




SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: First Results Report

Leslie Eudy
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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5600-50500
March 2011

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. H270.8150

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Acronyms and Abbreviations

AQMD	Air Quality Management District
AT	advanced technology
CARB	California Air Resources Board
CNG	compressed natural gas
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
FCB	fuel cell bus
ft	feet
FTA	Federal Transit Administration
GGE	gasoline gallon equivalent
HHICE	hydrogen hybrid internal combustion engine
hp	horsepower
HVAC	heating, ventilation, and air conditioning
in.	inches
kg	kilograms
kW	kilowatts
lb	pounds
MBRC	miles between roadcalls
mpDGE	miles per diesel gallon equivalent
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
psi	pounds per square inch
RC	roadcall

Executive Summary

SunLine Transit Agency has demonstrated hydrogen and fuel cell bus technologies for more than 10 years. This report describes operations at SunLine for their newest prototype fuel cell bus and five compressed natural gas (CNG) buses (with model year 2010-level emissions). SunLine provides public transit services to the Coachella Valley area of California.

The U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) has been evaluating alternative fuel and advanced propulsion equipped transit buses since the early 1990s. This fuel cell bus at SunLine is being evaluated to document the results and help determine the progress toward technology readiness. NREL uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations. This protocol was documented in a joint evaluation plan (with the Federal Transit Administration) for transit bus evaluations.[1]

In May 2010, SunLine began demonstrating the Advanced Technology (AT) bus—a new-generation fuel cell bus developed by Bluways, Ballard Power Systems, and New Flyer. The AT fuel cell bus has a hybrid electric propulsion system based on the Siemens ELFA system, integrated by Bluways with Ballard's newest version fuel cell power system, and lithium-based hybrid batteries. The design incorporates the latest improvements to reduce weight and increase reliability and performance. The AT fuel cell bus started revenue service on May 27, 2010. During the data period for this report (May 2010 to November 2010), the fuel cell bus operated 9,687 miles and 818 fuel cell system hours (for an average operating speed of 11.8 mph). The operation of this new fuel cell bus at SunLine has been limited by air conditioning issues during the hot desert summer, some fuel cell power system issues, and some bus body work.

Table ES-1 provides a summary of results for several categories of data presented in this report.

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell	CNG
Number of buses	1	5
Data period	May – Nov 2010	May – Nov 2010
Number of months	7	7
Total mileage in period	9,687	158,172
Average monthly mileage per bus	1,384	4,519
Availability (85% is target)	59%	90%
Fuel economy (miles/kg or GGE)	5.75	2.88
Miles between roadcalls (MBRC) – all	4,844	79,086
MBRC – propulsion only	4,844	79,086
Total maintenance, $/mile	0.47	0.38
Maintenance – propulsion only, $/mile	0.23	0.10

This NREL evaluation is planned to include at least 12 months of operation. The next evaluation report is expected toward the end of calendar year 2011.

[1] Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-560-49342-1, November 2010, www.nrel.gov/hydrogen/pdfs/49342-1.pdf.

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Introduction

SunLine Transit Agency has demonstrated hydrogen and fuel cell bus technologies for more than 10 years. In May 2010, the agency began operating its sixth-generation hydrogen fueled bus, which it unveiled in February 2010 during the 3rd Annual State of Public Transit Luncheon. This Advanced Technology (AT) fuel cell bus incorporates the latest design improvements to reduce weight and increase reliability and performance. SunLine is collaborating with the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) to evaluate the bus in revenue service. This report provides the early data results and implementation experience of the fuel cell bus since it was placed in service.

NREL Evaluations

NREL has been evaluating alternative fuel and advanced propulsion transit buses for DOE and the U.S. Department of Transportation's Federal Transit Administration (FTA) since the early 1990s. NREL's first evaluation of hydrogen fuel cell transit buses for DOE was in 2000 and continued with a series of evaluations at five transit agencies. These evaluations focus on determining the status of hydrogen and fuel cell systems and the corresponding infrastructure in transit applications to help DOE and FTA assess the progress toward technology readiness. NREL uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations. This protocol was documented in a joint evaluation plan for transit bus evaluations.[2]

Host Site Profile: SunLine

SunLine Transit Agency provides public transit services to Southern California's Coachella Valley (including Palm Springs). SunLine's headquarters are in Thousand Palms, California (see Figure 1), and its service area of more than 1,100 square miles includes nine member cities and a portion of Riverside County (Figure 2). SunLine has proactively adopted 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.

Figure 1. SunLine's headquarters, located in Thousand Palms, California

[2] Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-560-49342-1, November 2010, www.nrel.gov/hydrogen/pdfs/49342-1.pdf.

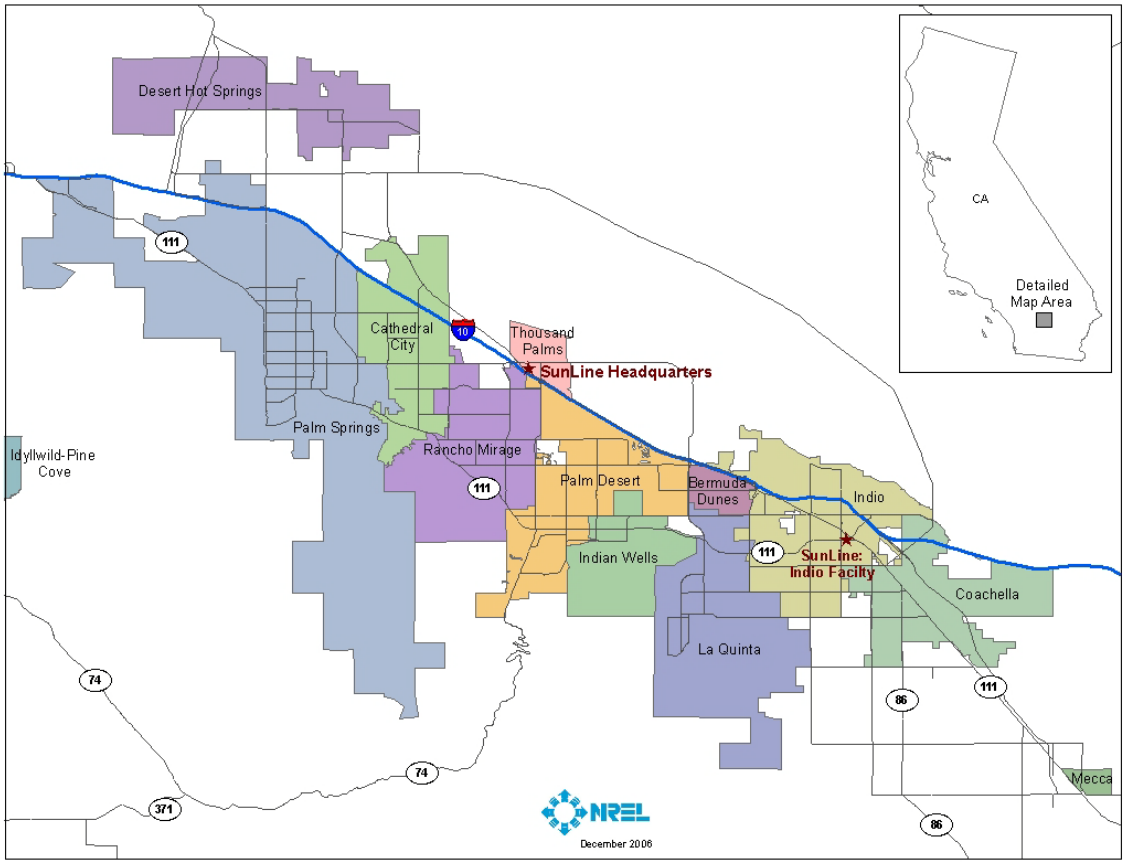

Figure 2. SunLine operating area in the Coachella Valley, California

SunLine operates 11 fixed routes (SunBus) and provides paratransit services (SunDial). Table 1 outlines SunLine's current bus fleet including the newest fuel cell bus. In addition to the 69 fixed-route buses, the agency's fleet includes 31 CNG paratransit vehicles. Its non-revenue vehicle fleet consists of 39 light- and medium-duty CNG vehicles and one hybrid light-duty vehicle.

