.
- Easy access to technical support is important to minimize downtime. SunLine was able to quickly tap into BAE Systems staff at the Southern California sales and service office for issues with the hybrid propulsion system. Problems that might otherwise have taken a week have been resolved in only 24 hours in many cases because of that support. The ability to remotely monitor bus and component performance can reduce the need for manufacturer staff to visit the site.
- Transit agencies with staff experienced in advanced technologies facilitate demonstrations of FCEBs. SunLine's experience with gaseous fuels and hydrogen fuel cells made the integration process go smoothly and resulted in less need for on-site support from the manufacturer. This will be very important as fleet demonstration sizes increase and allow a full transfer of maintenance to transit mechanics.

SECTION

6

Evaluation Results

In any evaluation, a starting point must be chosen. For NREL evaluations, this starting point is typically called a "clean point." 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 three to six months of operation before the evaluation can start. The AFCB began service in mid-December 2011. During the first few months, the team closely monitored the bus performance and made additional modifications and optimizations. For this evaluation, the clean point was March 2012. The results presented in this section are from the clean point through February 2013. The CNG baseline bus results are for the same period. A summary of the results shown in this section is provided in Appendix A, and the first page of the summary is repeated in Appendix B with results in metric (SI) units.

Route Assignments

In general, SunLine's buses are randomly dispatched on its routes. The overall system average speed is 17.1 mph. Table 6-1 summarizes the route use for the AFCB and CNG baseline buses during the evaluation period. The AFCB was used primarily on Line 111 (94%) with some additional service on Line 53. The overall average speed for the AFCB was 15.6 mph. The five CNG buses were randomly dispatched with the majority (87%) of time split between Line 111, Line 14, Line 30, and Line 70. Based on the dispatching information, the CNG buses operated at essentially the same average speed (15.5 mph) as the fuel cell bus did during the evaluation period.

Table 6-1

Summary of Route Use for AFCB and CNG Buses

Route	Percent of Time	Average Speed (mph)
AFCB		
111	94	16.2
53	6	14.5
CNG		
111	39	16.2
14	17	18.1
30	19	13.1
70	11	16.9

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage may indicate downtime for maintenance or purposeful reduction of planned work for the buses. This section summarizes bus usage and availability for the AFCB and CNG buses.

Table 6-2 and Figure 6-1 summarize average monthly mileage for the buses through February 2013. Using the CNG buses as the baseline, the AFCB had an average monthly mileage that was only 6 percent lower than that of the CNG buses. This is a strong indication of the reliability of the bus during the period. The AFCB averaged around 9 hours in-service time each day but achieved as many as 19 hours in a single day.

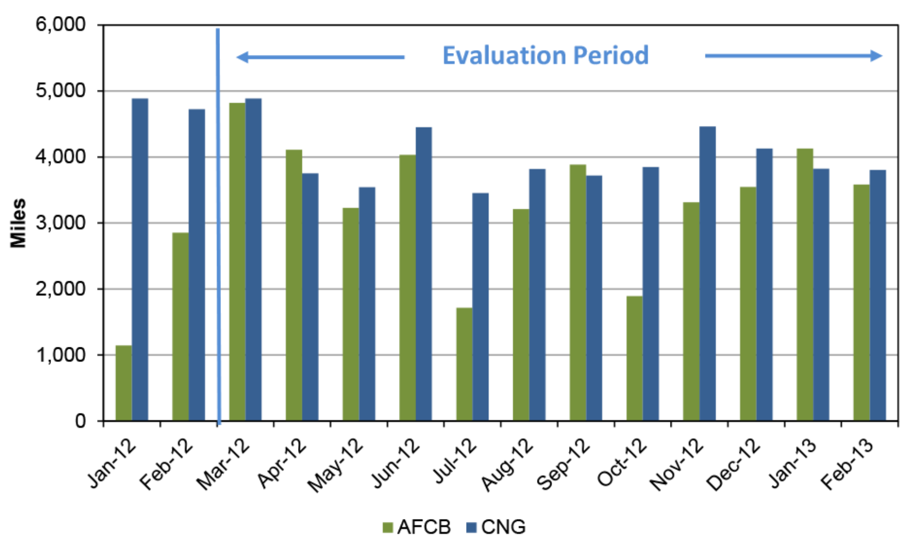
Table 6-2

Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage
AFCB	**6,040**	**49,028**	**42,988**	**12**	**3,582**
603	193,507	243,733	50,226	12	4,186
604	173,933	232,625	58,692	12	4,891
605	188,651	222,323	33,646	12	2,804
606	193,143	234,969	41,553	12	3,463
608	203,804	242,191	44,113	12	3,676
CNG Total			**228,230**	**60**	**3,804**

Figure 6-1

Monthly mileage for AFCB and CNG buses



Availability is the percentage of time that the buses are planned for operation compared with the time the buses are actually available for that planned operation. Availability for all of NREL's evaluations is calculated by including 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 AFCB and the CNG buses. Figure 6-2 presents the overall monthly availability for the AFCB and the CNG buses.

