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

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Technical Report
NREL/TP-5600-54427
May 2012

Contract No. DE-AC36-08GO28308

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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 provides public transit services to the Coachella Valley area of California. SunLine has demonstrated hydrogen and fuel cell bus technologies for more than 10 years. This report describes operations at SunLine for a prototype fuel cell bus and five compressed natural gas (CNG) buses.

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. Since it first went into service in May 2010, the fuel cell bus has operated nearly 32,000 miles and has accumulated more than 2,500 fuel cell system hours (for an average operating speed of 12.3 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.

The U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) is working with SunLine to evaluate the bus in real-world service 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. NREL has previously published two reports documenting the operation of the fuel cell bus in service. This report provides a summary of the results with a focus on the bus operation from July 2011 through January 2012.

Table ES-1 provides a summary of results for several categories of data presented in this report. The table includes summary data collected on all of the buses in service as well as summary data from only the most recent evaluation period, which is the focus of the report.

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell All Data	Fuel Cell Evaluation Period Data	CNG All Data	CNG Evaluation Period Data
Number of buses	1	1	5	5
Data period	5/10 – 1/12	7/11 – 1/12	5/10 – 1/12	7/11 – 1/12
Number of months	21	7	21	7
Total mileage in period	31,857	11,006	483,237	163,232
Average monthly mileage per bus	1,517	1,572	4,602	4,664
Availability (85% is target)	62	62	88	85
Fuel economy (miles/kg or GGE)	5.75	5.38	2.98	3.01
Miles between roadcalls (MBRC) – All	2,451	1,223	17,898	54,411
MBRC – propulsion only	2,451	1,223	32,216	81,616
MBRC – fuel cell system only	6,371	3,669	N/A	N/A
Total maintenance, $/mile	$0.99	$1.28	$0.39	$0.34
Maintenance – propulsion only, $/mile	$0.50	$0.89	$0.12	$0.10

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Introduction

SunLine Transit Agency has operated its advanced technology (AT) fuel cell bus since May 2010. The AT fuel cell bus, built by New Flyer, features a Bluways hybrid drive powered by a Ballard fuel cell power system. SunLine is collaborating with the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) to evaluate the bus in revenue service. NREL has published two reports documenting SunLine's experience and the performance of the bus including data collected from May 2010 through June 2011.[1,2] This report provides an update to the previous reports and covers data collected through January 2012 as well as a summary of the hydrogen station operation. This station also provides fuel to an additional fuel cell bus.

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 first evaluated hydrogen fuel cell transit buses in 2000 and continued with a series of evaluations at five transit agencies documenting results from a total of 26 buses. 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.[3]

Host Site Profile: SunLine

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 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.

Fuel Cell Bus Evaluation at SunLine

SunLine is committed to advancing hydrogen and fuel cell bus technologies for transit, and the agency continues to invest time and effort into projects that will facilitate commercialization. The AT fuel cell bus represents a sixth generation of hydrogen-fueled buses operated by the agency. The bus, shown in Figure 1, is a low floor, 40-foot New Flyer model with the latest advances designed to improve performance, reliability, and durability. The bus was designed in collaboration between Bluways,[4] Ballard, and New Flyer. The bus was originally developed as the pilot for an order of 20 buses for BC Transit in British Columbia, Canada. Once this bus completed its pilot testing in Canada, it was returned to Bluways where it was upgraded to match

[1] SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: First Results Report, NREL/TP-5600-50500, March 2011, www.nrel.gov/hydrogen/pdfs/50500.pdf.
[2] SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Second Results Report, NREL/TP-5600-52349, August 2011, www.nrel.gov/hydrogen/pdfs/52349.pdf.
[3] Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/TP-560-49342-1, November 2010, www.nrel.gov/hydrogen/pdfs/49342-1.pdf.
[4] In February 2011, Bluways acquired substantial assets and technology from ISE Corporation.

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, shown in Figure 2.

Figure 1. SunLine's advanced technology fuel cell bus

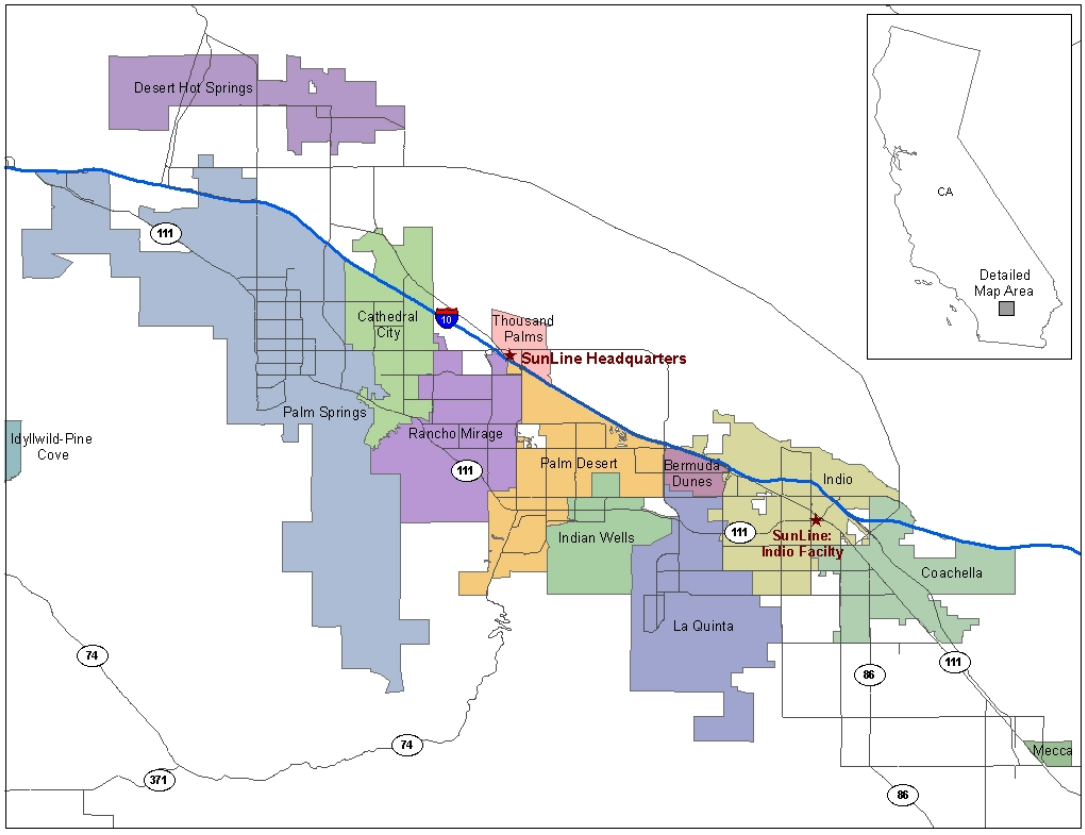

Figure 2. Map of SunLine's service area in Southern California's Coachella Valley

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. 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 3). Table 1 provides bus system descriptions for the AT fuel cell bus and CNG buses that were studied in this evaluation.