Table 1. SunLine Fixed-Route Bus Fleet

Number	Description
41	New Flyer 40-ft, low floor, CNG
15	Orion V 40-ft, CNG
10	ElDorado 30-ft, CNG
1	New Flyer Hybrid Hydrogen ICE (HHICE)
1	Van Hool 40-ft, Fuel Cell Bus
1	New Flyer 40-ft, Advanced Technology Fuel Cell Bus
69	**Total Bus Fleet**

SunLine's fixed routes in the Coachella Valley operate along State Highway 111 and Interstate 10. In 2009, SunLine conducted a Comprehensive Operational Analysis[3] to better understand the existing and future transit market in the area and to develop a plan for optimizing service to cost-effectively meet those needs. The Preferred Service Plan outlined in the study recommended a variety of modifications to the route structure to increase ridership and lower operational costs. The changes included realignment of select routes, establishment of new routes, and increased frequencies and spans on most routes. SunLine began implementing this plan during 2010. Table 2 shows a weekly summary of the updated bus use at SunLine and indicates that bus service operates at an average of 13.9 mph on the weekends and 14.0 mph during the week for an overall average of 13.9 mph.

Table 2. Summary of Total Weekly Bus Use at SunLine

Day of Week	Total Miles	Hours	Average Speed
Weekday	42,993.0	3,080.8	14.0
Weekend	11,388.6	820.9	13.9
Total	**54,381.6**	**3,901.7**	**13.9**

The weather in SunLine's service area can have an effect on vehicle performance. The Coachella Valley is a hot, desert climate with an annual rainfall between 2 and 4 inches. Average high temperatures are usually over 80°F for eight months of the year and can get as high as 120°F. This plays a role in how the SunLine buses are operated. During the eight months in the year when the average high temperature is above 80°F, drivers typically idle on the shorter layovers to keep the buses cool for passengers. This causes the bus average speed to go down and the air-conditioning load to go up, both of which have a significant impact on fuel efficiency.

Fuel Cell Bus Evaluation at SunLine

SunLine has successfully used its unique capabilities with gaseous fuels, small size, and high-temperature/low-humidity location to attract testing projects with government and manufacturer partners. Over the years, many projects have involved natural gas, hydrogen, fuel cells, and various combinations of these technologies. The objectives for these projects have been to advance clean transit bus propulsion systems and leverage project funding to afford SunLine additional equipment and infrastructure.

In May 2010, SunLine began demonstrating the AT bus—a new-generation fuel cell bus developed by Bluways,[4] Ballard Power Systems, and New Flyer. This report describes SunLine's operation of the AT fuel cell transit bus in revenue service. Five compressed natural gas (CNG) buses operating from the same SunLine location are being used as a baseline comparison. This evaluation report describes results and experiences with the AT fuel cell bus and CNG buses from May 2010 through November 2010.

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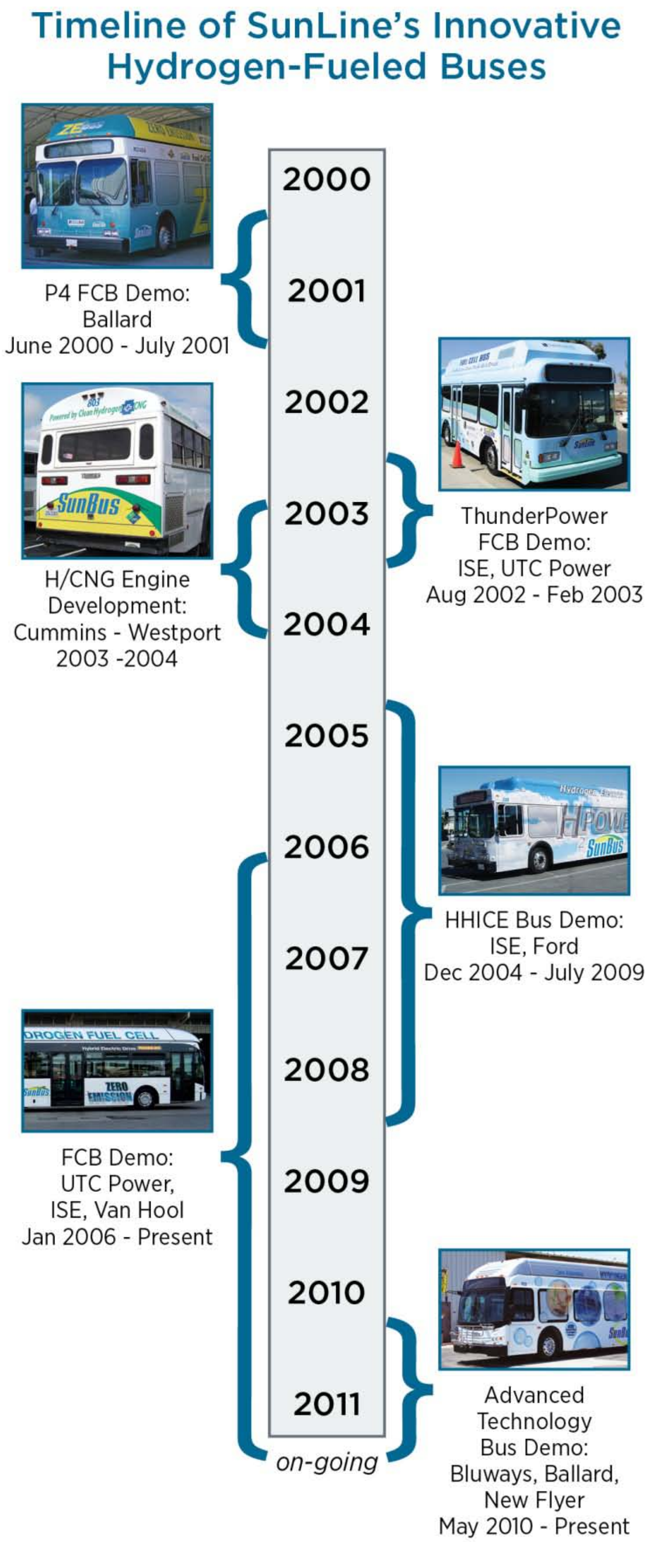
[3] Link to SunLine's Comprehensive Operational Analysis: http://www.sunline.org/pub/pdfs/COA_July2009.pdf.

[4] Bluways (www.bluways.com) supplies hybrid electric drive systems and components for heavy-duty applications.

SunLine's Experiences with Hydrogen Buses

SunLine's experience with hydrogen spans more than a decade of development and demonstration projects.



Ballard P4 Bus: SunLine participated in a demonstration of the Phase 4 version of the ZeBus. The bus was tested in SunLine's service area but was not used in actual revenue service.

ThunderPower FCB: This bus featured an ISE hybrid design powered by UTC Power's 60 kW fuel cell power system. SunLine demonstrated this 30-foot FCB in revenue service for six months. The bus accumulated more than 8,000 miles and 640 hours on the fuel cell system. Fuel economy averaged 12 mpDGE.

Cummins - Westport (CWI) engine development: SunLine worked with CWI to develop and demonstrate a natural gas engine capable of using hydrogen and CNG blended fuel. Using a blend of 20% hydrogen/80% CNG, the project demonstrated significant reductions of several pollutant emissions–including 50% lower oxides of nitrogen and 58% lower non-methane hydrocarbons–when compared to conventional CNG engines.

