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SunLine Transit Agency Hydrogen-Powered Transit Buses: Third Evaluation Report

Technical Report
NREL/TP-560-43741-1
June 2008

Kevin Chandler, Battelle
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Link to Appendices

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Prepared under Task No. H270.8200

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Office of Energy Efficiency and Renewable Energy
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Contract No. DE-AC36-99-GO10337

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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. DOE
John Garbak

National Renewable Energy Laboratory
Keith Wipke
George Sverdrup

SunLine
C. Mikel Oglesby
Tommy Edwards
Polo Del Toro
Ed Gallardo
Karen Thomas
Mike Hayes
Shawn Craycraft

UTC Power
Mike Tosca
Matthew Riley
Sandy Lajewski
Jennifer Stewart

ISE
Neil Flemmer
Tavin Tyler
Paul Scott
Dave Ticonchuk

HyRadix
Terry Schuster

Executive Summary

This report describes operations at SunLine Transit Agency for a prototype fuel cell bus; a prototype hydrogen hybrid internal combustion engine (HHICE) bus; and five new compressed natural gas (CNG) buses. This is the third evaluation report for this site, and it describes results and experiences from July 2007 through March 2008. These results are an addition to those provided in the previous two evaluation reports. The evaluation periods presented in this report are as follows:

- **Fuel Cell Bus** – January 2006 through March 2008 (27 months of operation)
- **HHICE Bus** – January 2006 through March 2008 (27 months of operation)
- **New CNG Buses** – July 2006 through March 2008 (21 months of operation)

Hydrogen and CNG Fueling

Hydrogen fuel is supplied at SunLine by a natural gas reformer. The fuel is compressed to approximately 5,000 psi and dispensed into vehicles. The SunLine hydrogen station dispensed a total of 16,994 kg of hydrogen during the evaluation period. The overall average daily usage was 28.2 kg per day. SunLine maintains the station, including parts and labor. Hydrogen fuel costs include the cost of natural gas for the reformer, maintenance of the station equipment, and capital costs amortization. The average cost for hydrogen during the evaluation period was $17.21 per kg. This high cost was because of low volume use, but 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 or less.

CNG is delivered to SunLine via a high-pressure natural gas line and then compressed to 3,600 psi for delivery into the vehicles. The SunLine CNG fueling station is open to the public. The high volume of CNG dispensed at the station allows SunLine to have a low cost as a commodity user; costs averaged $1.34 per gasoline gallon equivalent (GGE) during the evaluation period.

Evaluation Results

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

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell	HHICE	CNG
Number of Buses	1	1	5
Data Period	1/06-3/08	1/06-3/08	7/06-3/08
Number of Months	27	27	21
Total Mileage in Period	50,931	43,528	457,654
Average Monthly Mileage per Bus	1,886	1,612	4,359
Availability (85% is target)	66%	59%	83%
Fuel Economy (Miles/kg or GGE)	7.19	4.34	3.02
Miles between Roadcalls (MBRC) – All	1,455	2,073	9,949
MBRC – Propulsion Only	1,592	2,291	30,510
Total Maintenance, $/mile	0.44	0.59	0.30
Maintenance – Propulsion Only, $/mile	0.22	0.39	0.08

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Overview

SunLine Transit Agency provides public transit and community services to California's Coachella Valley. Headquartered in Thousand Palms, SunLine's service area of over 1,100 square miles includes nine member cities and a portion of Riverside County. SunLine has proactively adopted clean fuel technologies in their fleet, beginning with 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. Appendix A provides more information on SunLine.

In January of 2006, SunLine began demonstrating one prototype fuel cell bus. The prototype fuel cell bus, manufactured by Van Hool and ISE Corp., features an electric hybrid drive system with a UTC Power PureMotion[1] 120 Fuel Cell Power System and ZEBRA batteries for energy storage. SunLine has also been operating a prototype hydrogen hybrid internal combustion engine (HHICE) bus from New Flyer and ISE Corp. This HHICE bus has been operating at SunLine since December 2004, except for a few months in early 2006 when the bus was cold-weather tested in Canada. The HHICE bus has essentially the same electric hybrid drive system from ISE Corp. as the fuel cell bus, but with ultracapacitors for energy storage and a Ford V10 Triton engine customized to operate on hydrogen fuel. These two buses are shown in Figure 1.

