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

L. Eudy and K. Chandler

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Technical Report
NREL/TP-5600-57560
January 2013

Contract No. DE-AC36-08GO28308

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Prepared under Task No. HT12.8210

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Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721. Bus photo by Leslie Eudy, NREL.

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Acknowledgements

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

U.S. Department of Energy
Jason Marcinkoski

U.S. Federal Transit Administration
Walter Kulyk
Christina Gikakis

National Renewable Energy Laboratory
Keith Wipke
George Sverdrup

SunLine Transit Agency
C. Mikel Oglesby
Tommy Edwards
Mike Morrow
Polo Del Toro
Mike Hayes

Ballard Power Systems
Jeff Grant
Daljit Bawa
Byron Somerville

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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
FCEB	fuel cell electric bus
ft	feet
FTA	Federal Transit Administration
GGE	gasoline gallon equivalent
H2	hydrogen
HHICE	hydrogen hybrid internal combustion engine
hp	horsepower
HVAC	heating, ventilation, and air conditioning
in.	inches
kg	kilograms
kW	kilowatts
lb	pounds
LHV	lower heating value
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. In May 2010, SunLine began demonstrating the advanced technology (AT) fuel cell bus. The AT fuel cell bus has a hybrid electric propulsion system based on the Siemens ELFA system, integrated by Bluways with Ballard's FCvelocity HD6 fuel cell power system, and lithium-based hybrid batteries from Valence. The design incorporates the latest improvements to reduce weight and increase reliability and performance. This report describes operations at SunLine for the AT fuel cell bus and five compressed natural gas (CNG) buses.

Since it first went into service in May 2010, the fuel cell bus has driven more than 48,000 miles and has accumulated more than 3,600 fuel cell system hours (for an average operating speed of 12.3 mph). Problems encountered during the demonstration include some air conditioning issues during the hot desert summer, fuel cell power system issues, traction battery issues, and 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 three 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 February 2012 through November 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 – 11/12	2/12 – 11/12	5/10 – 11/12	2/12 – 11/12
Number of months	31	10	31	10
Total mileage in period	48,428	16,571	683,023	199,786
Average monthly mileage per bus	1,562	1,657	4,406	3,996
Availability (85% is target)	62	62	85	78
Fuel economy (miles/kg or GGE)	5.57	5.25	2.92	2.79
Miles between roadcalls (MBRC) – all	3,229	8,286	14,818	10,511
MBRC – propulsion only	3,229	8,286	29,636	24,963
MBRC – fuel cell system only	8,071	16,571	N/A	N/A
Total maintenance, $/mile	$0.99	$0.80	$0.43	$0.47
Maintenance – propulsion only, $/mile	$0.60	$0.60	$0.17	$0.21

In September 2012, DOE and the Federal Transit Administration (FTA) published performance, cost, and durability targets for fuel cell electric buses (FCEBs). These targets, established with industry input, include interim targets for 2016 and ultimate targets for commercialization. Table ES-2 summarizes the current performance results of the AT fuel cell bus compared to these targets. This table will be included in all future NREL reports.

Table ES-2. Summary of FCEB Performance Compared to DOE/FTA Targets[1]

	Units	Jan 2013 Report[a]	2012 Status[1]	2016 Target[1]	Ultimate Target[1]
Bus lifetime	years/miles	3/59,946[b]	5/100,000	12/500,000	12/500,000
Power plant lifetime[c]	hours	4,872[d]	12,000	18,000	25,000
Bus availability	%	62	60	85	90
Fuel fills[e]	per day	1	1	1 (< 10 min)	1 (< 10 min)
Bus cost[f]	$	1,200,000[g]	2,000,000	1,000,000	600,000
Power plant cost[c,f]	$	N/A[h]	700,000	450,000	200,000
Hydrogen storage cost	$	N/A[h]	100,000	75,000	50,000
Roadcall frequency (Bus/fuel cell system)	miles between roadcalls	8,286/ 16,571	2,500/ 10,000	3,500/ 15,000	4,000/ 20,000
Operation time	hours per day/days per week	7 – 14/ 5 – 7	19/7	20/7	20/7
Scheduled and unscheduled maintenance cost[i]	$/mile	0.80	1.20	0.75	0.40
Range	miles	226[j]	270	300	300
Fuel economy	miles per gallon diesel equivalent	6.29	7	8	8

a Summary of the results for the AT fuel cell bus in this report: data from February 2012 – November 2012.
b Accumulated totals for the AT fuel cell bus through November 2012; this buses has not reached end of life; targets are for lifetime.
c For the DOE/FTA targets, the power plant is defined as the fuel cell system and the battery system. The fuel cell system includes supporting subsystems such as the air, fuel, coolant, and control subsystems. Power electronics, electric drive, and hydrogen storage tanks are excluded.
d The status for power plant hours is for the fuel cell system only; battery lifetime hours were not available.
e Multiple sequential fuel fills should be possible without increase in fill time.
f Cost targets projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only and does not represent an anticipated level of sales.
g SunLine's purchase price for the AT bus; price was prorated based on the fact that it was previously demonstrated at BC Transit.
h Capital costs for subsystems are not currently reported by the manufacturers.
i Excludes mid-life overhaul of power plant.
j Based on fuel economy and tank capacity.

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

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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 Ballard's FCvelocity HD6 150-kW fuel cell power system. The energy storage system consists of lithium-ion batteries from Valence. SunLine is collaborating with the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) to evaluate the bus in revenue service. SunLine operates the bus in its service area and supplies hydrogen from a natural gas reformer. NREL has published three reports documenting SunLine's experience and the performance of the bus including data collected from May 2010 through January 2012.[2,3,4] This report provides an update to the previous reports and covers data collected through November 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. Since its first evaluation of a hydrogen fuel cell transit bus in 2000, NREL has documented results of a total of 28 fuel cell buses 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.[5]

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 (see Figure 1). 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.

[2] 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.
[3] SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Second Results Report, NREL/TP-5600-52349, August 2011, www.nrel.gov/hydrogen/pdfs/52349-1.pdf.
[4] SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Third Results Report, NREL/TP-5600-54427, May 2012, www.nrel.gov/hydrogen/pdfs/54427.pdf.
[5] 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.