Hydrogen Hybrid Internal Combustion Engine bus: SunLine demonstrated the HHICE bus in revenue service for several years. During that time, the bus accumulated more than 85,000 miles with an average fuel economy of 4.9 mpDGE.

Van Hool/UTC Power FCB: SunLine's first full-size FCB went into service in late 2006. This bus, developed by UTC Power, ISE, and Van Hool, continues to operate in revenue service in the fleet. The bus has accumulated more than 115,000 miles and 8,800 fuel cell system hours (through November 2010).

New Flyer/Bluways/Ballard FCB: SunLine's newest FCB, which is the subject of this report, has operated nearly 9,700 miles and accumulated 818 hours on the fuel cell system since it was put in service.

Bus Technology Descriptions

Table 3 provides bus system descriptions for the AT fuel cell bus and CNG buses that were studied in this evaluation. The AT bus is a low floor, 40-foot New Flyer model with the latest advances designed to improve performance, reliability, and durability. The fuel cell bus is pictured in Figure 3. Five compressed natural gas (CNG) buses operating from the same SunLine location are being used as a baseline comparison. 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 (see Figure 4).

Table 3. Fuel Cell and CNG Bus System Descriptions

Vehicle System	AT Fuel Cell Bus	CNG Bus
Number of buses	1	5
Bus manufacturer and model	New Flyer, H40LFR	New Flyer
Model year	2009	2008
Length/width/height	40 ft/102 in./137 in.	40 ft/102 in./130.8 in.
Gross vehicle weight rating	44,530 lb	42,540 lb
Passenger capacity	37 seated with no wheelchairs	39 seated with no wheelchairs
Hybrid system	Bluways hybrid-electric drive system incorporating Siemens ELFA components	N/A
Fuel cell or engine	Ballard Power Systems FCvelocity HD6, 150 kW	Cummins Westport ISL G, 280 hp @ 2,200 rpm
Propulsion motor	Two Siemens AC induction motors, 85 kW each	N/A
Energy storage	Valence, phosphate based lithium ion batteries, rated energy: 47 kWh	N/A
Accessories	Electric	Mechanical
Fuel/storage	Gaseous hydrogen, 43 kg at 5,000 psi, 6 Dynetek, Type 3 tanks	125 diesel gallon equivalent
Bus purchase cost	$1,200,000[5]	$402,900

[5] The purchase price for the AT bus was prorated based on the fact it was previously demonstrated at BC Transit.

Figure 3. SunLine's Advanced Technology fuel cell bus

Figure 4. New Flyer CNG bus at SunLine

Advanced Technology Fuel Cell Bus

This AT fuel cell bus was designed in collaboration between Bluways,[6] Ballard, and New Flyer. The bus was originally developed as the pilot for an order of 20 buses to be operated in British Columbia, Canada, beginning with the 2010 Winter Olympic Games. The transit operator, BC Transit, put the bus through a series of acceptance tests over a period of about six months. The data results from those tests enabled the manufacturers to make changes and optimize the design prior to building the larger fleet. Once this bus completed its pilot testing in Canada, it was returned to Bluways where it was upgraded to match the final design of the rest of the BC Transit fleet. With funding from California and federal government agencies, SunLine was able to purchase the bus for operation in its service area. The data gathered on the bus at SunLine will help the manufacturers determine how the system performs in a hot, dry climate.

[6] In February 2011, Bluways acquired substantial assets and technology from ISE Corporation.

Hybrid Fuel Cell System

The design is a next-generation system based on experiences with early hybrid and fuel cell bus demonstrations conducted by the manufacturers. Each partner brings a unique perspective and set of experiences to creating a fuel cell bus designed to compete in the market. For Ballard, the new fuel cell module included improvements and upgrades based on lessons learned with projects such as the CUTE and HyFLEET:CUTE programs. As part of these and other demonstrations, Ballard gathered data from fuel cell buses operating for more than 1.2 million miles of revenue service. The data collected during these demonstrations were used to refine and optimize the fuel cell and system components for higher efficiency and increased durability. Ballard now offers a 5-year, 12,000-hour warranty on the HD6 fuel cell module.

The Bluways hybrid system was designed as a plug-and-play architecture, which enables a variety of power sources or energy storage solutions to be easily incorporated. For this AT bus, Bluways integrated Ballard's 150-kW fuel cell module and lithium-ion batteries from Valence. The hybrid electric propulsion system is based on the Siemens ELFA system. The company's experience with early version fuel cell buses and a fleet of gasoline hybrids provided in-service data to aid in the development process.

Hydrogen and CNG Fueling

Hydrogen fuel is supplied at SunLine by a HyRadix natural gas reformer. The fuel is compressed to 5,000 psi and dispensed into the buses. CNG is brought into the SunLine property via a high-pressure natural gas line and then compressed to 3,600 psi for delivery into the vehicles. SunLine provides both hydrogen and CNG for purchase at its public dispensing island. Because of this, SunLine is required to track 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 a GGE for fuel-economy calculations. This report presents both GGE (kg for hydrogen) and diesel gallon equivalent (DGE) for hydrogen and CNG fuel consumption. The end of Appendix A shows energy-conversion calculations for GGE and DGE.

Fueling Station Data Analysis – SunLine currently operates two fuel cell buses in its service area: the AT fuel cell bus and a Van Hool fuel cell bus. To show overall performance of the station, the fueling analysis figures include hydrogen from both buses. Figure 5 shows the average hydrogen dispensed per day into SunLine's fuel cell buses from May 2010 through November 2010. The calculation for this rate includes only the days in which the station dispensed hydrogen. The station was used at least once per day to fill at least one of the two hydrogen buses for 83% of the calendar days during the period. In September, the buses were held out of service for several days because the station was low on fuel. The overall average daily use was 22.2 kg per day. During this period, SunLine dispensed a total of 3,924 kg of hydrogen. At times during the summer, one or the other fuel cell bus was out of service for maintenance issues. This resulted in lower hydrogen use during those months.

Figure 6 shows the distribution of hydrogen amounts dispensed per fill by bus. The buses were filled a total of 224 times during the evaluation period for a total of 3,675 kg.[7] The average amount of hydrogen per fill was 16.4 kg per fill. Figure 7 shows a cumulative fueling rate histogram for the SunLine hydrogen station from May 2010 through November 2010. The overall average fueling rate was 1.0 kg per minute, and the average time for a fill was 15.8 minutes.

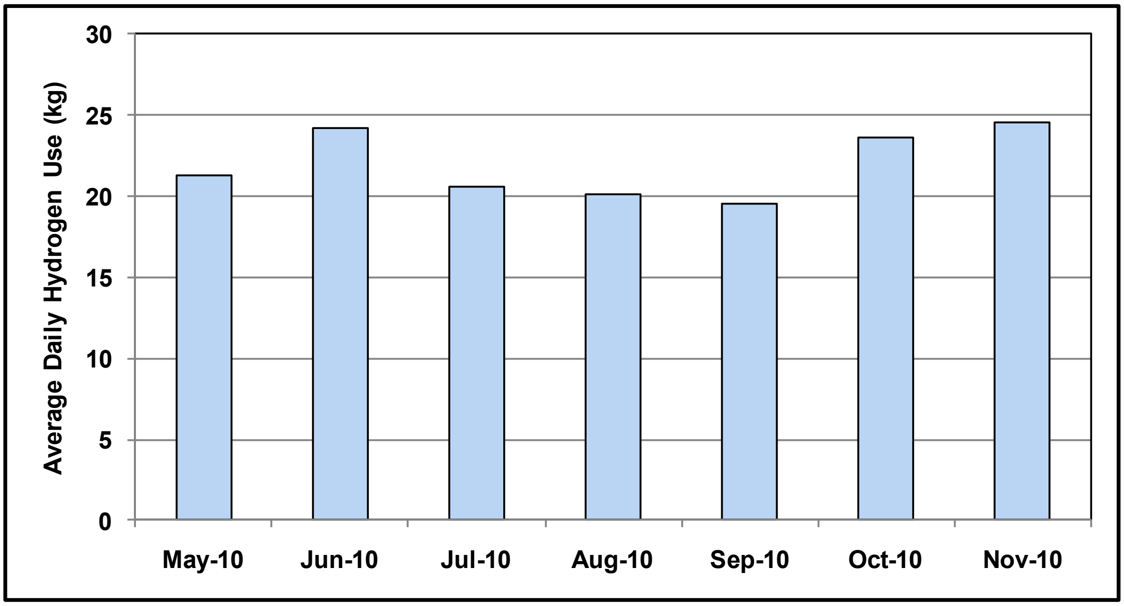


Figure 5. Average hydrogen dispensed per day (excluding 0 kg days)