Table 1. 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

Figure 3. New Flyer CNG bus at SunLine

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

Hydrogen and CNG Fueling

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 onto the SunLine property via a high-pressure natural gas line and then compressed to 3,600 psi for delivery 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.

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.

Fueling Station Data Analysis – During the data collection period for this bus, SunLine operated two fuel cell buses in its service area: the AT fuel cell bus and a Van Hool fuel cell bus. Toward the end of the period, SunLine also began operating a third fuel cell bus—the American Fuel Cell Bus. To show overall performance of the station, the fueling analysis figures include total hydrogen dispensed from the station. Figure 4 shows the total hydrogen dispensed per month into SunLine's fuel cell buses from May 2010 through January 2012. 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 80% of the calendar days during the period. The overall average daily use was 22.8 kg per day. During this period, SunLine dispensed a total of 11,630 kg of hydrogen. The months with the lowest hydrogen dispensed had downtime for one bus or the other during that month. December 2010 and April 2011 correspond with downtime for the AT fuel cell bus.

Figure 5 shows the distribution of hydrogen amounts dispensed per fill by bus. The buses were filled a total of 632 times during the evaluation period for a total of 10,595 kg hydrogen.[6] The average amount of hydrogen per fill was 16.9 kg per fill. Figure 6 shows a cumulative fueling rate histogram for the SunLine hydrogen station from December 2010 through January 2012. The overall average fueling rate was 1.01 kg per minute, and the average time for a fill was 16.8 minutes.

[6] 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.

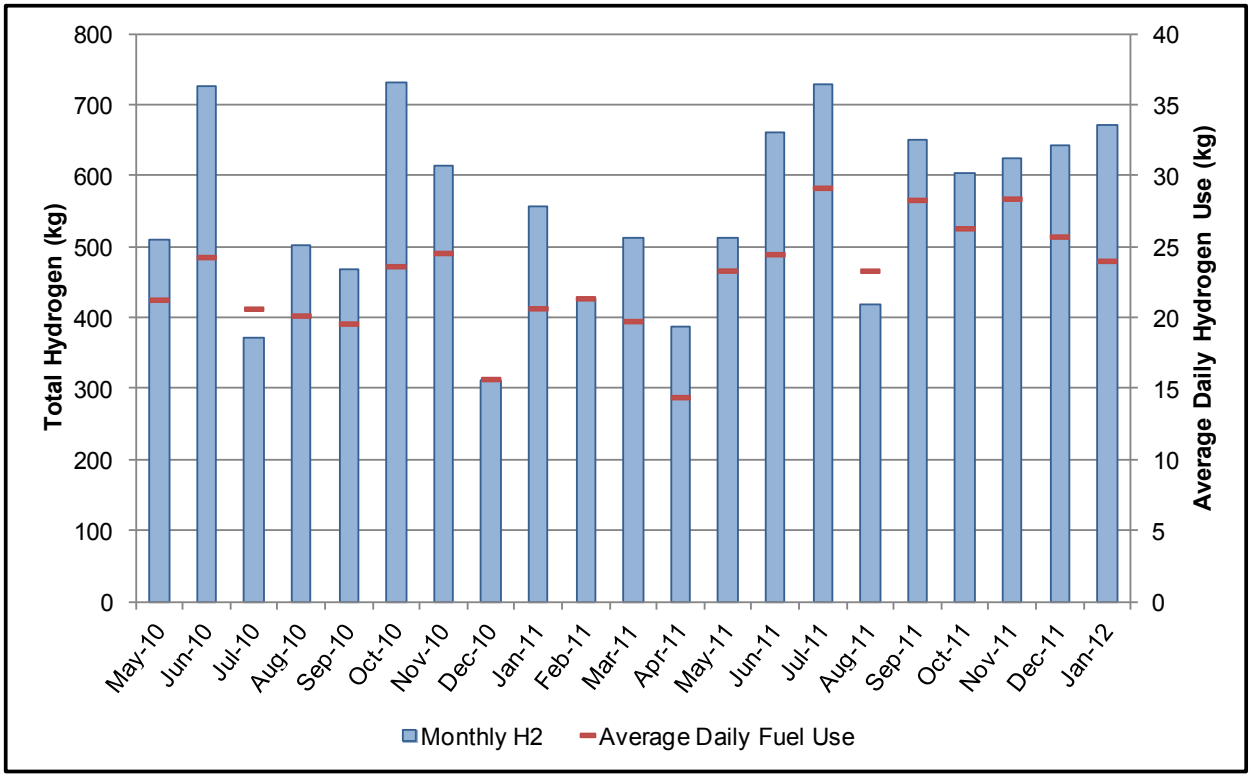

Figure 4. Total hydrogen dispensed per month and average hydrogen dispensed per day (excluding 0 kg days)