The stacked bars show the total number of days the AFCB was unavailable each month by primary system category. As shown in the chart, the availability goal is 85 percent for all buses.

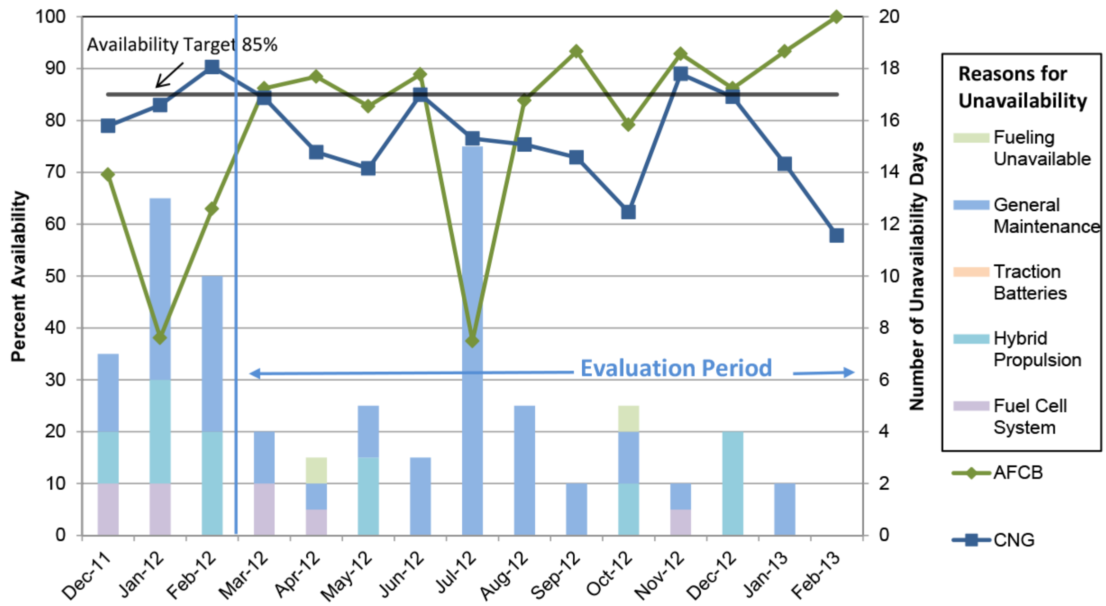


Figure 6-2

Monthly availability for AFCB and CNG buses

Table 6-3

Summary of Reasons for Availability and Unavailability of Buses for Service

Category	AFCB # Days	AFCB %	CNG # Days	CNG %
Planned work days	334		1,562	
Days available	284		1,181	
Available	***284***	***85***	***1,181***	***76***
On-route	274	97	1,147	97.0
Event/demonstration	9	1	3	0.3
Training	1	0	4	0.3
Not used	0	0	25	2.1
Unavailable	***50***		***381***	
Fuel cell propulsion	4	8	—	—
Hybrid propulsion	9	18	—	—
Traction batteries	0	0	—	—
SunLine maintenance	35	70	209	55
CNG engine	—	—	168	44
Fueling unavailable	2	4	0	0

Fuel Economy and Cost

Table 6-4 shows hydrogen and CNG fuel consumption and fuel economy for the AFCB and CNG buses during the evaluation period. Overall, the AFCB averaged 6.54 miles per kilogram of hydrogen, which equates to 7.39 miles per DGE. The energy conversion from kilograms of hydrogen to DGE appears at the end of Appendix A. Using the GGE fuel economy of the CNG buses as a baseline, the AFCB had a fuel economy 2.4 times higher than that of the CNG buses. Figure 6-3 shows the monthly fuel economy for the AFCB and CNG buses. The average monthly high temperature is included in the graph to track any seasonal variations in the fuel economy due to heating or cooling of the bus, which requires significant additional energy use.

The fuel costs per mile for the study bus groups for the evaluation period were $1.22 per mile for the AFCB and $0.32 per mile for the CNG buses. The CNG fuel cost at $0.91 per GGE is much lower than the typical diesel fuel average cost per gallon.