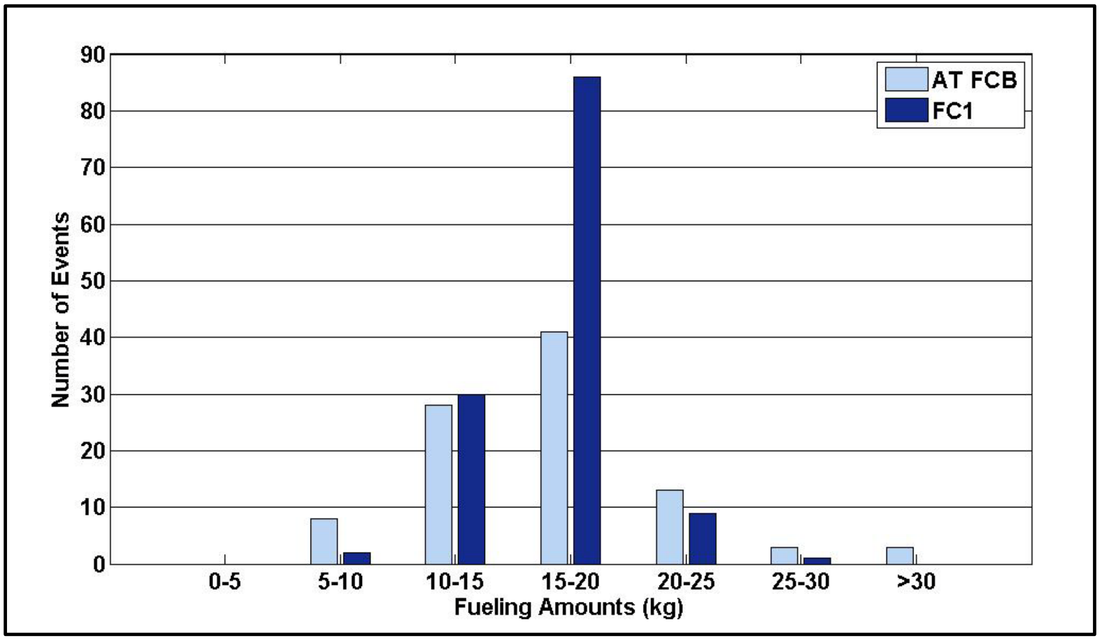


Figure 6. Histogram of fueling amounts by bus

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

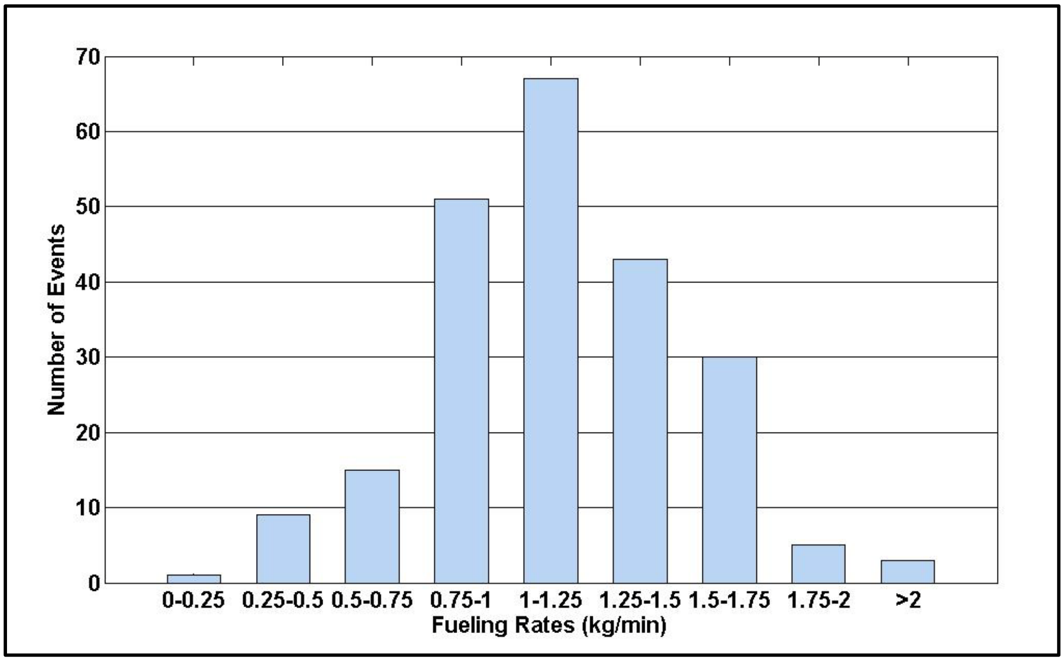


Figure 7. Histogram of fueling rates

Hydrogen fuel costs at SunLine consist of the cost of natural gas for the reformer, maintenance of the station equipment, and capital cost amortization. SunLine performs the maintenance of the station equipment, including parts and labor. The average cost for hydrogen during the evaluation period was $18.45/kg (monthly costs ranged from a low of $6.65/kg to a high of $29.68/kg). Lower use of the station (when the buses were out of service) and higher maintenance for the reformer during March 2009 were contributors to higher monthly costs. Figure 8 shows the monthly station use and hydrogen cost per kilogram since January 2008. DOE's target for hydrogen cost ($2–$4/kg) is also included. The figure illustrates the relationship between high hydrogen costs and low station use. Repair costs for the reformer are also factored into the total hydrogen costs, which causes spikes in the hydrogen cost for those months. Hydrogen costs for the months when less than 100 kg are produced are not representative and are shaded in grey on the graph. 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.

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. During the evaluation period, the CNG price at the dispenser for SunLine (not the public price) was $0.90 per GGE. This price includes all costs—natural gas, maintenance, and station amortization.