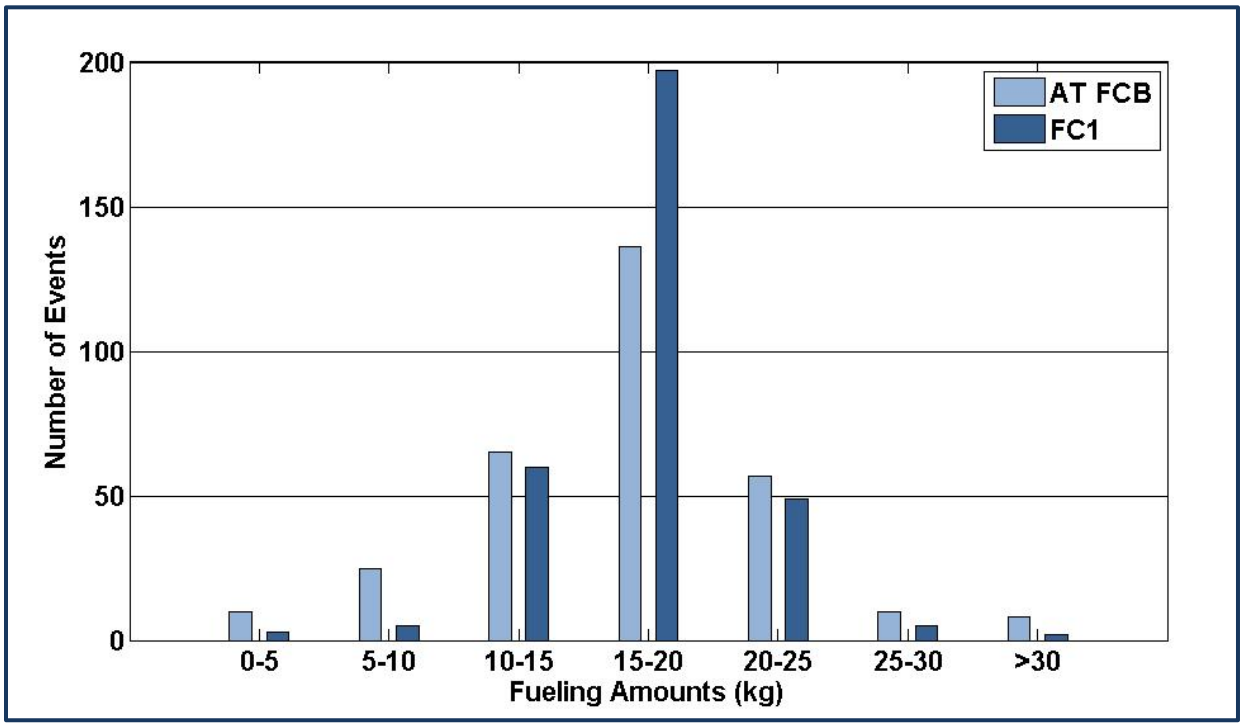

Figure 5. Histogram of fueling amounts by bus

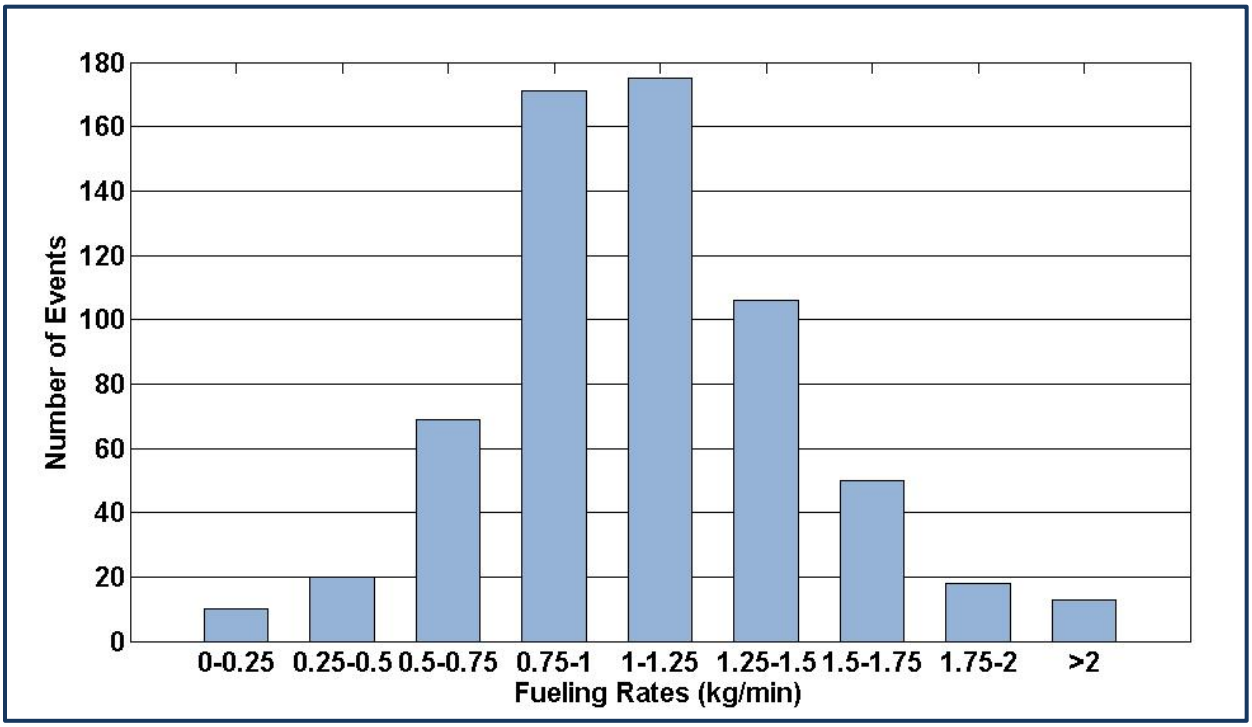

Figure 6. Histogram of fueling rates

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 cost for hydrogen during the evaluation period was $17.39 per kg (monthly costs ranged from a low of $4.04/kg to a high of $26.40/kg). Lower use of the station (when the buses were out of service) and higher maintenance costs contributed to higher monthly fuel costs. SunLine indicates that the best steady-state operating point for the reformer system would bring the average cost of hydrogen to around $8 per kg. This cost estimate is used in the cost calculations for the data results in the next section.

During the evaluation period, the CNG price at the dispenser for SunLine (not the public price) 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.

Evaluation Results

SunLine has operated the AT fuel cell bus in service since May 27, 2010. The focus of this report is the most recent operating data collected on the fuel cell and CNG buses from July 2011 through January 2012. 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. The overall system average speed is 13.9 mph. The AT fuel cell bus was used exclusively on Line 53 (average speed of 12.8 mph). The five CNG buses were randomly dispatched with the majority of time (82%) split between Line 111 (38% of time; 13.9 mph average speed), Line 14 (20% of time; 14.6 mph average speed), and Line 30 (25% of time; 10.8 mph average speed). Based on the dispatching information, the CNG buses operated at a slightly lower average speed than the fuel cell bus did during the evaluation period.