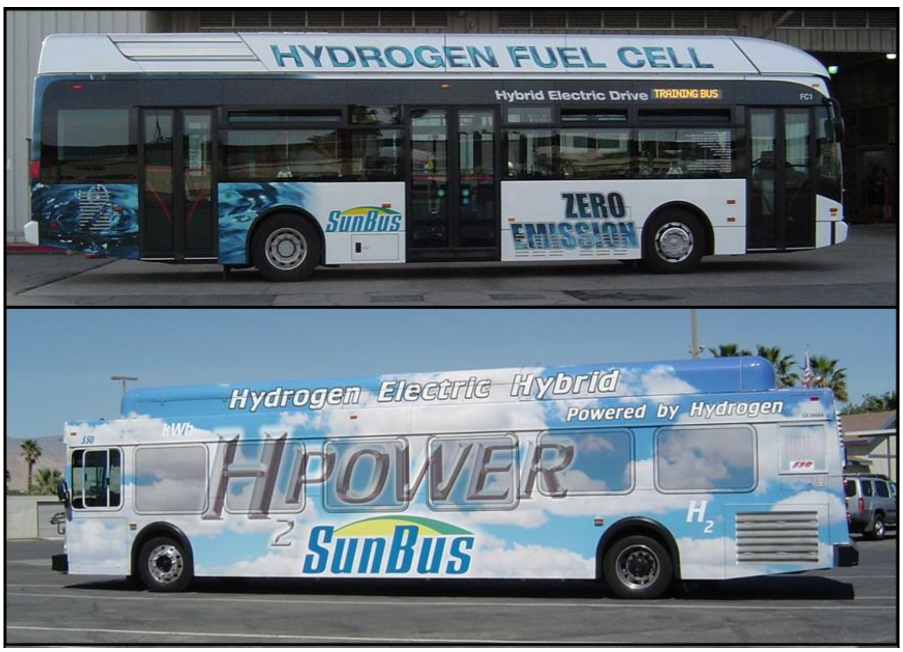

Figure 1. Fuel cell (top) and HHICE (bottom) transit buses at SunLine

This report includes operations at SunLine for both of these hydrogen-fueled transit buses in normal revenue service. Five new compressed natural gas (CNG) buses operating from the same SunLine location are being used as a baseline comparison. The new CNG buses from Orion Bus Industries use Cummins Westport C Gas Plus natural gas engines (see Figure 2). Appendix B provides more detail about the bus technologies included in this evaluation. Hydrogen and CNG

[1] PureMotion is a trademark of UTC Power

fueling infrastructure are discussed in the next section, and more detail is provided in Appendix C including facilities modifications for these two fuels.

Figure 2. Orion V CNG bus at SunLine

The Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) is evaluating these buses to help determine the status of hydrogen and fuel cell systems and corresponding hydrogen infrastructure in transit applications. Appendix D provides a description of NREL's transit bus evaluation activities for DOE and the Federal Transit Administration (FTA). NREL has published two previous evaluation reports for this ongoing study at SunLine.[2,3]

This third evaluation report describes results and experience from July 2007 through March 2008 in addition to the results from the entire evaluation period. The newest data are highlighted when possible. The entire evaluation time periods presented in this report are as follows:

- **Fuel Cell Bus**– January 2006 through March 2008 (27 months of operation)
- **HHICE Bus** – January 2006 through March 2008 (27 months of operation)
- **New CNG Buses** – July 2006 through March 2008 (21 months of operation)

Hydrogen and CNG Fueling

Hydrogen fuel is supplied at SunLine by a HyRadix natural gas reformer. The fuel is compressed to 5,000 psi and dispensed into vehicles. Figure 3 shows the fuel cell bus at the hydrogen dispenser. CNG is brought into the SunLine property via a high-pressure natural gas line and then compressed to 3,600 psi for delivery into the vehicles. General descriptions of SunLine's hydrogen and CNG fueling infrastructure along with maintenance facilities are provided in Appendix C.