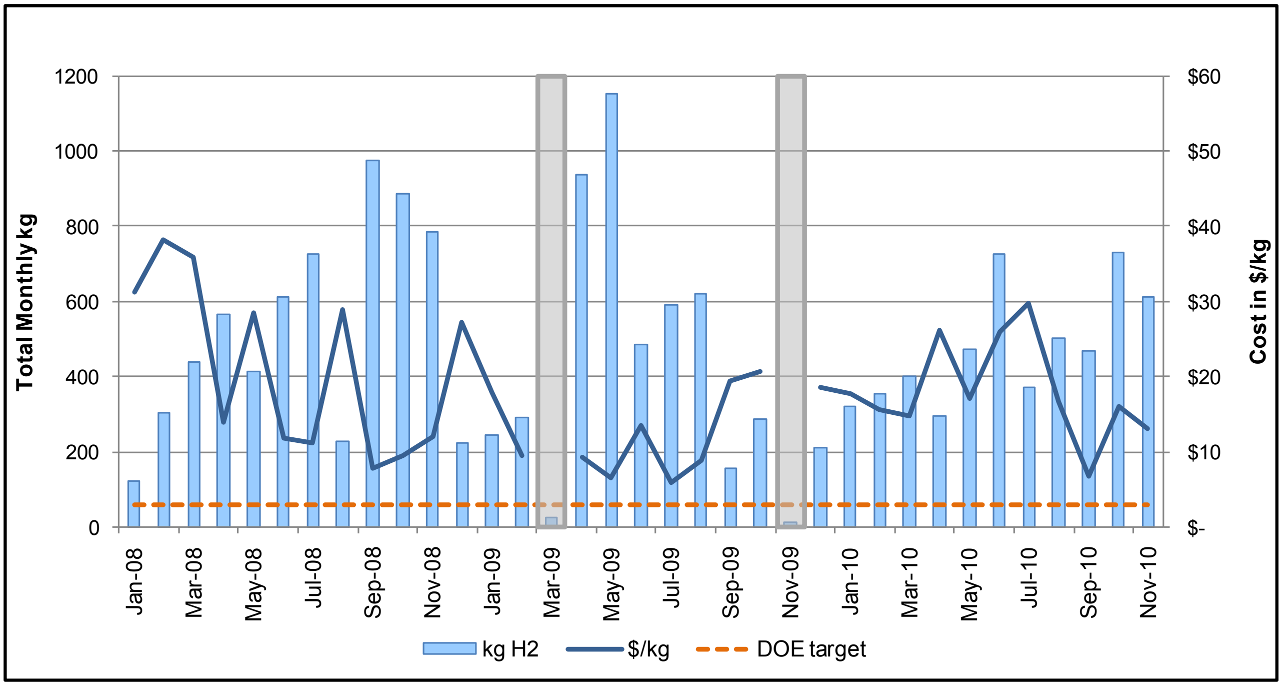


Figure 8. Comparison of monthly hydrogen use and cost per kg

Evaluation Results

SunLine placed the AT fuel cell bus in service on May 27, 2010. The focus of this report is the operating data collected on the fuel cell and CNG buses from May 2010 through November 2010. Appendix A provides a summary of all data. Appendix B provides a data summary in SI (metric) units.

Route Assignments

In general, SunLine's buses are randomly dispatched on its routes. As previously mentioned, the overall system average speed is 13.9 mph. When first placed in service, the AT fuel cell bus was used exclusively on Line 50, which had an average speed of 14.1 mph. When SunLine instituted the Preferred Service Plan in September 2010, Line 50 was realigned and became Line 53. At that time, the AT fuel cell bus was used exclusively on Line 53 (average speed of 12.9 mph). The five CNG buses were randomly dispatched with the majority of time (75%) split evenly between Line 111 (13.9 mph), Line 14 (14.6 mph), and Line 30 (10.8 mph).

Bus Use and Availability

Bus use and availability indicates reliability. Lower bus use may indicate downtime for maintenance or purposeful reduction of planned work for the buses. This section provides a summary of bus use and availability for the fuel cell and CNG buses.

The AT fuel cell bus has planned service of up to seven days per week. For this bus, total mileage accumulation for the evaluation period was 9,687 miles, and the fuel cell system accumulated 818 hours, which indicates an average speed of 11.8 mph. This average speed is slower than the overall 13.9 mph average speed for all SunLine routes. For in-service days during the evaluation period, the AT fuel cell bus averaged 7.6 hours per day with a maximum of 14.4 hours in one day.

Table 4 summarizes the average monthly mileage accumulation by bus and study group for the evaluation period. Using the CNG buses as the baseline, the AT fuel cell bus had an average monthly mileage that was 31% that of the CNG buses. This percentage is partly due to downtime of the fuel cell bus because of issues with the air conditioning.

Table 4. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average
AT FCB	**12,159**	**21,846**	**9,687**	**7**	**1,384**
603 CNG	92,951	127,214	34,263	7	4,895
604 CNG	84,664	114,908	30,244	7	4,321
605 CNG	89,238	123,453	34,215	7	4,888
606 CNG	81,301	115,209	33,908	7	4,844
608 CNG	93,618	119,160	25,542	7	3,649
Total CNG			**158,172**	**35**	**4,519**

Another measure of reliability is availability—the percentage of time that the buses are planned for operation compared with the time the buses are actually available for that planned operation. Figure 9 shows the monthly average availability for each of the study bus groups. As shown in the chart, the availability goal is 85% for all buses. Availability for all of NREL's evaluations is calculated by including the planned service days, which is 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 a holiday, it is not counted as unavailable. This strategy applies to both the AT fuel cell bus and the CNG buses.

Overall availability for the AT fuel cell bus was 59% of the time during the evaluation period. During the summer months, the bus experienced problems with its air conditioning system, which resulted in significant downtime. Because of the high summer temperatures in the area, SunLine can't operate a bus without air conditioning. Also, the cooling for the hybrid battery pack is provided as part of the bus cooling system, and some issues occurred with this cooling of the hybrid battery pack during the evaluation period. The chart shows that the CNG buses have consistently achieved availability above the 85% target.

Table 5 provides a summary of the availability and unavailability reasons for each of the study bus groups. Overall, during the evaluation period, the average availability for the fuel cell bus was 59%, and availability for the CNG buses was 90%. As discussed, the primary issues that kept the fuel cell bus out of service were downtime for transit agency maintenance—primarily for air conditioning and body work (58%), fuel cell propulsion (20%), and hybrid system issues (14%). Issues that kept the CNG buses out of service were general maintenance.

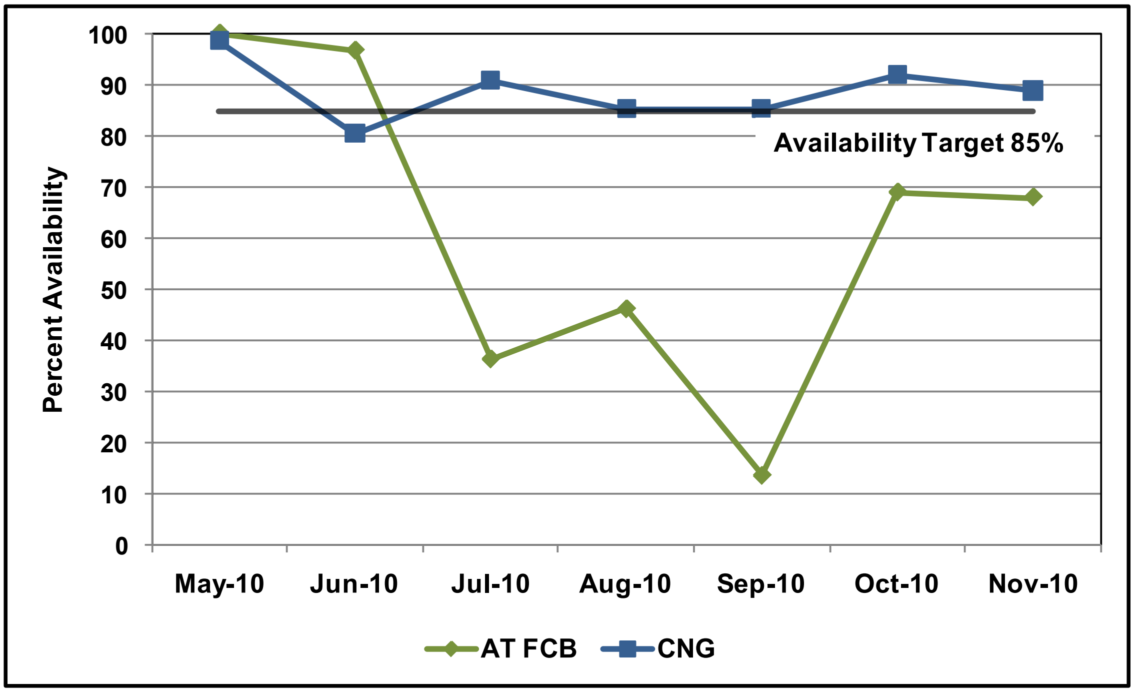


Figure 9. Availability for study bus groups

Table 5. Summary of Reasons for Availability and Unavailability of Buses for Service