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 11,006 miles, and the fuel cell system accumulated more than 800 hours. For in-service days during the evaluation period, the AT fuel cell bus averaged 7.4 hours per day with a maximum of 12.9 hours in one day.

Table 2 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 34% that of the CNG buses. This low percentage for the fuel cell bus is primarily due to downtime because of issues with the traction batteries and hybrid system.

Table 2. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Odometer[7]	Total Mileage	Months	Monthly Average
AT FCB	**33,010**	**43,375**	**11,006**	**7**	**1,572**
603 CNG	161,166	188,681	27,685	7	3,955
604 CNG	141,107	170,540	29,767	7	4,252
605 CNG	155,704	183,884	28,345	7	4,049
606 CNG	149,283	188,281	39,326	7	5,618
608 CNG	154,517	192,305	38,109	7	5,444
Total CNG			**163,232**	**35**	**4,664**

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.

[7] During the data period, SunLine switched from recording hubodometers to recording bus odometers. All mileage is accounted for in the total mileage; however a direct subtraction of the odometer readings will not give an accurate number.

Figure 7 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 62% of the time during the evaluation period. As mentioned earlier, this unavailability was caused by problems with the batteries and the hybrid system. The low point was in August, when the bus was in service for only five days. First the bus was down for a week because of a hydrogen leak at a PRD valve. Later during that month, battery issues caused the bus to be down for more than two weeks. The availability for the CNG buses dropped during the period because of accidents that caused significant downtime for two of the five buses. In both cases, the buses were out of service for nearly two months for repair.

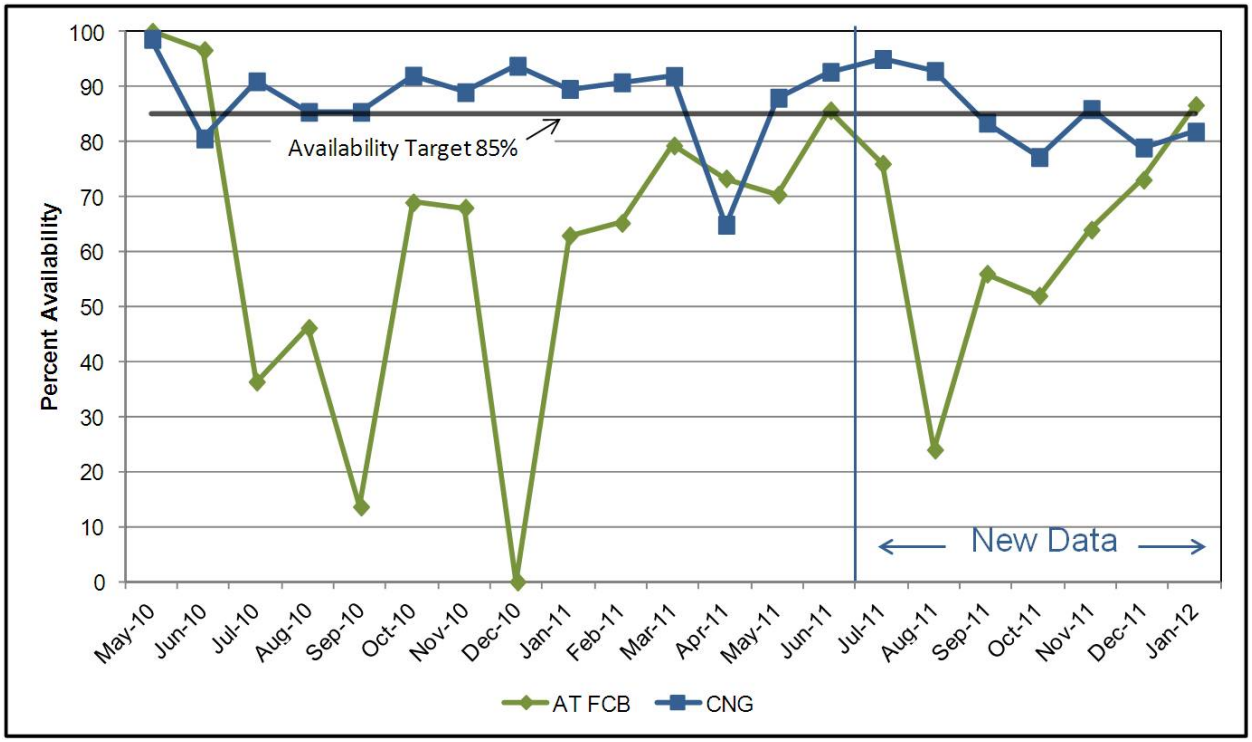

Figure 7. Availability for study bus groups

Table 3 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 62% and the average availability for the CNG buses was 85%. As discussed, the primary issues that kept the fuel cell bus out of service were downtime for traction batteries (50%), hybrid propulsion system (29%), and SunLine maintenance (16%). Repair time for accident damage was the primary reason for the CNG buses to be out of service.

Table 3. Summary of Reasons for Availability and Unavailability of Buses for Service

Category	AT FCB		CNG Buses	
	Number	Percent	Number	Percent
Planned work days	181		972	
Days available	113	62	830	85
Available	**113**	**100**	**830**	**100**
On-route	108	96	801	97
Event/demonstration	5	4	1	0
Training	0	0	0	0
Not used	0	0	28	3
Unavailable	**68**	**100**	**144**	**100**
Fuel cell propulsion	4	6	0	0
Hybrid propulsion	20	29	0	0
Traction batteries	34	50	0	0
SunLine maintenance	11	16	142	100
Fueling unavailable	0	0	0	0

Fuel Economy and Cost

Table 4 shows hydrogen and CNG fuel consumption and fuel economy for the study bus groups during the evaluation period. Using the GGE fuel economy of the CNG buses as a baseline, the AT fuel cell bus had a fuel economy 1.8 times higher than that of the CNG buses. Figure 8 shows the average fuel economy for each of the study bus groups.

The fuel costs per mile for the study bus groups for the evaluation period were $1.49 per mile for the fuel cell bus and $0.30 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 $0.92 per GGE is much lower than the typical diesel fuel average cost per gallon.