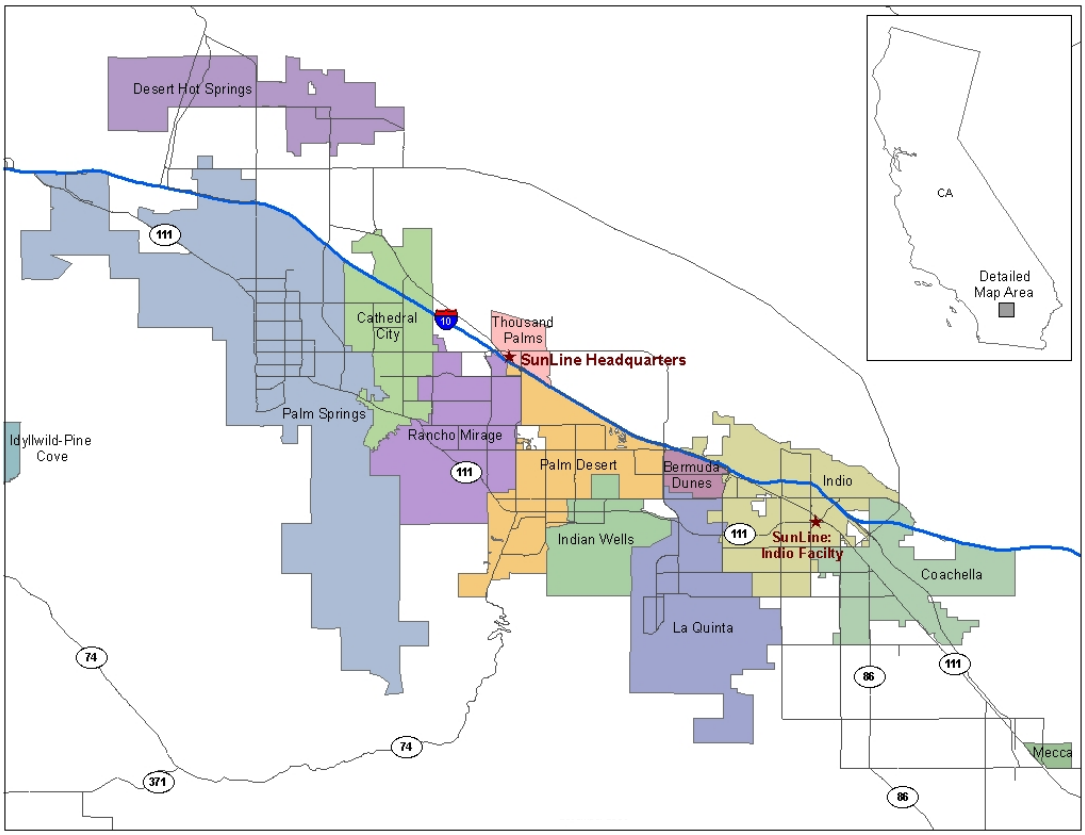

Figure 1. Map of SunLine's service area in Southern California's Coachella Valley

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. This report describes SunLine's operation of the AT fuel cell transit bus in revenue service. Five CNG buses operating from the same SunLine location are being used as a baseline comparison. Table 1 provides bus system descriptions for the AT fuel cell bus and CNG buses that were studied in this evaluation.

The AT fuel cell bus represents a sixth generation of hydrogen-fueled buses operated by the agency. The bus, shown in Figure 2, 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 by Bluways,[6] Ballard, and New Flyer. The hybrid electric propulsion system is based on the Siemens ELFA system. The primary power source is Ballard's FCvelocity HD6 150-kW proton exchange membrane (PEM) fuel cell module. The energy storage system consists of Valence lithium-ion batteries. 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 pilot testing in Canada, it was returned to Bluways where it was upgraded to match the final design of the rest of

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

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 baseline 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. 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, PEM	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[7]	$402,900

Figure 2. SunLine's advanced technology fuel cell bus

[7] This is SunLine's purchase price for the AT bus; the price was prorated based on the fact that it was previously demonstrated at BC Transit.

Figure 3. New Flyer CNG bus at SunLine

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 to the SunLine property via a high-pressure natural gas line and then compressed to 3,600 psi for dispensing into the vehicles. SunLine produces hydrogen onsite using a HyRadix natural gas reformer. SunLine typically operates the reformer at 4.5 kg per hour to meet current hydrogen demand, although the unit is capable of producing up to 9 kg of hydrogen per hour. Onsite storage of hydrogen is approximately 180 kg of hydrogen compressed to 6,000 psi for dispensing into the buses at 5,000 psi. SunLine estimates that this hydrogen fueling infrastructure can produce enough hydrogen to comfortably operate five full-size transit buses without running out of fuel for the small hydrogen vehicles expected to be fueled at this station.

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 entire data collection period for this bus, SunLine operated three fuel cell buses in its service area:

- The AT fuel cell bus
- A Van Hool fuel cell bus with a fuel cell system from UTC Power (VH FCEB, retired in December 2011)
- An ElDorado fuel cell bus with a BAE Systems hybrid drive and Ballard fuel cell—the American Fuel Cell Bus (AFCB, began operation in December 2011).

To show overall performance of the station, the fueling analysis figures include total hydrogen dispensed from the station into all three buses. Figure 4 shows the total hydrogen dispensed per month into SunLine's fuel cell buses from May 2010 through November 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 82% of the calendar days during the period. The overall average daily use was 25.8 kg per day. During this period, SunLine dispensed a total of 19,879 kg of hydrogen. The months with the lowest hydrogen dispensed had downtime for one bus during that month. December 2010 and April 2011 correspond with downtime for the AT fuel cell bus. The AT FCEB was out of service the entire month of July 2012.

Figure 5 shows the distribution of hydrogen amounts dispensed per fill by bus. The buses were filled a total of 1,001 times during the evaluation period for a total of 18,434 kg hydrogen.[8] The average amount of hydrogen per fill was 18.4 kg per fill. Figure 6 shows a cumulative fueling rate histogram for the SunLine hydrogen station from December 2010 through November 2012. The overall average fueling rate was 1.0 kg per minute, and the average time for a fill was 18.5 minutes.