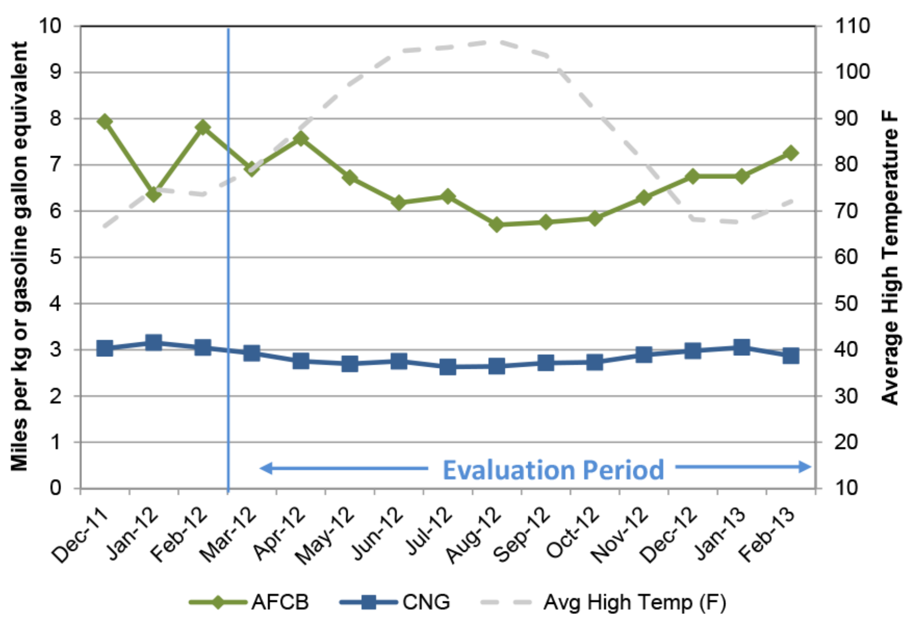
Table 6-4

Fuel Use and Economy (Evaluation Period)

Bus	Mileage (fuel base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (gallon)	Miles per Gallon (mi/DGE)
AFCB	**42,988**	**6,572.8**	**6.54**	**5,816.7**	**7.39**
603	50,226	17,503.9	2.87	15,666.0	3.21
604	58,692	20,857.7	2.81	18,667.7	3.14
605	33,646	12,072.8	2.79	10,805.2	3.11
606	41,553	15,409.2	2.70	13,791.2	3.01
608	44,113	15,571.0	2.83	13,936.1	3.17
CNG Total	**228,230**	**81,414.7**	**2.80**	**72,866.2**	**3.13**

Figure 6-3

Monthly fuel economy for AFCB and CNG buses



Maintenance Analysis

All work orders for the study buses were collected and analyzed for this evaluation. For consistency, the maintenance labor rate was set at $50 per hour for all work; this does not reflect an average rate for SunLine. Warranty costs are generally not included in the maintenance costs presented in this section.

Total Maintenance Costs

Total maintenance costs include the price of parts and labor rates at $50 per hour; they do not include warranty costs. Cost per mile is calculated as follows:

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

Table 6-5 shows total maintenance costs for the AFCB and CNG buses. Scheduled and unscheduled maintenance cost per mile is provided for each bus and study group of buses. Total maintenance costs for the AFCB are nearly the same as for the CNG buses. This is not typical for the introduction of a new-technology bus. Several factors have affected this result. The parts costs for the AFCB are low because parts for the propulsion system are currently covered by the manufacturer; however, SunLine's mechanics do nearly all of the work. The engine and body damage for the CNG buses during the evaluation period have greatly increased the total maintenance costs.

Table 6-5

Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Total Cost per Mile ($)	Scheduled Cost per Mile ($)	Unscheduled Cost per Mile ($)
AFCB	**42,988**	**1,508.73**	**304.25**	**0.39**	**0.11**	**0.28**
603	50,226	7,114.91	300.25	0.44	0.14	0.30
604	58,692	6,069.22	373.0	0.42	0.11	0.32
605	33,646	8,112.37	275.75	0.65	0.15	0.50
606	41,553	6,682.66	279.5	0.50	0.13	0.36
608	44,113	12,872.1	351.75	0.69	0.12	0.57
CNG Total	**228,230**	**40,851.26**	**1,580.25**	**0.53**	**0.13**	**0.40**

Maintenance Costs Categorized by System

Table 6-6 shows maintenance costs by vehicle system and bus study group (without warranty costs). The vehicle systems shown in the table are as follows:

- Cab, body, and accessories – includes body, glass, and paint repairs following accidents; cab and sheet metal repairs on seats and doors; and accessory repairs such as hubodometers and radios

- Propulsion-related systems – repairs for exhaust, fuel, engine, electric motors, fuel cell modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, and transmission
- Preventive maintenance inspections (PMI) – labor for inspections during preventive maintenance
- Brakes
- Frame, steering, and suspension
- Heating, ventilation, and air conditioning (HVAC)
- Lighting
- Air system, general
- Axles, wheels, and drive shaft
- Tires

Table 6-6

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	0.12	31	0.24	46
Cab, body, and accessories	0.13	33	0.11	20
PMI	0.10	27	0.08	16
Brakes	0.00	0	0.02	4
Frame, steering, and suspension	0.00	1	0.01	2
HVAC	0.01	2	0.03	6
Lighting	0.01	2	0.01	2
General air system repairs	0.01	3	0.01	1
Axles, wheels, and drive shaft	0.00	0	0.00	1
Tires	0.01	2	0.01	2
Total	**0.39**	**100**	**0.52**	**100**

For the AFCB, the systems with the highest percentage of maintenance costs were cab, body, and accessories; propulsion-related; and PMI. The same categories made up the highest percentage of maintenance costs for the CNG buses, but in a different order. Because of the extensive engine issues with two of the baseline CNG buses, the propulsion-related costs accounted for 46 percent of the total cost. The cab, body, and accessories costs had the next highest percentage, followed by PMI.