Table 4. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg) or CNG (GGE)	Miles per kg or Miles per GGE	Diesel Equivalent Amount (Gallon)	Miles per Gallon (DGE)
AT FCB	**11,006**	**2,046.0**	**5.38**	**1,810.7**	**6.08**
603 CNG	27,685	9,374.5	2.95	8,390.1	3.30
604 CNG	29,767	10,298.1	2.89	9,216.8	3.23
605 CNG	28,345	9,069.9	3.13	8,117.6	3.49
606 CNG	39,326	12,850.0	3.06	11,500.7	3.42
608 CNG	38,109	12,549.9	3.04	11,232.2	3.39
CNG Total	**163,232**	**54,142**	**3.01**	**48,457**	**3.37**

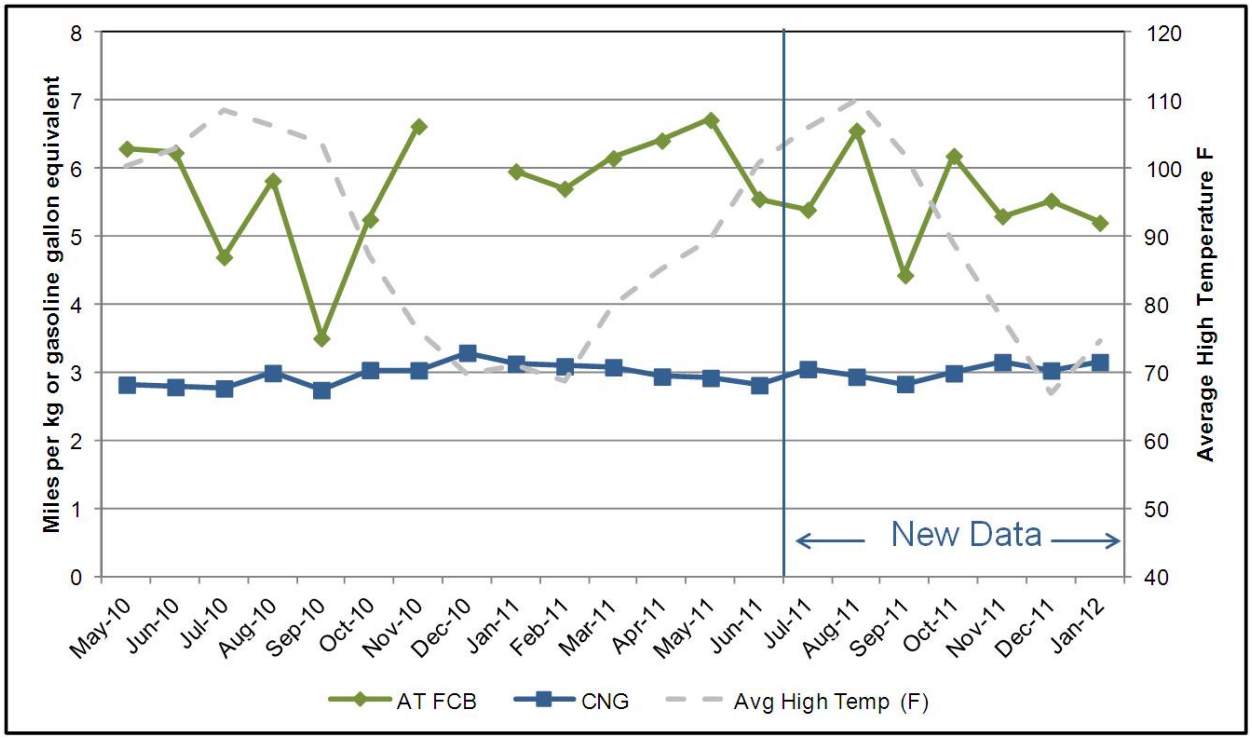

Figure 8. Average fuel economy (miles per kg or miles per GGE)

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 5 shows total maintenance costs for the AT fuel cell bus and CNG buses. The CNG buses have total maintenance costs 74% lower than those of the AT fuel cell bus. The parts costs continue to be low for the AT fuel cell bus because they typically are covered by the manufacturers for most of the propulsion system maintenance; however, SunLine's mechanics do nearly all of the work.

Table 5. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Cost ($) per Mile
AT FCB	**11,006**	**$78.72**	**281.00**	**$1.28**
603 CNG	27,685	$2,141.32	114.00	$0.28
604 CNG	29,767	$3,097.27	166.25	$0.38
605 CNG	28,345	$2,989.86	177.00	$0.42
606 CNG	39,326	$3,665.35	184.25	$0.33
608 CNG	38,109	$2,955.24	162.25	$0.29
Total CNG	**163,232**	**$14,849.04**	**803.75**	**$0.34**

Maintenance Costs Separated by System – Table 6 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 cab, body, and accessories. The same categories made up the highest percentage of maintenance costs for the CNG buses, but in a different order. The two accidents for the baseline CNG buses resulted in an increase in cab, body, and accessories maintenance costs to 36% of the total costs. The propulsion-related costs had the next highest percentage, followed by PMI.

Table 6. Vehicle System Maintenance Cost per Mile by System (Evaluation Period)

System	AT FCB Cost per Mile ($)	AT FCB Percent of Total (%)	CNG Cost per Mile ($)	CNG Percent of Total (%)
Cab, body, and accessories	0.11	8	0.12	35
Propulsion-related	0.89	70	0.10	29
PMI	0.14	11	0.08	24
Lighting	0.08	6	0.01	3
HVAC	0.05	4	0.01	3
Brakes	0.00	0	0.00	0
Frame, steering, and suspension	0.00	0	0.00	0
Axles, wheels, and drive shaft	0.00	0	0.00	0
General air system repairs	0.00	0	0.01	3
Tires	0.01	1	0.01	3
Total	**1.28**	**100**	**0.34**	**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 7 categorizes the propulsion-related system repairs for the study bus groups during the evaluation period (not including warranty). The fuel cell bus was under warranty during the entire evaluation period, and the CNG buses have continued to be under warranty for some engine issues. The SunLine mechanics continue to handle nearly all of the maintenance on the AT fuel cell bus themselves, with support as needed by the manufacturers. However, the manufacturers generally supplied the parts under warranty for the propulsion system, so the costs for these parts are not included.