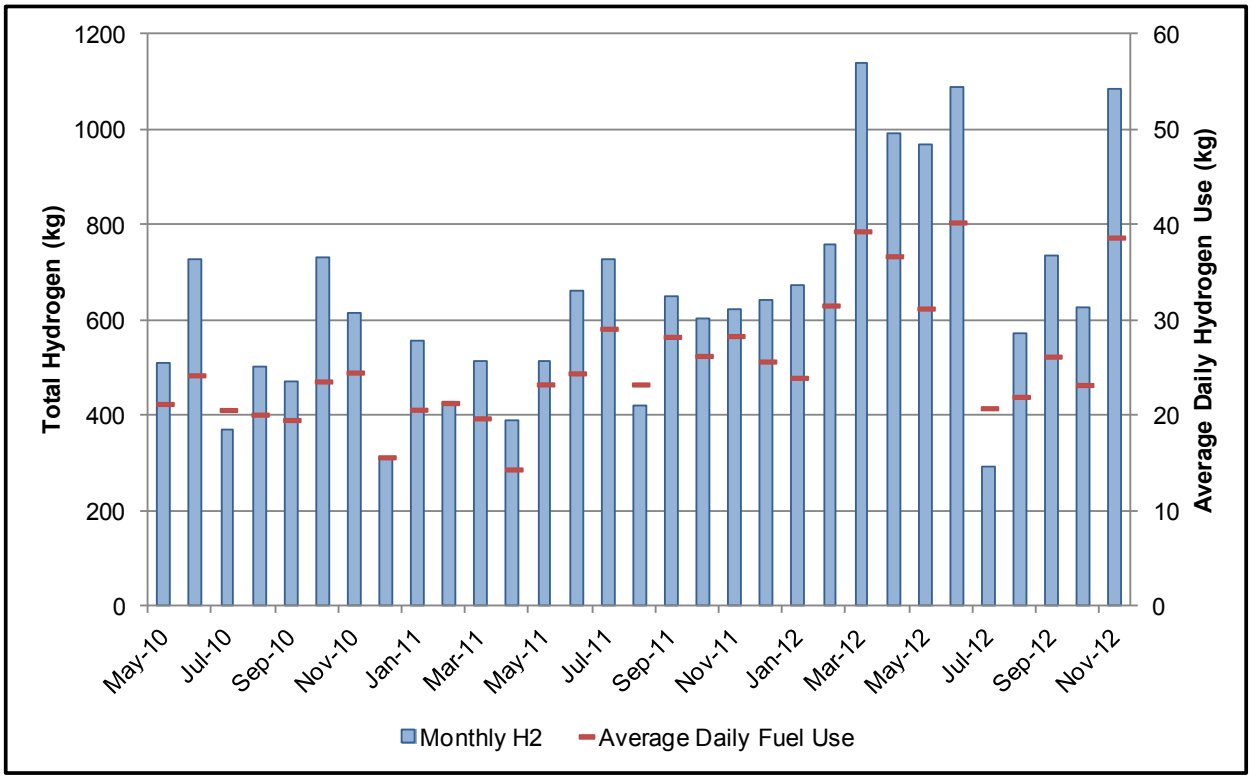

Figure 4. Total hydrogen dispensed per month and average hydrogen dispensed per day (excluding 0 kg days)

[8] 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.

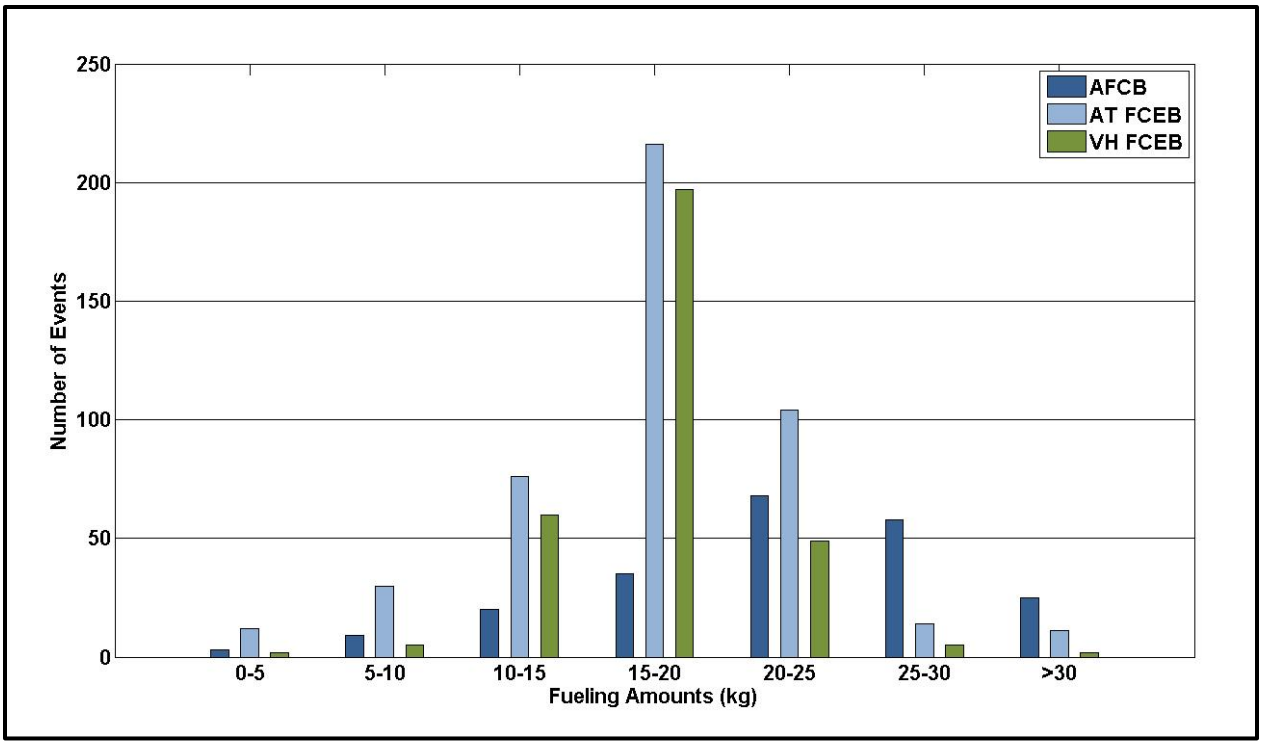

Figure 5. Histogram of fueling amounts by bus

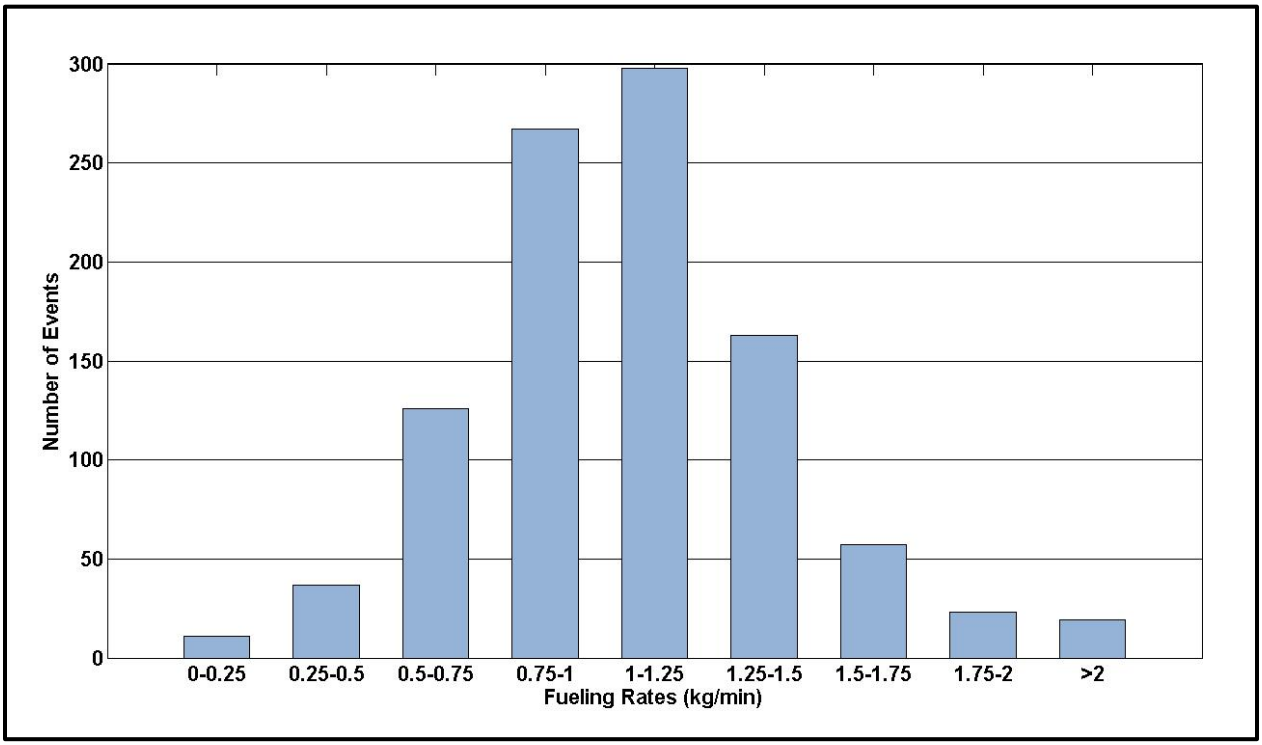

Figure 6. Histogram of fueling rates

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 2012 was $13.73 per kg (monthly costs ranged from a low of $7.66/kg to a high of $23.46/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.