Propulsion-Related Maintenance Costs

Propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. These systems have been separated to highlight maintenance costs most directly affected by the advanced propulsion system changes for the buses. Table 6-7 shows the propulsion-related system repairs by category for the AFCB and CNG buses during the evaluation period. The maintenance costs do not include the work done by the manufacturer.

Table 6-7

Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	AFCB	CNG
Mileage	42,988	228,230
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	526.92	23,854.60
Labor hours	92.75	618.5
Total cost ($)	5,164.42	54,779.60
Total cost ($) per mile	**0.12**	**0.24**
Exhaust System Repairs		
Parts cost ($)	0	1,658.96
Labor hours	0	6.5
Total cost ($)	0.00	1,983.96
Total cost ($) per mile	**0.00**	**0.01**
Fuel System Repairs		
Parts cost ($)	0	231.47
Labor hours	17	0
Total cost ($)	850.00	231.47
Total cost ($) per mile	**0.02**	**0.00**
Powerplant System Repairs		
Parts cost ($)	26.4	12,943.91
Labor hours	27	482.5
Total cost ($)	1,376.40	37,068.91
Total cost ($) per mile	**0.03**	**0.16**
Electric Motor and Propulsion Repairs		
Parts cost ($)	31.31	0
Labor hours	24	0
Total cost ($)	1,231.31	0.00
Total cost ($) per mile	**0.03**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	464.28	6,902.89
Labor hours	9.25	26.75
Total cost ($)	926.78	8,240.39
Total cost ($) per mile	**0.02**	**0.04**

Table 6-7 (cont.)

Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	AFCB	CNG
Air Intake System Repairs		
Parts cost ($)	0	730.87
Labor hours	0	0
Total cost ($)	0.00	730.87
Total cost ($) per mile	**0.00**	**0.00**
Cooling System Repairs		
Parts cost ($)	0	428.28
Labor hours	15.25	88
Total cost ($)	762.50	4,828.28
Total cost ($) per mile	**0.02**	**0.02**
Transmission Repairs		
Parts cost ($)	4.93	644.04
Labor hours	0.25	14.75
Total cost ($)	17.43	1,381.54
Total cost ($) per mile	**0.00**	**0.01**

The AFCB has propulsion-related maintenance costs slightly lower than that of the CNG buses. This is driven primarily by the high cost for engine issues for two of the CNG buses. Much of the maintenance costs for the AFCB were covered by the manufacturers.

Additional Costs

SunLine's fuel cell buses are fueled at the hydrogen dispenser, which is located at the public access station at the edge of the agency property. This requires SunLine to assign the fueling duties to maintenance staff outside of the normal procedures for fueling the rest of the fleet. (SunLine's CNG buses are fueled at the dispensers within the bus yard as part of the scheduled prep for service.) SunLine tracks these labor costs separately as work orders. During the data period, this fueling labor for the AFCB totaled 71 hours. This is not included in the cost summary.

Roadcall Analysis

A roadcall (RC) or revenue vehicle system failure (as named in the National Transit Database [NTD]) is defined as a failure of an in-service bus that causes the bus to be replaced while it is on route, or one that causes a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is maintained, then this is not considered an RC. The analysis provided here includes only RCs that were caused by "chargeable" failures. Chargeable RCs include systems that can physically disable the bus from operating while it is on route, such as interlocks (doors, air system) or engine, or things that are deemed safety issues if operation of the bus continued, such as headlights and windshield wipers. Chargeable RCs do not include roadcalls for things such as problems with radios or destination signs.

Table 6-8 shows the RCs and miles between roadcalls (MBRC) for the AFCB and CNG buses categorized by total bus RCs and propulsion-related-only RCs. The CNG buses have much better MBRC rates for both categories. The fuel cell system MBRC is included for the AFCB to provide an indication of reliability for that system. Figure 6-4 shows the monthly average MBRC for the two study groups of buses during the evaluation period.