- **Total propulsion-related –** The AT 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 –** Costs for this system for the study bus groups were low or zero.
- **Fuel system –** Costs for this system for the study bus groups were low or zero.
- **Powerplant and electric propulsion –** The AT fuel cell bus maintenance reported here was almost exclusively labor for SunLine mechanics—for troubleshooting and making the repairs on the bus or supporting manufacturer work on the bus. There are no electric propulsion costs for the CNG buses because they are not hybrids. The preventive maintenance for the CNG buses was almost exclusively in the powerplant category.
- **Non-lighting electrical (charging, cranking, and ignition) –** The AT fuel cell bus had no costs in this category. The CNG buses mostly had preventive maintenance repairs in this category for spark plugs at the 24,000-mile preventive-maintenance cycle for each bus.
- **Air intake –** Costs for this system for the study bus groups were low or zero.
- **Cooling –** Costs for this system for the study bus groups were low or zero
- **Transmission –** Costs for this system for the study bus groups were low or zero.

Table 7. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	AT FCB	CNG
Mileage	11,006	163,232
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	29.52	8,364.64
Labor hours	194.75	166.75
Total cost ($)	9,767.02	16,702.14
Total cost ($) per mile	**0.89**	**0.10**
Exhaust System Repairs		
Parts cost ($)	0.00	803.41
Labor hours	0.0	4.0
Total cost ($)	0.00	1,003.41
Total cost ($) per mile	**0.00**	**0.01**
Fuel System Repairs		
Parts cost ($)	0.00	271.86
Labor hours	0.0	0.0
Total cost ($)	0.00	271.86
Total cost ($) per mile	**0.00**	**0.00**
Powerplant System Repairs		
Parts cost ($)	29.52	3,718.65
Labor hours	90.25	102.25
Total cost ($)	4,542.02	8,831.15
Total cost ($) per mile	**0.41**	**0.05**
Electric Propulsion System Repairs		
Parts cost ($)	0.00	0.00
Labor hours	67.0	0.0
Total cost ($)	3,350.00	0.00
Total cost ($) per mile	**0.30**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	0.00	2,692.92
Labor hours	0.0	15.5
Total cost ($)	0.00	3,467.92
Total cost ($) per mile	**0.00**	**0.02**
Air Intake System Repairs		
Parts cost ($)	0.00	327.32
Labor hours	0.0	0.0
Total cost ($)	0.00	327.32
Total cost ($) per mile	**0.00**	**0.00**
Cooling System Repairs		
Parts cost ($)	0.00	244.03
Labor hours	37.5	31.5
Total cost ($)	1,875.00	1,819.03
Total cost ($) per mile	**0.17**	**0.01**
Transmission System Repairs		
Parts cost ($)	0.00	83.99
Labor hours	0	13.5
Total cost ($)	0.00	758.99
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 8 shows the RCs and miles between roadcalls (MBRC) for each study bus group in two categories: all RCs and propulsion-related-only RCs. All nine RCs for the AT bus were attributed to the propulsion system. Of these, only three were fuel cell related, resulting in a fuel cell system MBRC of 3,669.

Table 8. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC
AT FCB	**11,006**	**9**	**1,223**	**9**	**1,223**
603 CNG	27,685	0		0	
604 CNG	29,767	1	29,767	0	
605 CNG	28,345	0		0	
606 CNG	39,326	2	19,663	2	19,663
608 CNG	38,109	0		0	
Total CNG	**163,232**	**3**	**54,411**	**2**	**81,616**

Summary of Experience to Date

The AT FCB has been in operation for more than 20 months and each of the partners feel positive about the project and the technology. Many of the early issues were resolved; however, a few issues have continued and those issues are discussed in this section. Maintenance staff has come up to speed on the new bus systems and has learned to diagnose and repair most issues. Bluways and Ballard have only needed to come to SunLine on a few occasions to support maintenance of this bus. Ballard and Bluways both feel the project is going well and that they have addressed the majority of the problems experienced in the early demonstration period. This section summarizes the challenges and achievements that the team has had so far in the demonstration.

Pilot Bus – The AT FCB was originally designed as the pilot bus to a much larger project in British Columbia, Canada. The bus was delivered in 2009 and the transit operator, BC Transit, ran the bus through a series of acceptance and operational tests over a period of about six months. Prior to delivery to SunLine, Bluways upgraded this pilot bus to nearly match the final design of the BC Transit buses. Although this bus has been upgraded, it is not an exact match to the 20 fuel cell buses at BC Transit. This has caused some complications with maintenance documentation for the actual final integration of the systems on this bus.

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

Hydrogen Leak – During regular scheduled maintenance, SunLine detected a minor leak at a check valve in the hydrogen system. The leak was repaired and the PRD valve was replaced.

Propulsion System Issues – Problems that caused downtime for the bus included a faulty motor controller and coolant flow sensor. The motor controller issue was intermittent, which made it more difficult and time-consuming to diagnose. Replacing the controller cable resolved the major issues, but other issues surfaced, so the motor controller was replaced. SunLine had some difficulty getting the correct part, which resulted in a longer downtime than usual.

Traction Battery Issues – This bus has had some issues with the traction batteries, controller, and charger that have been resolved during the evaluation period for this report. Bluways has provided an external battery charger so that the batteries can be balanced on a more regular basis. Many hybrid electric propulsion systems use this type of strategy—external balancing of the batteries for better electric storage performance and longevity of the batteries. SunLine reports that the regular equalization of the batteries has had a positive effect on the bus performance.

Air Conditioning Issues – The extreme high summer temperatures at SunLine (in the desert) have resulted in problems with the air conditioning. The hybrid system is configured to cool the batteries with air from the bus's air conditioning unit. The summer heat in SunLine's service area affects how well the air conditioning can keep up with demand for cooling passengers while keeping the batteries within proper operating temperature range. Bluways has worked with ThermoKing to resolve the integration issues and believes these issues are now resolved.

What's Next for SunLine

This report covers SunLine's operation of the fuel cell and CNG buses from July 2011 through January 2012. The agency will continue working with DOE/NREL to collect data on the buses in service. The next report is expected to be published in late 2012.