The average CNG price at the dispenser for SunLine during 2012 (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 February 2012 through November 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 17.1 mph. The AT fuel cell bus was used exclusively on Line 53 (average speed of 14.7 mph). The five CNG buses were randomly dispatched with the majority of time (87%) split between Line 111 (39% of time; 16.2 mph average speed), Line 14 (17% of time; 18.1 mph average speed), Line 30 (19% of time; 13.1 mph average speed), and Line 70 (12% of time; 16.9 mph average speed). Based on the dispatching information, the CNG buses operated at a slightly higher average speed than the fuel cell bus did during the evaluation period.

Bus Use and Availability

Bus use and availability can indicate 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 16,571 miles, and the fuel cell system accumulated more than 1,520 hours. For in-service days during the evaluation period, the AT fuel cell bus averaged 7.25 hours per day with a maximum of 12.4 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 59% 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 the fuel cell system.

Table 2. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Odometer[9]	Total Mileage	Months	Monthly Average
AT FCEB	**43,375**	**59,946**	**16,571**	**10**	**1,657**
603 CNG	188,681	228,378	39,697	10	3,969
604 CNG	170,540	218,106	47,566	10	4,757
605 CNG	183,884	208,954	25,039	10	2,504
606 CNG	188,281	231,783	43,502	10	4,350
608 CNG	192,305	236,287	43,982	10	4,398
Total CNG			**199,786**	**50**	**3,995**

Availability is the percentage of time that the buses are planned for operation compared with the time the buses are actually available for that planned operation. Availability for all of NREL's evaluations is calculated by including the planned service days, which are typically every weekday. Weekends and holidays are included in the calculation only if the bus operated in service on those days. If a bus does not operate on the weekend or a holiday, it is not counted as unavailable. This strategy applies to both the AT fuel cell bus and the CNG buses. Figure 7 presents the overall monthly availability for the AT fuel cell bus and the CNG buses. The stacked bars show the total number of days the AT fuel cell bus was unavailable each month by primary system category. As shown in the chart, the availability goal is 85% for all buses.

Overall availability for the AT fuel cell bus was 62% of the time during the evaluation period. This unavailability was caused by problems with the batteries and the fuel cell system. The bus was pulled from service in late June for issues with the batteries. The bus was down the entire months of July and August and the majority of September. Some of the downtime was caused by issues with getting parts. Another mitigating factor was the lack of support from the hybrid manufacturer. SunLine has had to take on more of the necessary work on the hybrid system. SunLine's ability to quickly diagnose and repair problems was also affected when one technician who was familiar with the technology left the agency.

The availability for the CNG buses also dropped significantly during this period because of issues that caused significant downtime. The majority of downtime was attributed to engine issues (52%) and accidents/body damage (33%). CNG bus 605 had the most days out of service, accounting for 50% of the total downtime.

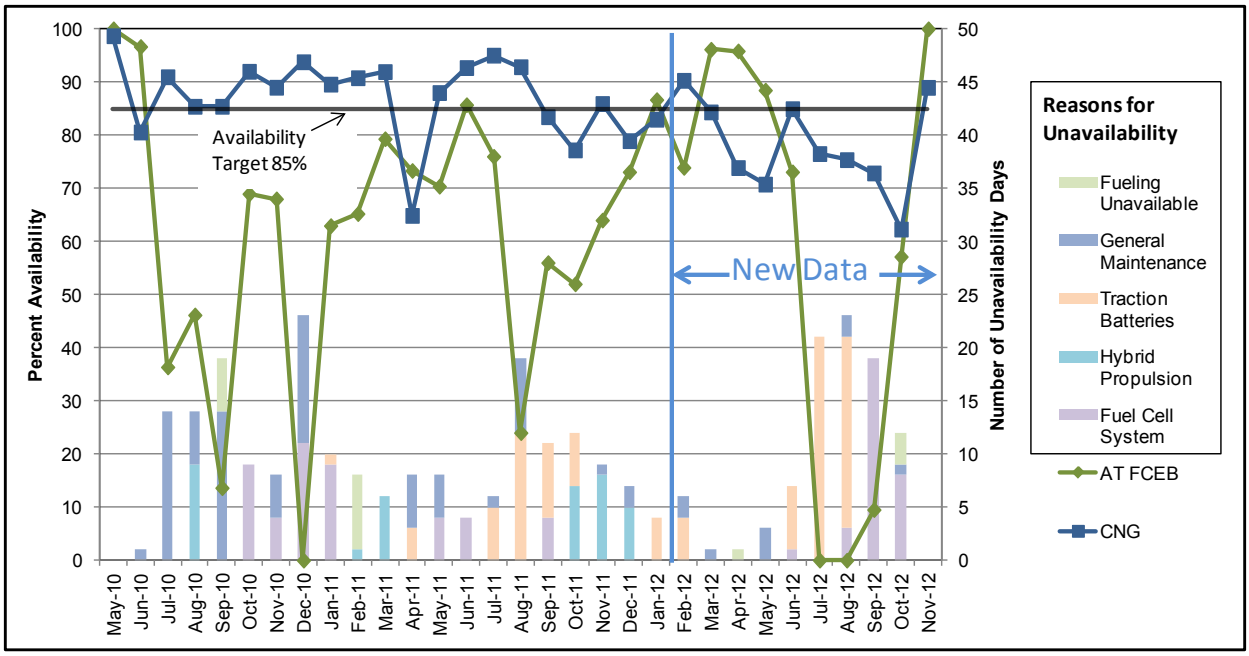

Figure 7. Availability for study bus groups

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 78%. As discussed, the primary issues that kept the fuel cell bus out of service were downtime for traction batteries (49%) and the fuel cell system (31%).

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

Category	AT FCEB		CNG Buses	
	Number	Percent	Number	Percent
Planned work days	245		1,330	
Days available	152	62	1,039	78
Available	**152**	**100**	**1,039**	**100**
On route	148	97.4	1,008	97
Event/demonstration	4	2.6	3	0.3
Training	0	0	2	0.2
Not used	0	0	25	2.4
Unavailable	**93**	**100**	**291**	**100**
Fuel cell propulsion	31	33.3	0	0
Hybrid propulsion	0	0	0	0
Traction batteries	49	52.7	0	0
SunLine maintenance	9	9.7	291	100
Fueling unavailable	4	4.3	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 1.9 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 $1.25 per mile for the fuel cell bus and $0.29 per mile for the CNG buses. The CNG fuel cost at $0.91 per GGE is much lower than the typical diesel fuel average cost per gallon. The cost to produce hydrogen is much higher, and includes the cost of the CNG used for reforming.