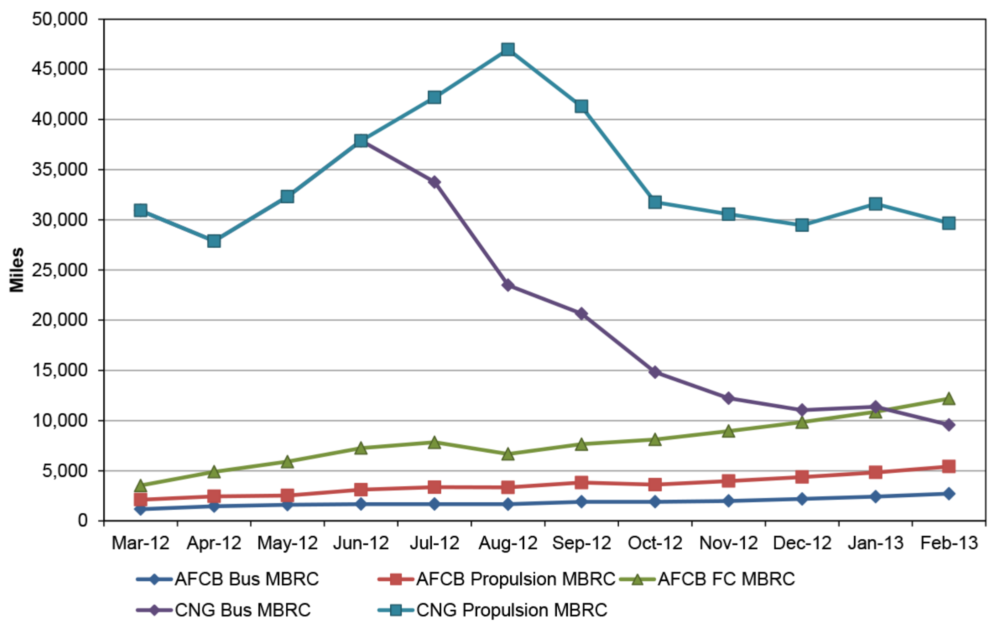
Table 6-8

Roadcalls and MBRC (Evaluation Period)

	AFCB	CNG
Mileage	42,988	228,230
Bus roadcalls	11	28
Bus MBRC	3,908	8,151
Propulsion-related roadcalls	6	7
Propulsion-related MBRC	7,165	32,604
Fuel-cell-related roadcalls	3	
FC system MBRC	14,329	

Figure 6-4

Cumulative monthly MBRC for AFCB and CNG buses



SECTION 7

What's Next for this Project

This report covers SunLine's operation of the AFCB and CNG buses from March 2012 through February 2013. The agency will continue working with FTA/NREL to collect data on the buses in service. The next report is expected to be published in late fall 2013.

SunLine will continue to operate the AFCB and its other fuel cell bus. Under another FTA program (Transit Investments for Greenhouse Gas and Energy Reduction—TIGGER), this team is building two additional AFCBs for operation at SunLine. The first of the buses is expected to be delivered by the first quarter of 2014. Once both buses arrive, SunLine will have a total of four FCEBs operating in its service area. The agency was awarded additional funding through the NFCBP to extend support to the AFCB and another of its FCEBs for an additional 10 years. SunLine is working through contract details with BAE Systems and Ballard for this support.

BAE Systems, Ballard, and ElDorado are building three additional AFCBs for demonstration:

- Chicago Transit Authority will demonstrate an AFCB under the NFCBP funding.
- Massachusetts Bay Transportation Authority will demonstrate an AFCB under NFCBP funding.
- Connecticut Transit will add an AFCB to its fleet purchased under federal grant funds.

These demonstrations will provide the team with data on AFCB performance in colder climates and allow the technology to be optimized to meet the needs of any U.S. transit agency. BAE Systems is moving forward with commercialization and plans to include components necessary to support fully electric ZEV applications in its product line. As reported in the final project report to FTA,[8] BAE Systems and SunLine see the primary challenges to commercialization being 1) cost reduction of components and 2) moving the technology into the standard procurement process where the bus original equipment manufacturer (OEM) takes the lead in providing the propulsion system for transit buses.

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[8]BAE Systems and SunLine, *American Fuel Cell Bus Project Final Report*, Report to FTA, January 2013.

Moving the technology to commercial deployment and meeting DOE/DOT price targets will require cost reductions at the component level. This is challenging under the current financial climate with limited funding availability. FCEB development needs several design iterations to improve reliability and reduce overall platform costs. Large-scale deployments will help push the process forward and drive down the cost. There is also a need for stable supply chains for advanced components such as batteries. Recent economic and market developments have resulted in both consolidation and suppliers shifting their product focus to other areas in the market, slowing the pace of commercialization of fuel cell bus systems.

For FCEBs to be fully commercialized, the fuel cell hybrid propulsion system needs to be an option offered by the bus OEM in response to increased market demand, as is the case with current diesel hybrid systems. Hybrid buses are currently offered by most OEMs, which order and install the propulsion system at the bus manufacturing plant. BAE Systems' role is as supplier and integrator of propulsion and electric power systems that enable the capability offered by the OEM. In the case of the AFCB project, the integrator and transit agency have taken the lead role in developing the bus. This role needs to transition to the bus OEM for the technology to be fully adopted. The current market for FCEBs is small and has not led any bus OEMs to take on this lead role. With the SunLine TIGGER order for two AFCBs, the team is taking steps to make this transition. The first bus glider will be shipped to BAE Systems for integration of the propulsion system. BAE Systems will work with ElDorado staff to complete the installation. The second bus will be entirely built at the ElDorado factory with support of BAE Systems.