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[2] SunLine Transit Agency, Hydrogen-Powered Transit Buses: Preliminary Evaluation Results, February 2007, NREL/TP-560-41001, www.nrel.gov//hydrogen/pdfs/41001.pdf

[3] SunLine Transit Agency, Hydrogen-Powered Transit Buses: Evaluation Results Update, September 2007, NREL/TP-560-42080, www.nrel.gov/hydrogen/pdfs/42080.pdf

SunLine provides both hydrogen and CNG for purchase at its public dispensing island. This has caused SunLine to track all of its fueling events in gasoline gallon equivalent (GGE) units to comply with state fuel sales regulations. In the case of hydrogen, the unit used is typically kilograms (kg)—one kg contains essentially the same energy as a GGE. The analysis in this report presents both GGE (or kg for hydrogen) and diesel gallon equivalent (DGE) for hydrogen and CNG fuel consumption. Energy conversion calculations for GGE and DGE are shown at the end of Appendix E.

Figure 3. Fuel Cell Bus at Hydrogen Dispenser

Figure 4 shows the total monthly hydrogen dispensed into the two hydrogen-fueled buses for January 2006 through March 2008. The calculation for this rate only includes the days in which hydrogen was dispensed from the station. The station was used at least once per day to fill at least one of the two hydrogen buses for 73% of the calendar days during the period. The overall average daily usage was 28.2 kg per day. During this period, SunLine dispensed a total of 16,994 kg of hydrogen.

The data for the July 2007-March 2008 period show that the monthly usage for hydrogen was generally lower compared to previous periods. This occurred because the HHICE bus was out of service during most of the period, except for August and September 2007. Another contributing factor for lower hydrogen usage was due to restricted use of the fuel cell bus between October 2007 and January 2008. This occurred because the fuel cell power system had degraded and was approaching the threshold where it might not have enough power to complete service (as defined by UTC Power). The fuel cell power system was replaced in early February 2008 and the fuel cell bus was released for full service. The issues with the fuel cell power system will be discussed further in the Evaluation Results section.

Figure 5 shows the distribution of hydrogen amounts dispensed per fill. The two buses were filled a total of 907 times during the evaluation period, with an average fill amount of 18.7 kg. The HHICE bus fuelings averaged 20.8 kg, while the fuel cell bus averaged 16.5 kg.