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 FCEB	**16,571**	**3,148.3**	**5.25**	**2,786.1**	**5.93**
603 CNG	39,697	14,030.0	2.83	12,556.8	3.16
604 CNG	47,566	17,147.4	2.77	15,346.9	3.10
605 CNG	25,039	8,992.0	2.78	8,047.8	3.11
606 CNG	43,502	16,069.4	2.71	14,382.1	3.02
608 CNG	43,982	15,450.9	2.84	13,828.6	3.18
CNG Total	**199,786**	**71,689.7**	**2.79**	**64,162.3**	**3.11**

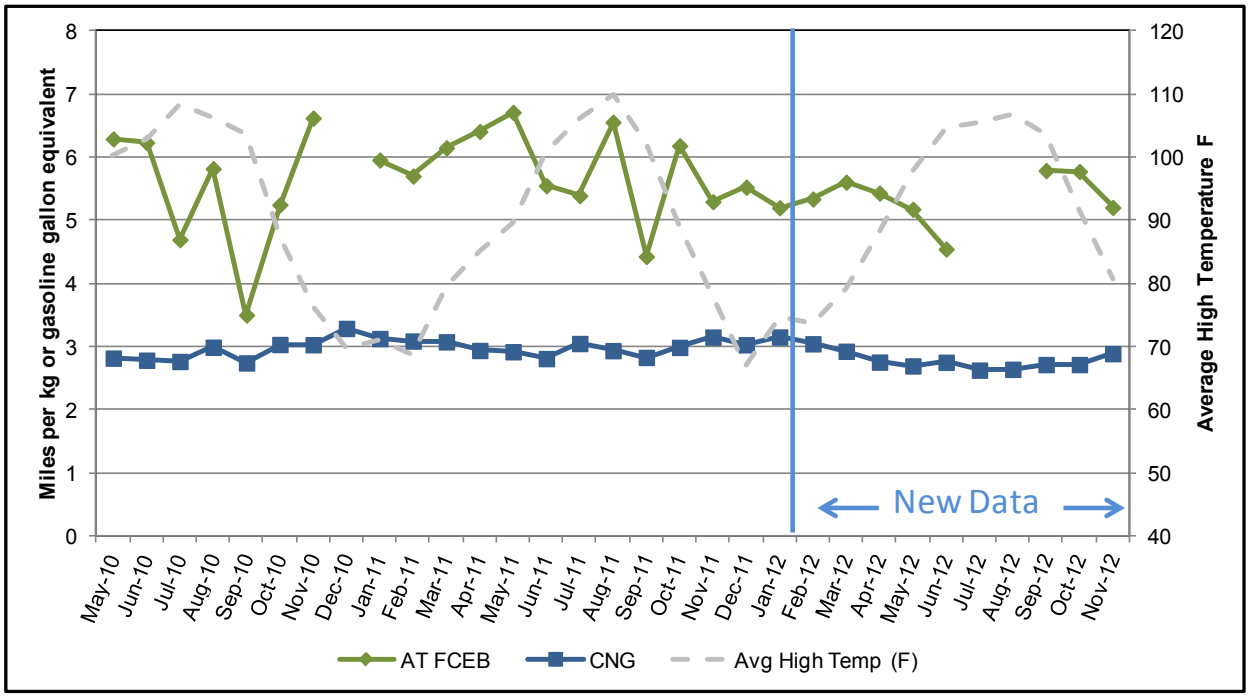

Figure 8. Average fuel economy (miles per kg or miles per GGE)

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 68% lower than those of the AT fuel cell bus. The parts costs continue to be low for the AT fuel cell bus because parts for the propulsion system are typically covered by the manufacturer under warranty; 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 FCEB	**16,571**	**$571.88**	**253.00**	**$0.80**
603 CNG	39,697	$5,869.26	220.75	$0.43
604 CNG	47,566	$4,883.56	319.00	$0.44
605 CNG	25,039	$7,522.33	242.75	$0.79
606 CNG	43,502	$5,501.01	278.25	$0.45
608 CNG	43,982	$6,143.11	263.00	$0.41
Total CNG	**199,786**	**$29,919.27**	**1,296.75**	**$0.47**

Maintenance Costs Separated by System – Table 6 shows maintenance costs by vehicle system and bus study group (without warranty costs). The vehicle systems shown in the table include the following:

- **Cab, body, and accessories –** Includes body, glass, and paint repairs following accidents; cab and sheet metal repairs on seats and doors; and accessory repairs such as hubodometers and radios
- **Propulsion-related systems –** Repairs for exhaust, fuel, engine, electric motors, fuel cell modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, and transmission
- **Preventive maintenance inspections (PMI) –** Labor for inspections during preventive maintenance
- **Brakes**
- **Frame, steering, and suspension**
- **Heating, ventilation, and air conditioning (HVAC)**
- **Lighting**
- **Air system, general**
- **Axles, wheels, and drive shaft**
- **Tires**

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

System	AT FCEB Cost per Mile ($)	AT FCEB Percent of Total (%)	CNG Cost per Mile ($)	CNG Percent of Total (%)
Cab, body, and accessories	0.07	8	0.11	22
Propulsion-related	0.60	75	0.21	44
PMI	0.10	12	0.08	16
Lighting	0.01	1	0.01	2
HVAC	0.00	1	0.04	7
Brakes	0.00	1	0.01	2
Frame, steering, and suspension	0.01	1	0.01	2
Axles, wheels, and drive shaft	0.00	0	0.00	1
General air system repairs	0.00	0	0.00	1
Tires	0.01	1	0.01	3
Total	**0.80**	**100**	**0.47**	**100**

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 extensive engine issues with two of the baseline CNG buses resulted in an increase in propulsion-related costs to 44%. The cab, body, and accessories costs had the next highest percentage, followed by PMI.

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 for most of the key systems during the entire evaluation period. The CNG buses are no longer under warranty. The SunLine mechanics continue to handle nearly all of the maintenance on the AT fuel cell bus, with support as needed by the manufacturers. However, the manufacturers generally supplied the parts under warranty for the propulsion system, so the costs for these parts are not included in the maintenance costs.

- **Total propulsion-related –** The 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 engine issues for the CNG buses caused a significant increase in the powerplant category.

- **Non-lighting electrical (charging, cranking, and ignition) –** The AT fuel cell bus had low 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.
- **Cooling –** Costs for this system for the study bus groups were low.
- **Transmission –** Costs for this system for the study bus groups were low.

Additional Costs – SunLine's fuel cell buses are fueled at the hydrogen dispenser, which is located at the public access station at the edge of the agency property. This requires SunLine to assign the fueling duties to maintenance staff outside the normal procedures for fueling the rest of the fleet. (SunLine's CNG buses are fueled at the dispensers within the bus yard as part of the scheduled prep for service.) SunLine tracks these labor costs separately as work orders. During the data period, this fueling labor for the AT fuel cell bus totaled 43.75 hours. At the standard rate of $50 per hour, this adds $2,187.50 to the operating cost of the bus. This is not included in the cost summary.