APPENDIX

A

Fleet Summary Statistics

Fleet Summary Statistics: Fuel Cell Bus and Diesel Bus Groups and Evaluation Periods

Table A-1

Fleet Operations and Economics, AFCB and CNG Buses

	AFCB	CNG Buses
Number of vehicles	1	5
Period used for fuel and oil op analysis	March 2012–February 2013	March 2012–February 2013
Total number of months in period	12	12
Fuel and oil analysis base fleet mileage	42,988	228,230
Period used for maintenance op analysis	March 2012–February 2013	March 2012–February 2013
Total number of months in period	12	12
Maintenance analysis base fleet mileage	42,988	228,230
Average monthly mileage per vehicle	3,582	3,804
Availability	85	77
Fleet fuel usage in CNG GGE/H2 kg	6,572.8	81,415
All roadcalls	11	28
MBRC	3,908	8,151
Propulsion roadcalls	6	7
Propulsion MBRC	7,165	32,604
Fleet miles/kg hydrogen (1.13 kg H2/gal diesel fuel)	6.54	2.80
Representative fleet MPG (energy equiv)	7.39	3.13
Hydrogen cost per kg	8.00	
GGE cost		0.91
Fuel cost per mile	**1.22**	**0.32**
Total scheduled repair cost per mile	0.11	0.13
Total unscheduled repair cost per mile	0.28	0.40
Total maintenance cost per mile	**0.39**	**0.53**
Total operating cost per mile	**1.61**	**0.85**

Table A-2

Maintenance Costs, AFCB and CNG Buses

	AFCB	CNG Buses
Fleet mileage	42,988	228,230
Total parts cost	1,508.73	40,851.26
Total labor hours	304.3	1580.3
Average labor cost (@ $50 per hour)	15,212.50	79,012.50
Total maintenance cost	16,721.23	119,863.76
Total maintenance cost per bus	16,721.23	23,972.75
Total maintenance cost per mile	**0.39**	**0.53**

Table A-3

Breakdown of Maintenance Costs by Vehicle System, AFCB and CNG buses

	AFCB	CNG Buses
Fleet mileage	42,988	228,230
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)		
Parts cost	526.92	23,854.60
Labor hours	92.75	618.50
Average labor cost	4,637.50	30,925.00
Total cost (for system)	5,164.42	54,779.60
Total cost (for system) per bus	5,164.42	10,955.92
Total cost (for system) per mile	**0.12**	**0.24**
Exhaust System Repairs (ATA VMRS 43)		
Parts cost	0.00	1,658.96
Labor hours	0.0	6.5
Average labor cost	0.00	325.00
Total cost (for system)	0.00	1,983.96
Total cost (for system) per bus	0.00	396.79
Total cost (for system) per mile	**0.00**	**0.01**
Fuel System Repairs (ATA VMRS 44)		
Parts cost	0.00	231.47
Labor hours	17.0	0.0
Average labor cost	850.00	0.00
Total cost (for system)	850.00	231.47
Total cost (for system) per bus	850.00	46.29
Total cost (for system) per mile	**0.02**	**0.00**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts cost	26.40	12,943.91
Labor hours	27.0	482.5
Average labor cost	1,350.00	24,125.00
Total cost (for system)	1,376.40	37,068.91
Total cost (for system) per bus	1,376.40	7,413.78
Total cost (for system) per mile	**0.03**	**0.16**

Table A-3 (cont.)

Breakdown of Maintenance Costs by Vehicle System, AFCB and CNG buses

	AFCB	CNG Buses
Electric Propulsion Repairs (ATA VMRS 46)		
Parts cost	31.31	0.00
Labor hours	24.0	0.0
Average labor cost	1,200.00	0.00
Total cost (for system)	1,231.31	0.00
Total cost (for system) per bus	1,231.31	0.00
Total cost (for system) per mile	**0.03**	**0.00**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging,		
32-Cranking, 33-Ignition)		
Parts cost	464.28	6,902.89
Labor hours	9.3	26.8
Average labor cost	462.50	1,337.50
Total cost (for system)	926.78	8,240.39
Total cost (for system) per bus	926.78	1,648.08
Total cost (for system) per mile	**0.02**	**0.04**
Air Intake System Repairs (ATA VMRS 41)		
Parts cost	0.00	730.87
Labor hours	0.0	0.0
Average labor cost	0.00	0.00
Total cost (for system)	0.00	730.87
Total cost (for system) per bus	0.00	146.17
Total cost (for system) per mile	**0.00**	**0.00**
Cooling System Repairs (ATA VMRS 42)		
Parts cost	0.00	428.28
Labor hours	15.3	88.0
Average labor cost	762.50	4,400.00
Total cost (for system)	762.50	4,828.28
Total cost (for system) per bus	762.50	965.66
Total cost (for system) per mile	**0.02**	**0.02**
Hydraulic System Repairs (ATA VMRS 65)		
Parts cost	0.00	314.18
Labor hours	0.0	0.0
Average labor cost	0.00	0.00
Total cost (for system)	0.00	314.18
Total cost (for system) per bus	0.00	62.84
Total cost (for system) per mile	**0.00**	**0.00**

Table A-3 (cont.)