Category	AT FCB		CNG Buses	
	Number	Percent	Number	Percent
Planned work days	159		1,010	
Days available	94	59	909	90
Available	**94**	**100**	**909**	**100**
On-route	93	99	865	95
Event/demonstration	0	0	5	1
Training	0	0	0	0
Not used	1	1	39	4
Unavailable	**65**	**100**	**96**	**100**
Fuel cell propulsion	13	20		
Hybrid propulsion	9	14		
Traction batteries	0	0		
SunLine maintenance	38	58	96	100
Fueling unavailable	5	8		

Fuel Economy and Cost

Table 6 shows hydrogen and CNG fuel consumption and fuel economy for the study bus groups during the evaluation period. Using the GGE fuel economy and the CNG buses as a baseline, the AT fuel cell bus had a fuel economy nearly two times higher than the CNG buses. Figure 10 shows average fuel economies for each of the study bus groups.

The fuel costs per mile for the study bus groups for the evaluation period were $1.40 per mile for the fuel cell bus and $0.31 per mile for the CNG buses. The fuel cost for CNG has been much lower than the cost for hydrogen production. And, the CNG fuel cost at $0.90 per GGE is much lower than the typical diesel fuel average cost per gallon.

Table 6. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg) or CNG (GGE)	Miles per kg or GGE	Diesel Equivalent Amount (Gallon)	Miles per Gallon (DGE)
AT FCB	**9,580**	**1,665.0**	**5.75**	**1,474.4**	**6.50**
603 CNG	34,263	12,062.7	2.84	10,796.1	3.17
604 CNG	30,244	10,520.5	2.87	9,415.8	3.21
605 CNG	34,215	11,995.9	2.85	10,736.3	3.19
606 CNG	33,908	11,792.2	2.88	10,554.0	3.21
608 CNG	25,542	8,624.8	2.96	7,719.2	3.31
CNG Total	**158,172**	**54,996.0**	**2.88**	**49,221.4**	**3.21**

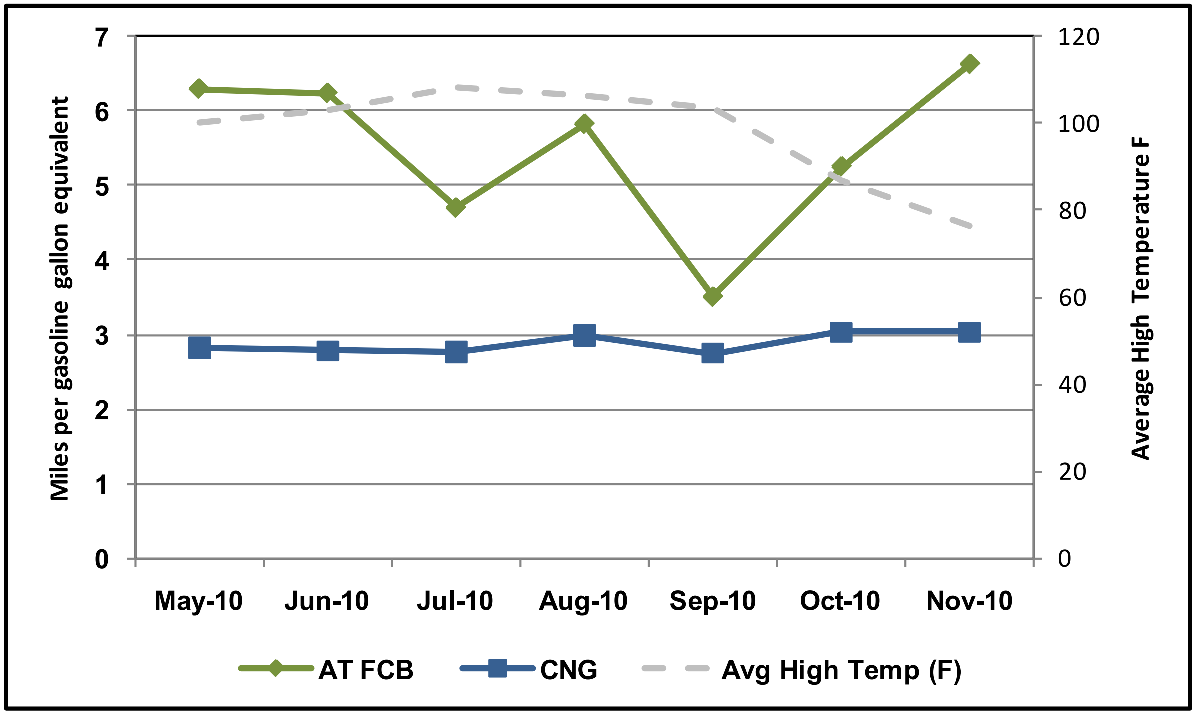


Figure 10. Average fuel economy (miles per kg or GGE)

Maintenance Analysis

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. All work orders for the study buses were collected and analyzed for this evaluation. For consistency, we set the maintenance labor rate at $50 per hour, which does not reflect an average rate for SunLine. 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 fuel cell bus and CNG buses. The CNG buses have total maintenance costs 27% lower than those of the fuel cell bus. The parts costs are low for the fuel cell bus because they typically are covered by the manufacturers for most of the propulsion system maintenance; however, SunLine's mechanics do most of the work.

Table 7. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Cost ($) per Mile
AT FCB	**9,687**	**153.22**	**88.0**	**0.47**
603 CNG	34,263	5,053.43	166.3	0.39
604 CNG	30,244	4,606.42	192.4	0.47
605 CNG	34,215	3,333.56	187.8	0.37
606 CNG	33,908	2,700.06	144.5	0.29
608 CNG	25,542	2,688.06	139.8	0.38
Total CNG	**158,172**	**18,381.53**	**830.8**	**0.38**

Maintenance Costs Separated by System – Table 8 shows maintenance costs by vehicle system and bus study group (without warranty costs included). 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.
- **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**.

For the AT fuel cell bus, the systems with the highest percentage of maintenance costs were propulsion-related, PMI, and HVAC. The CNG buses had highest percentage of maintenance costs for cab, body, and accessories; propulsion-related; and PMI.

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

System	AT FCB		CNG	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Cab, body, and accessories	0.05	11	0.13	34
Propulsion-related	0.23	49	0.10	26
PMI	0.11	23	0.09	24
Brakes	0.00	0	0.00	0
Frame, steering, and suspension	0.00	0	0.02	4
HVAC	0.06	13	0.01	3
Lighting	0.02	4	0.01	3
Axles, wheels, and drive shaft	0.00	0	0.01	3
General air system repairs	0.00	0	0.00	0
Tires	0.00	0	0.01	3
Total	**0.47**	**100**	**0.38**	**100**

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 study bus groups during the evaluation period (no warranty). The fuel cell bus was under warranty during the entire evaluation period, and the CNG buses have continued to be under warranty for any engine issues. During the evaluation period of this report, the SunLine mechanics did nearly all of the maintenance on the fuel cell bus themselves, supported by the manufacturers; however, as mentioned above, the manufacturers generally supplied the parts under warranty for the propulsion system, so the costs for these parts are not included.