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

Maintenance System Costs	AT FCEB	CNG
Mileage	16,571	199,786
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	132.08	17,068.55
Labor hours	195.00	489.25
Total cost ($)	9,882.08	41,531.05
Total cost ($) per mile	**0.60**	**0.21**
Exhaust System Repairs		
Parts cost ($)	0.00	1,013.83
Labor hours	0.0	11.0
Total cost ($)	0.00	1,563.83
Total cost ($) per mile	**0.00**	**0.01**
Fuel System Repairs		
Parts cost ($)	0.00	214.61
Labor hours	0.5	0.0
Total cost ($)	25.00	214.61
Total cost ($) per mile	**0.00**	**0.00**
Powerplant System Repairs		
Parts cost ($)	25.85	8,819.51
Labor hours	35.0	368.8
Total cost ($)	1,775.85	27,257.01
Total cost ($) per mile	**0.11**	**0.14**
Electric Propulsion System Repairs		
Parts cost ($)	8.00	0.00
Labor hours	101.8	0.0
Total cost ($)	5,087.50	0.00
Total cost ($) per mile	**0.31**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	84.50	5,260.36
Labor hours	13.3	22.5
Total cost ($)	747.00	6,385.36
Total cost ($) per mile	**0.05**	**0.03**
Air Intake System Repairs		
Parts cost ($)	13.73	677.88
Labor hours	1.0	0.0
Total cost ($)	63.73	677.88
Total cost ($) per mile	**0.00**	**0.00**
Cooling System Repairs		
Parts cost ($)	0.00	275.80
Labor hours	43.0	73.8
Total cost ($)	2,150.00	3,963.30
Total cost ($) per mile	**0.13**	**0.02**
Transmission System Repairs		
Parts cost ($)	0.00	635.47
Labor hours	0.5	13.3
Total cost ($)	25.00	1,297.97
Total cost ($) per mile	**0.00**	**0.01**

Roadcall Analysis

A roadcall (RC), or revenue vehicle system failure[10], 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 (MBRCs) for each study bus group in two categories: all RCs and propulsion-related-only RCs. Two RCs for the AT bus were attributed to the propulsion system. Of these, only one was fuel cell related, resulting in a fuel cell system MBRC of 16,571 for the evaluation period.

Table 8. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC
AT FCEB	**16,571**	**2**	**8,286**	**2**	**8,286**
603 CNG	39,697	3	13,232	1	39,697
604 CNG	47,566	4	11,892	2	23,783
605 CNG	25,039	2	12,520	2	12,520
606 CNG	43,502	9	4,834	3	14,501
608 CNG	43,982	1	43,982	0	
Total CNG	**199,786**	**19**	**10,511**	**8**	**24,963**

Summary of Experience to Date

The AT fuel cell bus has been in operation for more than 31 months. Many of the early issues were resolved; however, a few issues have continued and those issues are discussed in this section. SunLine maintenance staff has come up to speed on the new bus systems and has learned to diagnose and repair most issues, although the loss of one of the experienced technicians has made this a challenge. This section summarizes the challenges and achievements that the team has had so far in the demonstration.

Manufacturer support – Developing advanced propulsion systems for buses takes a cohesive team of manufacturers working closely to identify and solve some potentially complex problems. In the current economic climate, many manufacturers have had difficulties remaining engaged in the process. This was particularly true for the AT fuel cell bus. Since the early development of this bus design, the original hybrid system manufacturer (ISE Corporation) declared bankruptcy. This has resulted in the need for the remaining partners, primarily SunLine and Ballard, to step up their level of support. Because SunLine's maintenance technicians have had many years of experience with gaseous fuels and advanced technology systems, they were able to take on the majority of the troubleshooting and repair for the hybrid system. Ballard has also worked closely with SunLine to aid in maintenance for the fuel cell system as well as the hybrid system. Issues with getting parts or having access to diagnosis and software upgrades have contributed to

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

extended downtime. Both Ballard and SunLine feel positively about the project and are currently working on a new service contract that will allow Ballard to continue providing support for the bus.

Traction Battery Issues – During the data period, the AT fuel cell bus had some issues with the traction batteries. SunLine continues to use an external charger to balance the batteries for better electric storage performance and longevity. This regular equalization of the batteries has had a positive effect on the bus performance. The AT fuel cell bus was down for an extended problem with the batteries. Diagnosing the problem proved to be a challenge. A bad battery in the pack needed to be replaced. SunLine purchased a new battery and got support from the battery manufacturer to install it and update the software settings.

Fuel Cell System Issues – During the data period the AT fuel cell bus also experienced some issues attributed to the fuel cell system. The fire suppression/smoke detection inside the fuel cell module triggered error codes. Troubleshooting the problem took some time, but was eventually traced to a bad connection on the power supply/control board. Once repaired, the issues did not reoccur.

What's Next for SunLine

This report covers SunLine's operation of the fuel cell and CNG buses from February 2012 through November 2012. The agency will continue working with DOE/NREL to collect data on the buses in service.

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). The AFCB was funded under the FTA's National Fuel Cell Bus Program. 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. Under another FTA program (Transit Investments for Greenhouse Gas and Energy Reduction–TIGGER), this team is building two additional AFCBs for operation at SunLine. The first of the buses is expected to be delivered by the third quarter of 2013. Once both buses arrive, SunLine will have a total of four FCEBs operating in its service area.

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Fuel Cell Bus Related Reports

This section provides a list of the most recent fuel cell bus-related reports from NREL. 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.

SunLine

Eudy, L.; Chandler, K. (2012). *SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Third Results Report*. NREL/TP-5600-54427, Golden, CO: National Renewable Energy Laboratory.

Eudy, L. (2012). *American Fuel Cell Bus Project: Developing and Demonstrating the Next-Generation Fuel Cell Electric Bus Made in America.* DOT/FTA – NFCBP – FC4 – March 2012.

Eudy, L.; Chandler, K. (2011). *SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Second Results Report and Appendices*. NREL/TP-5600-52349-1, NREL/TP-5600-52349-2, Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Chandler, K. (2011). *SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: First Results Report*. NREL/TP-5600-50500, Golden, CO: National Renewable Energy Laboratory.

Eudy, L.; Chandler, K. (2009). *SunLine Transit Agency, Fuel Cell Transit Bus: Fifth Evaluation Report and Appendices*. NREL/TP-560-46346-1, NREL/TP-560-46346-2. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2009). *SunLine Transit Agency, Fuel Cell Transit Bus: Fourth Evaluation Report and Appendices*. NREL/TP-560-44646-1, NREL/TP-560-44646-2. Golden, CO: National Renewable Energy Laboratory.

General

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

Chandler, K.; Eudy, L. (2012). *FTA Fuel Cell Bus Program: Research Accomplishments through 2011*. FTA Report No. 0014, Washington, DC: Federal Transit Administration.

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

Eudy, L. (2010). *Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*. NREL/TP-560-49342. Golden, CO: National Renewable Energy Laboratory.

AC Transit

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

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

Eudy, L. (2010). *Bay Area Transit Agencies Propel Fuel Cell Buses Toward Commercialization.* DOE/GO-102010-3067. Golden, CO: National Renewable Energy Laboratory.

Chandler, K.; Eudy, L. (2010). *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2 and Appendices*. FTA-CO-26-7004-2010.1. Golden, CO: National Renewable Energy Laboratory.

BurbankBus

Eudy, L. (2010). *Fuel Cell Bus Takes a Starring Role in the BurbankBus Fleet.* DOE/GO-102010-3035. Golden, CO: National Renewable Energy Laboratory.