Breakdown of Maintenance Costs by Vehicle System, AFCB and CNG buses

	AFCB	CNG Buses
General Air System Repairs (ATA VMRS 10)		
Parts cost	0.00	113.66
Labor hours	9.5	26.5
Average labor cost	475.00	1,325.00
Total cost (for system)	475.00	1,438.66
Total cost (for system) per bus	475.00	287.73
Total cost (for system) per mile	**0.01**	**0.01**
Brake System Repairs (ATA VMRS 13)		
Parts cost	0.00	2,655.24
Labor hours	0.0	33.3
Average labor cost	0.00	1,662.50
Total cost (for system)	0.00	4,317.74
Total cost (for system) per bus	0.00	863.55
Total cost (for system) per mile	**0.00**	**0.02**
Transmission Repairs (ATA VMRS 27)		
Parts cost	4.93	644.04
Labor hours	0.3	14.8
Average labor cost	12.50	737.50
Total cost (for system)	17.43	1,381.54
Total cost (for system) per bus	17.43	276.31
Total cost (for system) per mile	**0.00**	**0.01**
Inspections Only - NoPparts Replacements (101)		
Parts cost	0.00	0.00
Labor hours	89.8	386.0
Average labor cost	4,487.50	19,300.00
Total cost (for system)	4,487.50	19,300.00
Total cost (for system) per bus	4,487.50	3,860.00
Total cost (for system) per mile	**0.10**	**0.08**
Cab, Body, and Accessories Systems Repairs		
Parts cost	905.26	6,519.32
Labor hours	92.8	356.0
Average labor cost	4,637.50	17,800.00
Total cost (for system)	5,542.76	24,319.32
Total cost (for system) per bus	5,542.76	4,863.86
Total cost (for system) per mile	**0.13**	**0.11**
HVAC System Repairs (ATA VMRS 01)		
Parts cost	48.30	5,094.91
Labor hours	5.0	52.0
Average labor cost	250.00	2,600.00
Total cost (for system)	298.30	7,694.91
Total cost (for system) per bus	298.30	1,538.98
Total cost (for system) per mile	**0.01**	**0.03**

Table A-3 (cont.)

Breakdown of Maintenance Costs by Vehicle System, AFCB and CNG buses

	AFCB	CNG Buses
Lighting System Repairs (ATA VMRS 34)		
Parts cost	17.03	899.36
Labor hours	6.3	33.8
Average labor cost	312.50	1,687.50
Total cost (for system)	329.53	2,586.86
Total cost (for system) per bus	329.53	517.37
Total cost (for system) per mile	**0.01**	**0.01**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts cost	11.22	1,106.88
Labor hours	2.5	14.3
Average labor cost	125.00	712.50
Total cost (for system)	136.22	1,819.38
Total cost (for system) per bus	136.22	363.88
Total cost (for system) per mile	**0.00**	**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	564.45
Labor hours	0.0	4.5
Average labor cost	0.00	225.00
Total cost (for system)	0.00	789.45
Total cost (for system) per bus	0.00	157.89
Total cost (for system) per mile	**0.00**	**0.00**
Tire Repairs (ATA VMRS 17)		
Parts cost	0.00	0.00
Labor hours	5.8	55.0
Average labor cost	287.50	2,750.00
Total cost (for system)	287.50	2,750.00
Total cost (for system) per bus	287.50	550.00
Total cost (for system) per mile	**0.01**	**0.01**

Notes

1. To compare hydrogen fuel dispensed and fuel economy to diesel, hydrogen dispensed was also converted into diesel energy equivalent gallons. Actual energy content will vary by locations, but general energy conversions are as follows:
   Lower heating value (LHV) for hydrogen = 51,532 Btu/lb
   LHV for diesel = 128,400 Btu/lb
   1 kg = 2.205 × lb
   51,532 Btu/lb × 2.205 lb/kg = 113,628 Btu/kg
   Diesel/hydrogen = 128,400 Btu/gal /113,628 Btu/kg = 1.13 kg/diesel gal
2. Propulsion-related systems were chosen to include only those systems of vehicles that could be affected directly by selection of fuel/advanced technology.
3. ATA VMRS coding based on parts that were replaced. If no part was replaced in a given repair, then code was chosen by system being worked on.
4. In general, inspections (with no part replacements) were included only in 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 such as fire extinguishers, test kits, etc.; ATA VMRS 71-Body represents mostly windows and windshields.
6. Average labor cost assumed to be $50 per hour.
7. Warranty costs not included.