- **Total propulsion-related** – The fuel cell bus had more than double the maintenance cost for propulsion-related maintenance compared with the CNG buses. The majority of this maintenance for the fuel cell bus has been labor.
- **Exhaust system** – There were no costs for this system for the study bus groups.
- **Fuel system** – Costs for the fuel system were low for both bus groups.
- **Powerplant and electric propulsion** – The fuel cell bus maintenance reported here involved almost exclusively SunLine mechanics supporting manufacturer work on the bus. The preventive maintenance for the CNG buses was almost exclusively in the powerplant category (with none for electric propulsion – the CNG buses are not hybrids).
- **Non-lighting electrical (charging, cranking, and ignition)** – The fuel cell bus had some minor costs in this category relating to 24-volt batteries. The CNG buses mostly had preventive maintenance repairs in this category for spark plugs at the 24,000-mile preventive-maintenance cycle (and the 48,000-mile cycle) for each bus.
- **Air intake** – The fuel cell bus had no costs in this category, and the CNG buses had only air filter changeouts.
- **Cooling** – The fuel cell bus had a few hours of maintenance on this system, and the CNG buses had low costs in this category.
- **Transmission** – Only the CNG buses had costs in this category for filters under preventive maintenance.

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

Maintenance System Costs	AT FCB	CNG
Mileage	9,687	158,172
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	13.00	9,005.83
Labor hours	44.75	128.75
Total cost ($)	2,250.50	15,443.33
Total cost ($) per mile	**0.23**	**0.10**
Exhaust System Repairs		
Parts cost ($)	0.00	0.00
Labor hours	0.0	0.0
Total cost ($)	0.00	0.00
Total cost ($) per mile	**0.00**	**0.00**
Fuel System Repairs		
Parts cost ($)	0.00	344.34
Labor hours	1.0	0.0
Total cost ($)	50.00	344.34
Total cost ($) per mile	**0.01**	**0.00**
Powerplant System Repairs		
Parts cost ($)	13.00	2,650.34
Labor hours	20.5	64.5
Total cost ($)	1,038.00	5,875.34
Total cost ($) per mile	**0.11**	**0.04**
Electric Propulsion System Repairs		
Parts cost ($)	0.00	0.00
Labor hours	13.5	0.0
Total cost ($)	675.00	0.00
Total cost ($) per mile	**0.07**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	0.00	5,006.16
Labor hours	4.5	45.0
Total cost ($)	225.00	7,256.16
Total cost ($) per mile	**0.02**	**0.05**
Air Intake System Repairs		
Parts cost ($)	0.00	420.35
Labor hours	0.0	0.0
Total cost ($)	0.00	420.35
Total cost ($) per mile	**0.00**	**0.00**
Cooling System Repairs		
Parts cost ($)	0.00	257.16
Labor hours	5.3	16.8
Total cost ($)	262.50	1,094.66
Total cost ($) per mile	**0.03**	**0.01**
Transmission System Repairs		
Parts cost ($)	0.00	133.96
Labor hours	0.0	2.5
Total cost ($)	0.00	258.96
Total cost ($) per mile	**0.00**	**0.00**

Roadcall Analysis

A roadcall (RC), or revenue vehicle system failure (as named in the National Transit Database[8]), 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 RC. The analysis provided here includes only RCs caused by "chargeable" failures. Chargeable RCs include systems that can physically disable the bus from operating on route, such as interlocks (doors and wheelchair lift) and engine problems. Chargeable RCs do not include RCs for things such as radios or destination signs.

Table 10 shows the RCs and miles between roadcalls (MBRC) for each study bus group in two categories: all RCs and propulsion-related-only RCs. Only two RCs for each study group have been reported so far in the evaluation.

Table 10. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC
AT FCB	**9,687**	**2**	**4,844**	**2**	**4,844**
603 CNG	34,263	0		0	
604 CNG	30,244	1		1	
605 CNG	34,215	1		1	
606 CNG	33,908	0		0	
608 CNG	25,542	0		0	
Total CNG	**158,172**	**2**	**79,086**	**2**	**79,086**

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

What’s Next for SunLine

This report covers SunLine’s operation of the fuel cell and CNG buses from May 2010 through November 2010. The agency will continue working with DOE/NREL to collect data on the buses in service. The next report, which will include at least 12 months of data, is expected to be published in fall of 2011.

SunLine is also leading a team to develop a purpose-built fuel cell bus that meets FTA “Buy America” requirements. Funded under the FTA’s National Fuel Cell Bus Program, the **American Fuel Cell Bus Project** brings a new team of manufacturers to the fuel cell bus industry—ElDorado, BAE SYSTEMS, and Ballard. The design features a number of advancements that are expected to result in a highly efficient bus. Elements include advanced energy storage and new power electronics, high-efficiency accessories, and the newest-generation fuel cell on a U.S.-built chassis. This bus is in development and is expected to be ready for demonstration in late 2011 or early 2012.

Figure 11. Advanced Technology fuel cell bus in service

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Appendix A: Fleet Summary Statistics

Fleet Summary Statistics: SunLine Transit Agency
Fuel Cell Bus (FCB) and Compressed Natural Gas (CNG) Study Groups
Fleet Operations and Economics

	AT FCB	CNG Buses
Number of vehicles	1	5
Period used for fuel and oil op analysis	5/10–11/10	5/10–11/10
Total number of months in period	7	7
Fuel and oil analysis base fleet mileage	9,580	158,172
Period used for maintenance op analysis	5/10–11/10	5/10–11/10
Total number of months in period	7	7
Maintenance analysis base fleet mileage	9,687	158,172
Average monthly mileage per vehicle	1,384	4,519
Availability	59%	90%
Fleet fuel usage in CNG GGE/H_2 kg	1,665	54,996
Roadcalls	2	2
RCs MBRC	4,844	79,086
Propulsion roadcalls	2	2
Propulsion MBRC	4,844	79,086
Fleet miles/kg hydrogen or CNG GGE	5.75	2.88
(1.13 kg H_2/gal diesel fuel)		
Representative fleet MPG (energy equiv)	6.50	3.21
Hydrogen cost per kg	8.00	
GGE cost		0.90
Fuel cost per mile	**1.39**	**0.31**
Total scheduled repair cost per mile	0.11	0.14
Total unscheduled repair cost per mile	0.36	0.24
Total maintenance cost per mile	**0.47**	**0.38**
Total operating cost per mile	**1.86**	**0.69**

Maintenance Costs

	AT FCB	CNG Buses
Fleet mileage	9,687	158,172
Total parts cost	153.22	18,381.53
Total labor hours	88.0	830.8
Average labor cost (@ $50.00 per hour)	4,400.00	41,537.50
Total maintenance cost	4,553.22	59,919.03
Total maintenance cost per bus	4,553.22	11,983.81
Total maintenance cost per mile	**0.47**	**0.38**

Maintenance Costs by Vehicle System

	AT FCB	CNG Buses
Fleet mileage	9,687	158,172
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)		
Parts cost	13.00	9,005.83
Labor hours	44.75	128.75
Average labor cost	2,237.50	6,437.50
Total cost (for system)	2,250.50	15,443.33
Total cost (for system) per bus	2,250.50	3,088.67
Total cost (for system) per mile	**0.23**	**0.10**
Exhaust System Repairs (ATA VMRS 43)		
Parts cost	0.00	0.00
Labor hours	0.0	0.0
Average labor cost	0.00	0.00
Total cost (for system)	0.00	0.00
Total cost (for system) per bus	0.00	0.00
Total cost (for system) per mile	**0.00**	**0.00**
Fuel System Repairs (ATA VMRS 44)		
Parts cost	0.00	344.34
Labor hours	1.0	0.0
Average labor cost	50.00	0.00
Total cost (for system)	50.00	344.34
Total cost (for system) per bus	50.00	68.87
Total cost (for system) per mile	**0.01**	**0.00**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts cost	13.00	2,650.34
Labor hours	20.5	64.5
Average labor cost	1,025.00	3,225.00
Total cost (for system)	1,038.00	5,875.34
Total cost (for system) per bus	1,038.00	1,175.07
Total cost (for system) per mile	**0.11**	**0.04**
Electric Propulsion Repairs (ATA VMRS 46)		
Parts cost	0.00	0.00
Labor hours	13.5	0.0
Average labor cost	675.00	0.00
Total cost (for system)	675.00	0.00
Total cost (for system) per bus	675.00	0.00
Total cost (for system) per mile	**0.07**	**0.00**