Columbia, SC

Eudy, L., Chandler, K. (2011). *National Fuel Cell Bus Program: CTE/Proterra Hydrogen Hybrid Bus Report, Columbia Demonstration*. FTA Report No. 0003. Washington, DC: Federal Transit Administration.

Connecticut Transit

Eudy, L., Chandler, K. (2012). *Connecticut Nutmeg Fuel Cell Bus Project: First Analysis Report*. FTA Report No. 00xx. Washington, DC: Federal Transit Administration.

Eudy, L. (2011). *Connecticut Nutmeg Fuel Cell Bus Project: Demonstrating Advanced-Design Hybrid Fuel Cell Buses in Connecticut.* DOT/FTA – NFCBP – FC3 – July 2011.

Chandler, K.; Eudy, L. (2010). *Connecticut Transit (**CT**TRANSIT) Fuel Cell Transit Bus: Third Evaluation Report and Appendices*. NREL/TP-560-47334-1, NREL/TP-560-47334-2. Golden, CO: National Renewable Energy Laboratory.

San Francisco Municipal Transportation Agency

Eudy, L. (2011). *Compound Fuel Cell Hybrid Bus Hits the Streets of San Francisco: San Francisco Hosts National Fuel Cell Bus Program Demonstration.* DOT/FTA – NFCBP – FC2 – July 2011.

Appendix A: Fleet Summary Statistics

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

	AT FCEB All Data	AT FCEB New Data	CNG All Data	CNG New Data
Number of vehicles	1	1	5	5
Period used for fuel and oil op analysis	5/10 - 11/12	2/12 - 11/12	5/10 - 11/12	2/12 - 11/12
Total number of months in period	31	10	31	10
Fuel and oil analysis base fleet mileage	48,267	16,571	660,735	199,786
Period used for maintenance op analysis	5/10 - 11/12	2/12 - 11/12	5/10 - 11/12	2/12 - 11/12
Total number of months in period	31	10	31	10
Maintenance analysis base fleet mileage	48,428	16,571	683,023	199,786
Average monthly mileage per vehicle	1,562	1,657	4,407	3,996
Availability	62	62	78	78
Fleet fuel usage in CNG GGE/H2 kg	8,111	2,593	226,369	63,976
Roadcalls	15	2	46	19
RCs MBRC	3,229	8,286	14,848	10,515
Propulsion roadcalls	15	2	23	8
Propulsion MBRC	3,229	8,286	29,697	24,973
Fleet miles/kg hydrogen (1.13 kg H2/gal diesel fuel)	5.95	6.39	2.92	3.12
Representative fleet MPG (energy equiv)	6.72	7.22	3.26	3.49
Hydrogen cost per kg	8.00	8.00		
GGE cost			0.89	0.91
Fuel cost per mile	**1.34**	**1.25**	**0.30**	**0.29**
Total scheduled repair cost per mile	0.15	0.10	0.13	0.12
Total unscheduled repair cost per mile	0.84	0.70	0.30	0.35
Total maintenance cost per mile	**0.99**	**0.80**	**0.43**	**0.47**
Total operating cost per mile	**2.33**	**2.05**	**0.73**	**0.77**

Maintenance Costs

	AT FCEB All Data	AT FCEB New Data	CNG All Data	CNG New Data
Fleet mileage	48,428	16,571	683,023	199,786
Total parts cost	2,599.82	571.88	89,355.05	29,919.27
Total labor hours	845.5	253.0	3,847.8	1296.8
Average labor cost (@ $50.00 per hour)	42,275.00	12,650.00	192,389.00	64,837.50
Total maintenance cost	44,874.82	13,221.88	281,744.05	94,756.77
Total maintenance cost per bus	44,874.82	13,221.88	56,348.81	18,951.35
Total maintenance cost per mile	**0.93**	**0.80**	**0.41**	**0.47**

Maintenance Costs by Vehicle System

	AT FCEB All Data	AT FCEB New Data	CNG All Data	CNG New Data
Fleet mileage	48,428	16,571	683,023	199,786
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	219.72	132.08	49,569.00	17,068.55
Labor hours	542.00	195.00	1,318.00	489.25
Average labor cost	27,100.00	9,750.00	65,900.00	24,462.50
Total cost (for system)	27,319.72	9,882.08	115,469.00	41,531.05
Total cost (for system) per bus	27,319.72	9,882.08	23,093.80	8,306.21
Total cost (for system) per mile	**0.56**	**0.60**	**0.17**	**0.21**
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	1,817.24	1,013.83
Labor hours	0.0	0.0	15.0	11.0
Average labor cost	0.00	0.00	750.00	550.00
Total cost (for system)	0.00	0.00	2,567.24	1,563.83
Total cost (for system) per bus	0.00	0.00	513.45	312.77
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.01**
Fuel System Repairs (ATA VMRS 44)				
Parts cost	3.00	0.00	873.15	214.61
Labor hours	0.5	0.5	0.0	0.0
Average labor cost	25.00	25.00	0.00	0.00
Total cost (for system)	28.00	25.00	873.15	214.61
Total cost (for system) per bus	28.00	25.00	174.63	42.92
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	110.49	25.85	25,347.52	8,819.51
Labor hours	232.8	35.0	995.3	368.8
Average labor cost	11,637.50	1,750.00	49,762.50	18,437.50
Total cost (for system)	11,747.99	1,775.85	75,110.02	27,257.01
Total cost (for system) per bus	11,747.99	1,775.85	15,022.00	5,451.40
Total cost (for system) per mile	**0.24**	**0.11**	**0.11**	**0.14**
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	8.00	8.00	0.00	0.00
Labor hours	179.0	101.8	0.0	0.0
Average labor cost	8,950.00	5,087.50	0.00	0.00
Total cost (for system)	8,958.00	5,095.50	0.00	0.00
Total cost (for system) per bus	8,958.00	5,095.50	0.00	0.00
Total cost (for system) per mile	**0.18**	**0.31**	**0.00**	**0.00**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	84.50	84.50	17,241.22	5,260.36
Labor hours	23.5	13.3	124.5	22.5
Average labor cost	1,175.00	662.50	6,225.00	1,125.00
Total cost (for system)	1,259.50	747.00	23,466.22	6,385.36
Total cost (for system) per bus	1,259.50	747.00	4,693.24	1,277.07
Total cost (for system) per mile	**0.03**	**0.05**	**0.03**	**0.03**

Maintenance Costs by Vehicle System (continued)