SunLine will continue to operate the AT fuel cell bus as well as its newest fuel cell electric bus, the American Fuel Cell Bus (AFCB). Funded under the FTA's National Fuel Cell Bus Program, the AFCB 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. The bus was delivered to the agency in late 2011 and is now in service.

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Fuel Cell Bus Related Reports

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

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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

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Number of vehicles	1	1	5	5
Period used for fuel and oil op analysis	5/10-1/12	7/11-1/12	5/10-1/12	7/11-1/12
Total number of months in period	21	7	21	7
Fuel and oil analysis base fleet mileage	31,750	11,006	483,237	163,232
Period used for maintenance op analysis	5/10-1/12	7/11-1/12	5/10-1/12	7/11-1/12
Total number of months in period	21	7	21	7
Maintenance analysis base fleet mileage	31,857	11,006	483,237	163,232
Average monthly mileage per vehicle	1,517	1,572	4,602	4,664
Availability	62%	62%	88%	85%
Fleet fuel usage in CNG GGE/H_2 kg	5,518	2,046	162,392	51,142
Roadcalls	13	9	27	3
RCs MBRC	2,451	1,223	17,898	54,411
Propulsion roadcalls	13	9	15	2
Propulsion MBRC	2,451	1,223	32,216	81,616
Fleet miles/kg hydrogen or CNG GGE	5.75	5.38	2.98	3.01
(1.13 kg H_2/gal diesel fuel)				
Representative fleet MPG (energy equiv)	6.50	6.08	3.32	3.37
Hydrogen cost per kg	8.00	8.00		
GGE cost			0.93	0.91
Fuel cost per mile	**1.39**	**1.49**	**0.31**	**0.30**
Total scheduled repair cost per mile	0.16	0.16	0.12	0.11
Total unscheduled repair cost per mile	0.83	1.13	0.26	0.23
Total maintenance cost per mile	**0.99**	**1.28**	**0.39**	**0.34**
Total operating cost per mile	**2.38**	**2.77**	**0.70**	**0.64**

Maintenance Costs

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Fleet mileage	31,857	11,006	483,237	163,232
Total parts cost	2,093.77	78.72	59,090.52	14,849.04
Total labor hours	591.50	281.0	2,543.1	803.8
Average labor cost (@ $50.00 per hour)	29,575.00	14,050.00	127,152.50	40,187.50
Total maintenance cost	31,602.94	14,128.72	186,243.02	55,036.54
Total maintenance cost per bus	31,602.94	14,128.72	37,248.60	11,007.31
Total maintenance cost per mile	**0.99**	**1.28**	**0.39**	**0.34**

Maintenance Costs by Vehicle System

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Fleet mileage	31,857	11,006	483,237	163,232
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	89.16	29.52	31,115.28	8,364.64
Labor hours	317.50	194.75	513.25	166.75
Average labor cost	15,875.00	9,737.50	25,662.50	8,337.50
Total cost (for system)	15,964.16	9,767.02	56,777.78	16,702.14
Total cost (for system) per bus	15,964.16	9,767.02	11,355.56	3,340.43
Total cost (for system) per mile	**0.50**	**0.89**	**0.12**	**0.10**
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	972.36	803.41
Labor hours	0.0	0.0	6.0	4.0
Average labor cost	0.00	0.00	300.00	200.00
Total cost (for system)	0.00	0.00	1,272.36	1,003.41
Total cost (for system) per bus	0.00	0.00	254.47	200.68
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.01**
Fuel System Repairs (ATA VMRS 44)				
Parts cost	4.45	0.00	948.12	271.86
Labor hours	1.0	0.0	0.5	0.0
Average labor cost	50.00	0.00	25.00	0.00
Total cost (for system)	54.45	0.00	973.12	271.86
Total cost (for system) per bus	54.45	0.00	194.62	54.37
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	42.52	29.52	13,658.25	3,718.65
Labor hours	148.3	90.3	323.0	102.3
Average labor cost	7,412.50	4,512.50	16,150.00	5,112.50
Total cost (for system)	7,455.02	4,542.02	29,808.25	8,831.15
Total cost (for system) per bus	7,455.02	4,542.02	5,961.65	1,766.23
Total cost (for system) per mile	**0.23**	**0.41**	**0.06**	**0.05**
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	90.0	11.8	0.0	0.0
Average labor cost	4,500.00	587.50	0.00	0.00
Total cost (for system)	4,500.00	587.50	0.00	0.00
Total cost (for system) per bus	4,500.00	587.50	0.00	0.00
Total cost (for system) per mile	**0.14**	**0.0534**	**0.0000**	**0.0000**

Maintenance Costs by Vehicle System (continued)

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	0.00	0.00	12,363.06	2,692.92
Labor hours	13.5	0.0	86.5	15.5
Average labor cost	675.00	0.00	4,325.00	775.00
Total cost (for system)	675.00	0.00	16,688.06	3,467.92
Total cost (for system) per bus	675.00	0.00	3,337.61	693.58
Total cost (for system) per mile	**0.02**	**0.00**	**0.03**	**0.02**
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	0.00	0.00	1,079.29	327.32
Labor hours	0.0	0.0	0.0	0.0
Average labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	1,079.29	327.32
Total cost (for system) per bus	0.00	0.00	215.86	65.46
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Cooling System Repairs (ATA VMRS 42)				
Parts cost	42.19	0.00	1,084.51	244.03
Labor hours	64.8	37.5	81.3	31.5
Average labor cost	3,237.50	1,875.00	4,062.50	1,575.00
Total cost (for system)	3,279.69	1,875.00	5,147.01	1,819.03
Total cost (for system) per bus	3,279.69	1,875.00	1,029.40	363.81
Total cost (for system) per mile	**0.10**	**0.17**	**0.01**	**0.01**
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0.00	0.00	679.25	222.46
Labor hours	0.0	0.0	0.0	0.0
Average labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	679.25	222.46
Total cost (for system) per bus	0.00	0.00	135.85	44.49
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)				
Parts cost	0.00	0.00	58.72	42.86
Labor hours	4.5	0.0	34.5	20.5
Average labor cost	225.00	0.00	1,725.00	1,025.00
Total cost (for system)	225.00	0.00	1,783.72	1,067.86
Total cost (for system) per bus	225.00	0.00	356.74	213.57
Total cost (for system) per mile	**0.01**	**0.00**	**0.00**	**0.01**