Maintenance Costs by Vehicle System (continued)

	AT FCB	CNG Buses
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts cost	0.00	5,006.16
Labor hours	4.5	45.0
Average labor cost	225.00	2,250.00
Total cost (for system)	225.00	7,256.16
Total cost (for system) per bus	225.00	1,451.23
Total cost (for system) per mile	**0.02**	**0.05**
Air Intake System Repairs (ATA VMRS 41)		
Parts cost	0.00	420.35
Labor hours	0.0	0.0
Average labor cost	0.00	0.00
Total cost (for system)	0.00	420.35
Total cost (for system) per bus	0.00	84.07
Total cost (for system) per mile	**0.00**	**0.00**
Cooling System Repairs (ATA VMRS 42)		
Parts cost	0.00	257.16
Labor hours	5.3	16.8
Average labor cost	262.50	837.50
Total cost (for system)	262.50	1,094.66
Total cost (for system) per bus	262.50	218.93
Total cost (for system) per mile	**0.03**	**0.01**
Hydraulic System Repairs (ATA VMRS 65)		
Parts cost	0.00	193.52
Labor hours	0.0	0.0
Average labor cost	0.00	0.00
Total cost (for system)	0.00	193.52
Total cost (for system) per bus	0.00	38.70
Total cost (for system) per mile	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)		
Parts cost	0.00	0.00
Labor hours	1.0	14.0
Average labor cost	50.00	700.00
Total cost (for system)	50.00	700.00
Total cost (for system) per bus	50.00	140.00
Total cost (for system) per mile	**0.01**	**0.00**

Maintenance Costs by Vehicle System (continued)

	AT FCB	CNG Buses
Brake System Repairs (ATA VMRS 13)		
Parts cost	0.00	31.61
Labor hours	0.0	1.5
Average labor cost	0.00	75.00
Total cost (for system)	0.00	106.61
Total cost (for system) per bus	0.00	21.32
Total cost (for system) per mile	**0.00**	**0.00**
Transmission Repairs (ATA VMRS 27)		
Parts cost	0.00	133.96
Labor hours	0.0	2.5
Average labor cost	0.00	125.00
Total cost (for system)	0.00	258.96
Total cost (for system) per bus	0.00	51.79
Total cost (for system) per mile	**0.00**	**0.00**
Inspections Only - No Parts Replacements (101)		
Parts cost	0.00	0.00
Labor hours	20.8	286.5
Average labor cost	1,037.50	14,325.00
Total cost (for system)	1,037.50	14,325.00
Total cost (for system) per bus	1,037.50	2,865.00
Total cost (for system) per mile	**0.11**	**0.09**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts cost	23.16	6,610.56
Labor hours	8.3	286.3
Average labor cost	412.50	14,312.50
Total cost (for system)	435.66	20,923.06
Total cost (for system) per bus	435.66	4,184.61
Total cost (for system) per mile	**0.05**	**0.13**
HVAC System Repairs (ATA VMRS 01)		
Parts cost	0.00	297.41
Labor hours	11.5	27.5
Average labor cost	575.00	1,375.00
Total cost (for system)	575.00	1,672.41
Total cost (for system) per bus	575.00	334.48
Total cost (for system) per mile	**0.06**	**0.01**

Maintenance Costs by Vehicle System (continued)

	AT FCB	CNG Buses
Lighting System Repairs (ATA VMRS 34)		
Parts cost	117.06	170.36
Labor hours	0.8	14.3
Average labor cost	37.50	712.50
Total cost (for system)	154.56	882.86
Total cost (for system) per bus	154.56	176.57
Total cost (for system) per mile	**0.02**	**0.01**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts cost	0.00	2,012.65
Labor hours	0.8	23.3
Average labor cost	37.50	1,162.50
Total cost (for system)	37.50	3,175.15
Total cost (for system) per bus	37.50	635.03
Total cost (for system) per mile	**0.00**	**0.02**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts cost	0.00	251.11
Labor hours	0.0	15.5
Average labor cost	0.00	775.00
Total cost (for system)	0.00	1,026.11
Total cost (for system) per bus	0.00	205.22
Total cost (for system) per mile	**0.00**	**0.01**
Tire Repairs (ATA VMRS 17)		
Parts cost	0.00	0.00
Labor hours	0.3	33.3
Average labor cost	12.50	1,662.50
Total cost (for system)	12.50	1,662.50
Total cost (for system) per bus	12.50	332.50
Total cost (for system) per mile	**0.00**	**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

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 B: Fleet Summary Statistics – SI Units

Fleet Summary Statistics: SunLine Transit Agency
Fuel Cell Bus (FCB) and Compressed Natural Gas (CNG) Study Groups
Fleet Operations and Economics

	AT FCB	CNG Buses
Number of vehicles	1	5
Period used for fuel and oil op analysis	5/10–11/10	5/10–11/10
Total number of months in period	7	7
Fuel and oil analysis base fleet kilometers	15,417	254,546
Period used for maintenance op analysis	5/10–11/10	5/10–11/10
Total number of months in period	7	7
Maintenance analysis base fleet kilometers	15,589	254,546
Average monthly kilometers per vehicle	2,210	7,273
Availability	59%	90%
Fleet fuel usage in CNG liter equiv/H_2 kg	1,665	208,160
Roadcalls	2	2
RCs KMBRC	7,795	127,273
Propulsion roadcalls	2	2
Propulsion KMBRC	7,795	127,273
Fleet kg hydrogen/100 km	10.80	81.78
(1.13 kg H_2/gal diesel fuel)		
Rep. fleet fuel consumption (L/100 km)	36.17	73.19
Hydrogen cost per kg	8.00	
GGE cost/liter		0.24
Fuel cost per kilometer	**0.86**	**0.19**
Total scheduled repair cost per kilometer	0.07	0.09
Total unscheduled repair cost per kilometer	0.22	0.15
Total maintenance cost per kilometer	**0.29**	**0.24**
Total operating cost per kilometer	**1.16**	**0.43**

Maintenance Costs

	AT FCB	CNG Buses
Fleet mileage	15,589	254,546
Total parts cost	153.22	18,381.53
Total labor hours	88.0	830.8
Average labor cost (@ $50.00 per hour)	4,400.00	41,537.50
Total maintenance cost	4,553.22	59,919.03
Total maintenance cost per bus	4,553.22	11,983.81
Total maintenance cost per kilometer	**0.29**	**0.24**

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14. ABSTRACT *(Maximum 200 Words)*
This report describes operations at SunLine Transit Agency for their newest prototype fuel cell bus and five compressed natural gas (CNG) buses. In May 2010, SunLine began operating its sixth-generation hydrogen fueled bus, an Advanced Technology (AT) fuel cell bus that incorporates the latest design improvements to reduce weight and increase reliability and performance. The agency is collaborating with the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) to evaluate the bus in revenue service. This report provides the early data results and implementation experience of the AT fuel cell bus since it was placed in service.

15. SUBJECT TERMS
SunLine; fuel cell bus; FCB; advanced technology; AT; hydrogen; transit; bus evaluations; Bluways; Ballard Power Systems; New Flyer.

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