APPENDIX

B

Fleet Summary Statistics–SI Units

Fleet Summary Statistics: Fuel Cell Bus and Diesel Bus Groups and Evaluation Periods

Table B-1

Fleet Operations and Economics, AFCB and CNG buses

	AFCB	CNG Buses
Number of vehicles	1	5
Period used for fuel and oil op analysis	March 2012–February 2013	March 2012–February 2013
Total number of months in period	12	12
Fuel and oil analysis base fleet kilometers	69,181	367,291
Period used for maintenance op analysis	March 2012–February 2013	March 2012–February 2013
Total number of months in period	12	12
Maintenance analysis base fleet kilometers	69,181	367,291
Average monthly kilometers per vehicle	5,765	6,122
Availability	85	77
Fleet fuel usage in H2 kg	6,573	308,155
All roadcalls	11	28
KBRC	6,289	13,118
Propulsion roadcalls	6	7
Propulsion KBRC	11,530	52,470
Fleet kg hydrogen/100 km (1.13 kg H2/gal diesel fuel)	9.50	
Representative fleet fuel consumption (L/100 km)	31.82	75.09
Hydrogen cost per kg	8.00	
CNG cost/liter		0.24
Fuel cost per kilometer	**0.76**	**0.20**
Total scheduled repair cost per kilometer	0.07	0.08
Total unscheduled repair cost per kilometer	0.18	0.25
Total maintenance cost per kilometer	**0.24**	**0.33**
Total operating cost per kilometer	**1.00**	**0.53**

Table B-2

Maintenance Costs, AFCB and CNG buses

	AFCB	CNG Buses
Fleet mileage	69,181	367,291
Total parts cost	1,508.73	40,851.26
Total labor hours	304.25	1,580.25
Average labor cost (@ $50 per hour)	15,212.50	79,012.50
Total maintenance cost	16,721.23	119,863.76
Total maintenance cost per bus	16,721.23	23,972.75
Total maintenance cost per kilometer	**0.24**	**0.33**

ACRONYMS AND ABBREVIATIONS

AC	Alternating current
Ah	Amp-hours
CTE	Center for Transportation and the Environment
DC	Direct current
DGE	Diesel gallon equivalent
DOE	U.S. Department of Energy
DPF	Diesel particulate filter
FCEB	Fuel cell electric bus
FCPP	Fuel cell power plant
ft	Feet
FTA	Federal Transit Administration
gal	Gallons
GGE	Gasoline gallon equivalent
HP	horsepower
HVAC	Heating, ventilation, and air conditioning
in.	Inches
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
lb	Pounds
MBRC	Miles between roadcalls
mph	Miles per hour
NAVC	Northeast Advanced Vehicle Consortium
NiMH	Nickel metal hydride
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
PEM	Proton exchange membrane
PMI	Preventive maintenance inspection
psi	Pounds per square inch
RC	Roadcall
rpm	revolutions per minute
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SI	International System of Units
TIGGER	Transit Investments for Greenhouse Gas and Energy Reduction

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REFERENCES AND RELATED REPORTS

National Fuel Cell Bus Program Publications

Eudy, L., and K. Chandler. 2012. *Connecticut Nutmeg Fuel Cell Bus Project: First Analysis Report*. DOT/FTA Report No. 0020.

Chandler, K., and L. Eudy. 2012. *FTA Fuel Cell Bus Program: Research Accomplishments through 2011*. DOT/FTA Report No. 0014.

Eudy, L. 2012. *American Fuel Cell Bus Project: Developing and Demonstrating the Next-Generation Fuel Cell Electric Bus Made in America*. DOT/FTA-NFCBP-FS4-March 2012.

Eudy, L., and K. Chandler. 2011. *National Fuel Cell Bus Program: Proterra Fuel Cell Hybrid Bus Report, Columbia Demonstration*. DOT/FTA Report No. 0003.

Eudy, L.(2011. *Connecticut Nutmeg Fuel Cell Bus Project: Demonstrating Advanced-Design Hybrid Fuel Cell Buses in Connecticut*. DOT/FTA-NFCBP-FS3-July 2011.

Eudy, L. 2011. *Compound Fuel Cell Hybrid Bus Hits the Streets of San Francisco*. DOT/FTA-NFCBP-FS2-July 2011.

Chandler, K., and L. Eudy. 2010. *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2 and Appendices*. NREL/TP-560-48106-1, NREL/TP-560-48106-2. Golden, CO: National Renewable Energy Laboratory.

Curtin, S., L. Jerram, and L. Justice. 2009. *A Report on Worldwide Hydrogen Bus Demonstrations, 2002-2007*. FTA-GA-04-7001-2009.01. Federal Transit Administration.

Chandler, K., and L. Eudy. 2009. *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report and Appendices*. NREL/TP-560-44646-1, NREL/TP-560-44646-2. Golden, CO: National Renewable Energy Laboratory.

Other Recent Fuel Cell Bus-Related Publications

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

Eudy, L., K. Chandler, and C. Gikakis. 2012. *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012*. NREL/TP-5600-56406. Golden, CO: National Renewable Energy Laboratory.

Eudy, L., and K. Chandler. 2012. *Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: Second Results Report*. NREL/TP-5600-55367. Golden, CO: National Renewable Energy Laboratory.

Eudy, L., K. Chandler, and C. Gikakis. 2011. *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2011*. NREL/TP-5600-52927. Golden, CO: National Renewable Energy Laboratory.

Chandler, K., and L. Eudy. 2011. *Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: First Results Report*. NREL/TP-5600-52015. Golden, CO: National Renewable Energy Laboratory.

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