Maintenance Costs by Vehicle System (continued)

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Brake System Repairs (ATA VMRS 13)				
Parts cost	4.99	0.00	4,791.59	70.99
Labor hours	0.0	0.0	86.3	0.5
Average labor cost	0.00	0.00	4,312.50	25.00
Total cost (for system)	4.99	0.00	9,104.09	95.99
Total cost (for system) per bus	4.99	0.00	1,820.82	19.20
Total cost (for system) per mile	**0.00**	**0.00**	**0.02**	**0.00**
Transmission Repairs (ATA VMRS 27)				
Parts cost	0.00	0.00	330.44	83.99
Labor hours	0.0	0.0	16.0	13.5
Average labor cost	0.00	0.00	800.00	675.00
Total cost (for system)	0.00	0.00	1,130.44	758.99
Total cost (for system) per bus	0.00	0.00	226.09	151.80
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.01**
Inspections Only - no parts replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	97.5	32.3	782.0	236.3
Average labor cost	4,875.00	1,612.50	39,100.00	11,812.50
Total cost (for system)	4,875.00	1,612.50	39,100.00	11,812.50
Total cost (for system) per bus	4,875.00	1,612.50	7,820.00	2,362.50
Total cost (for system) per mile	**0.15**	**0.15**	**0.08**	**0.07**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	1,501.13	15.65	15,912.37	5,549.53
Labor hours	107.0	23.0	827.5	284.3
Average labor cost	5,350.00	1,150.00	41,375.00	14,212.50
Total cost (for system)	6,851.13	1,165.65	57,287.37	19,762.03
Total cost (for system) per bus	6,851.13	1,165.65	11,457.47	3,952.41
Total cost (for system) per mile	**0.22**	**0.11**	**0.12**	**0.12**
HVAC System Repairs (ATA VMRS 01)				
Parts cost	22.73	0.00	2,795.15	276.93
Labor hours	37.0	11.0	70.3	19.5
Average labor cost	1,850.00	550.00	3,512.50	975.00
Total cost (for system)	1,872.73	550.00	6,307.65	1,251.93
Total cost (for system) per bus	1,872.73	550.00	1,261.53	250.39
Total cost (for system) per mile	**0.06**	**0.05**	**0.01**	**0.01**

Maintenance Costs by Vehicle System (continued)

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Lighting System Repairs (ATA VMRS 34)				
Parts cost	180.32	30.00	1,349.07	456.67
Labor hours	21.0	17.0	68.8	31.3
Average labor cost	1,050.00	850.00	3,437.50	1,562.50
Total cost (for system)	1,230.32	880.00	4,786.57	2,019.17
Total cost (for system) per bus	1,230.32	880.00	957.31	403.83
Total cost (for system) per mile	**0.04**	**0.08**	**0.01**	**0.01**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	226.06	0.00	2,816.23	87.42
Labor hours	2.3	0.0	37.5	5.8
Average labor cost	112.50	0.00	1,875.00	287.50
Total cost (for system)	338.56	0.00	4,691.23	374.92
Total cost (for system) per bus	338.56	0.00	938.25	74.98
Total cost (for system) per mile	**0.01**	**0.00**	**0.01**	**0.00**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	3.55	3.55	251.11	0.00
Labor hours	0.0	0.0	22.0	0.0
Average labor cost	0.00	0.00	1,100.00	0.00
Total cost (for system)	3.55	3.55	1,351.11	0.00
Total cost (for system) per bus	3.55	3.55	270.22	0.00
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Tire Repairs (ATA VMRS 17)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	4.8	3.0	100.3	38.3
Average labor cost	237.50	150.00	5,012.50	1,912.50
Total cost (for system)	237.50	150.00	5,012.50	1,912.50
Total cost (for system) per bus	237.50	150.00	1,002.50	382.50
Total cost (for system) per mile	**0.01**	**0.01**	**0.01**	**0.01**

Notes

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

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

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

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Number of vehicles	1	1	5	5
Period used for fuel and oil op analysis	5/10-1/12	7/11-1/12	5/10-1/12	7/11-1/12
Total number of months in period	21	7	21	7
Fuel and oil analysis base fleet kilometers	51,095	17,712	777,673	262,689
Period used for maintenance op analysis	5/10-1/12	7/11-1/12	5/10-1/12	7/11-1/12
Total number of months in period	21	7	21	7
Maintenance analysis base fleet kilometers	51,267	17,712	777,673	262,689
Average monthly kilometers per vehicle	2,441	2,530	7,406	7,505
Availability	62%	62%	88%	85%
Fleet fuel usage in CNG liter equiv/H2 kg	5,027	1,555	614,653	183,412
Roadcalls	13	9	27	3
RCs KMBRC	3,944	1,968	28,803	87,563
Propulsion roadcalls	13	9	15	2
Propulsion KMBRC	3,944	1,968	51,845	131,345
Fleet kg hydrogen/100 km	9.84	8.78	79.04	69.82
(1.13 kg H_2/gal diesel fuel)				
Rep. fleet fuel consumption (L/100 km)	32.95	29.41	70.74	62.49
Hydrogen cost per kg	8.00	8.00		
GGE cost/liter			0.24	0.26
Fuel cost per kilometer	**0.79**	**0.70**	**0.19**	**0.18**
Total scheduled repair cost per kilometer	0.10	0.10	0.08	0.07
Total unscheduled repair cost per kilometer	0.52	0.70	0.16	0.14
Total maintenance cost per kilometer	**0.62**	**0.80**	**0.24**	**0.21**
Total operating cost per kilometer	**1.40**	**1.50**	**0.43**	**0.39**

Maintenance Costs

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Fleet mileage	51,267	17,712	777,673	262,689
Total parts cost	2,027.94	78.72	59,090.52	14,849.04
Total labor hours	591.50	281.0	2543.1	803.8
Average labor cost (@ $50.00 per hour)	29,575.00	14,050.00	127,152.50	40,187.50
Total maintenance cost	31,602.94	14,128.72	186,243.02	55,036.54
Total maintenance cost per bus	31,602.94	14,128.72	37,248.60	11,007.31
Total maintenance cost per kilometer	**0.62**	**0.80**	**0.24**	**0.21**