	AT FCEB All Data	AT FCEB New Data	CNG All Data	CNG New Data
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	13.73	13.73	1,822.76	677.88
Labor hours	1.0	1.0	0.0	0.0
Average labor cost	50.00	50.00	0.00	0.00
Total cost (for system)	63.73	63.73	1,822.76	677.88
Total cost (for system) per bus	63.73	63.73	364.55	135.58
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Cooling System Repairs (ATA VMRS 42)				
Parts cost	0.00	0.00	1,069.56	275.80
Labor hours	101.5	43.0	154.0	73.8
Average labor cost	5,075.00	2,150.00	7,700.00	3,687.50
Total cost (for system)	5,075.00	2,150.00	8,769.56	3,963.30
Total cost (for system) per bus	5,075.00	2,150.00	1,753.91	792.66
Total cost (for system) per mile	**0.10**	**0.13**	**0.01**	**0.02**
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0.00	0.00	431.64	171.09
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	431.64	171.09
Total cost (for system) per bus	0.00	0.00	86.33	34.22
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	162.46	82.32
Labor hours	1.5	0.5	67.3	15.5
Average labor cost	75.00	25.00	3,364.00	775.00
Total cost (for system)	75.00	25.00	3,526.46	857.32
Total cost (for system) per bus	75.00	25.00	705.29	171.46
Total cost (for system) per mile	**0.00**	**0.00**	**0.01**	**0.00**
Brake System Repairs (ATA VMRS 13)				
Parts cost	0.00	0.00	2,648.50	228.66
Labor hours	3.0	1.5	112.8	26.5
Average labor cost	150.00	75.00	5,637.50	1,325.00
Total cost (for system)	150.00	75.00	8,286.00	1,553.66
Total cost (for system) per bus	150.00	75.00	1,657.20	310.73
Total cost (for system) per mile	**0.00**	**0.00**	**0.01**	**0.01**
Transmission Repairs (ATA VMRS 27)				
Parts cost	0.00	0.00	965.91	635.47
Labor hours	3.8	0.5	29.3	13.3
Average labor cost	187.50	25.00	1,462.50	662.50
Total cost (for system)	187.50	25.00	2,428.41	1,297.97
Total cost (for system) per bus	187.50	25.00	485.68	259.59
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.01**

Maintenance Costs by Vehicle System (continued)

	AT FCEB All Data	AT FCEB New Data	CNG All Data	CNG New Data
Inspections Only - no parts replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	97.5	33.0	798.8	308.0
Average labor cost	4,875.00	1,650.00	39,937.50	15,400.00
Total cost (for system)	4,875.00	1,650.00	39,937.50	15,400.00
Total cost (for system) per bus	4,875.00	1,650.00	7,987.50	3,080.00
Total cost (for system) per mile	**0.10**	**0.10**	**0.06**	**0.08**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	1,801.89	299.24	23,756.91	5,500.31
Labor hours	122.5	15.8	1,135.8	313.8
Average labor cost	6,125.00	787.50	56,787.50	15,687.50
Total cost (for system)	7,926.89	1,086.74	80,544.41	21,187.81
Total cost (for system) per bus	7,926.89	1,086.74	16,108.88	4,237.56
Total cost (for system) per mile	**0.16**	**0.07**	**0.12**	**0.11**
HVAC System Repairs (ATA VMRS 01)				
Parts cost	42.76	20.03	7,599.26	4,709.40
Labor hours	38.0	1.0	117.8	47.5
Average labor cost	1,900.00	50.00	5,887.50	2,375.00
Total cost (for system)	1,942.76	70.03	13,486.76	7,084.40
Total cost (for system) per bus	1,942.76	70.03	2,697.35	1,416.88
Total cost (for system) per mile	**0.04**	**0.00**	**0.02**	**0.04**
Lighting System Repairs (ATA VMRS 34)				
Parts cost	209.46	29.14	1,882.49	1,054.10
Labor hours	31.5	2.3	83.5	25.5
Average labor cost	1,575.00	112.50	4,175.00	1,275.00
Total cost (for system)	1,784.46	141.64	6,057.49	2,329.10
Total cost (for system) per bus	1,784.46	141.64	1,211.50	465.82
Total cost (for system) per mile	**0.04**	**0.01**	**0.01**	**0.01**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	317.45	91.39	2,449.80	711.48
Labor hours	1.8	1.0	42.8	15.8
Average labor cost	87.50	50.00	2,137.50	787.50
Total cost (for system)	404.95	141.39	4,587.30	1,498.98
Total cost (for system) per bus	404.95	141.39	917.46	299.80
Total cost (for system) per mile	**0.01**	**0.01**	**0.01**	**0.01**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	8.54	0.00	1,286.63	564.45
Labor hours	0.0	0.0	19.5	3.5
Average labor cost	0.00	0.00	975.00	175.00
Total cost (for system)	8.54	0.00	2,261.63	739.45
Total cost (for system) per bus	8.54	0.00	452.33	147.89
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**

Maintenance Costs by Vehicle System (continued)

	AT FCEB All Data	AT FCEB New Data	CNG All Data	CNG New Data
Tire Repairs (ATA VMRS 17)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	7.8	3.0	151.8	51.5
Average labor cost	387.50	150.00	7,587.50	2,575.00
Total cost (for system)	387.50	150.00	7,587.50	2,575.00
Total cost (for system) per bus	387.50	150.00	1,517.50	515.00
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 no parts were 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 Electric Bus (FCEB) and Compressed Natural Gas (CNG) Study Groups
Fleet Operations and Economics

	AT FCEB All Data	AT FCEB New Data	CNG All Data	CNG New Data
Number of vehicles	1	1	5	5
Period used for fuel and oil op analysis	5/10 - 11/12	2/12 - 11/12	5/10 - 11/12	2/12 - 11/12
Total number of months in period	31	10	31	10
Fuel and oil analysis base fleet kilometers	77,676	26,668	1,063,321	321,516
Period used for maintenance op analysis	5/10 - 11/12	2/12 - 11/12	5/10 - 11/12	2/12 - 11/12
Total number of months in period	31	10	31	10
Maintenance analysis base fleet kilometers	77,935	26,668	1,099,189	321,516
Average monthly kilometers per vehicle	2,514	2,667	7,092	6,430
Availability	62	62	78	78
Fleet fuel usage in CNG liter equiv/H2 kg	8,111	2,593	856,805	242,149
Roadcalls	15	2	46	19
RCs KMBRC	5,196	13,334	23,895	16,922
Propulsion roadcalls	15	2	23	8
Propulsion KMBRC	5,196	13,334	47,791	40,189
Fleet kg hydrogen/100 km (1.13 kg H2/gal diesel fuel)	10.44	9.72		
Rep. fleet fuel consumption (L/100 km)	34.97	32.57	72.12	67.41
Hydrogen cost per kg	8.00	8.00		
GGE cost/liter			0.24	0.24
Fuel cost per kilometer	**0.89**	**0.78**	**0.19**	**0.18**
Total scheduled repair cost per kilometer	0.09	0.13	0.08	0.08
Total unscheduled repair cost per kilometer	0.52	0.44	0.18	0.22
Total maintenance cost per kilometer	**0.61**	**0.57**	**0.26**	**0.29**
Total operating cost per kilometer	**1.50**	**1.35**	**0.45**	**0.48**

Maintenance Costs

	AT FCEB All Data	AT FCEB New Data	CNG All Data	CNG New Data
Fleet mileage	77,935	26,668	1,099,189	321,516
Total parts cost	2,599.82	571.88	89,355.05	29,919.27
Total labor hours	845.50	253.00	3,847.78	1,296.75
Average labor cost (@ $50.00 per hour)	42,275.00	12,650.00	192,389.00	64,837.50
Total maintenance cost	44,874.82	13,221.88	281,744.05	94,756.77
Total maintenance cost per bus	44,874.82	13,221.88	56,348.81	18,951.35
Total maintenance cost per kilometer	**0.58**	**0.50**	**0.26**	**0.29**