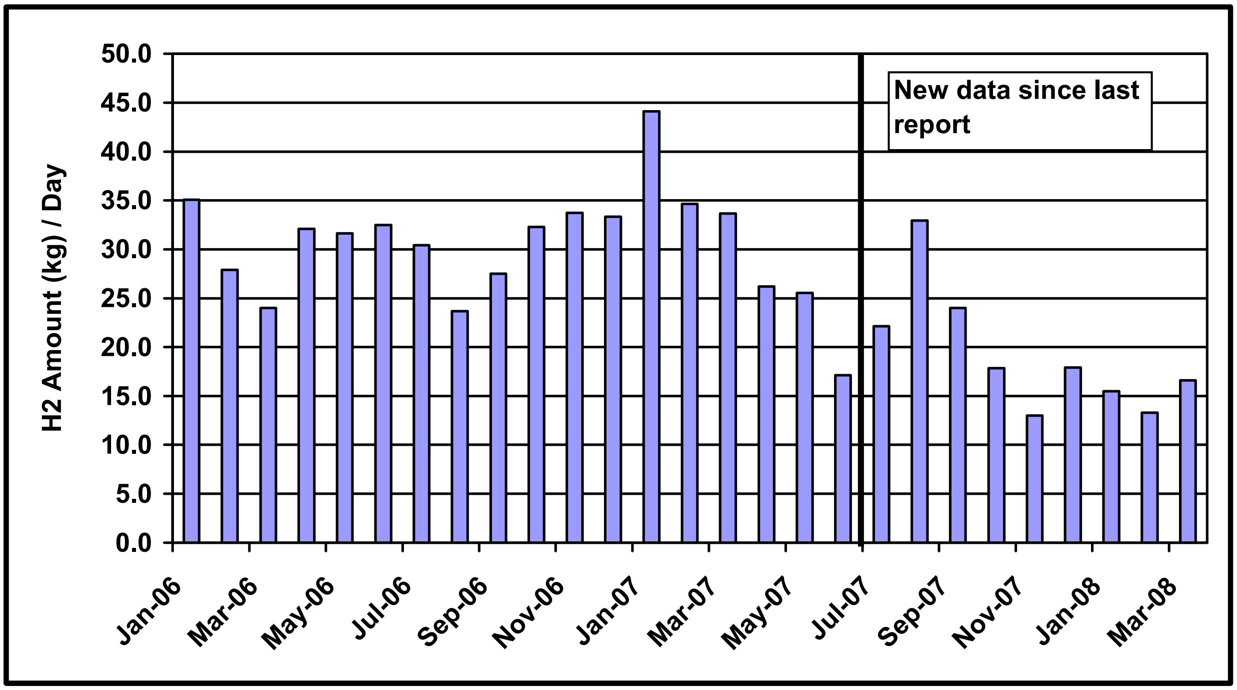

Figure 4. Average hydrogen dispensed per day (excluding 0 kg days)

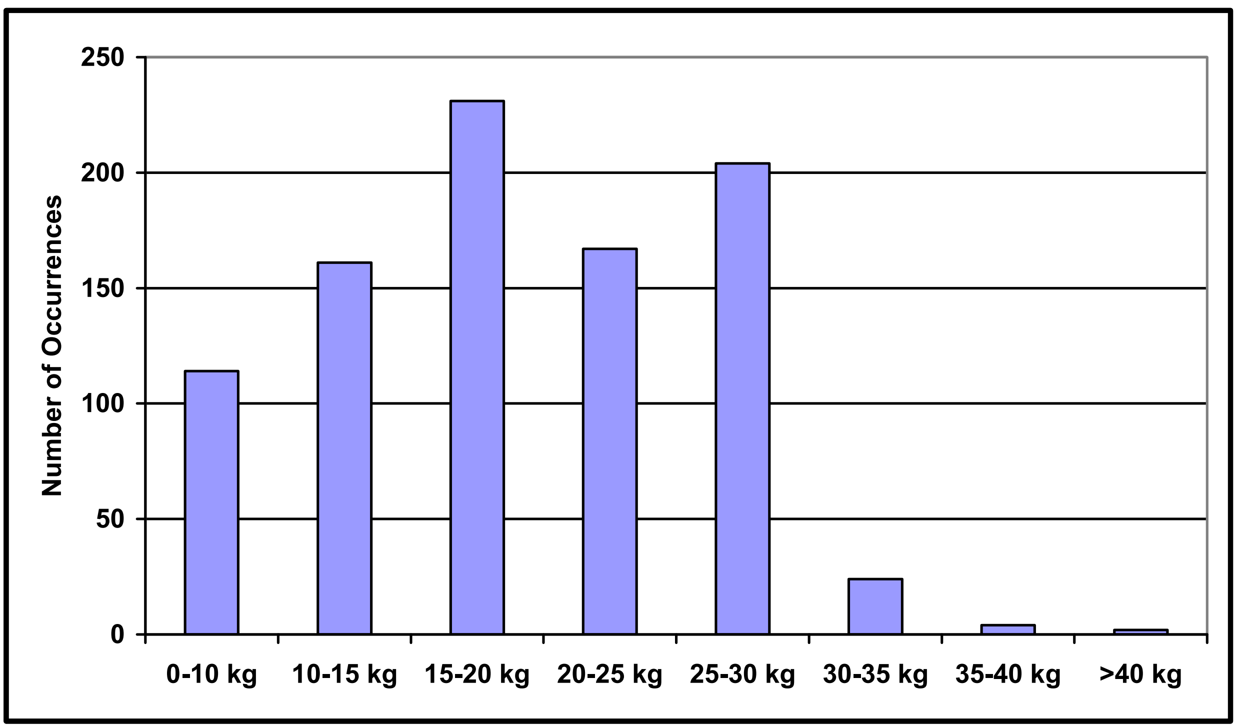

Figure 5. Distribution of fueling amounts

Figure 6 shows a cumulative fueling rate histogram for the SunLine station from March 2007 through March 2008. (Prior to March 2007, these data were not available.) During this time, there were 285 fueling events for a total of 5,399 kg. The overall average fueling rate was 0.89 kg/min.

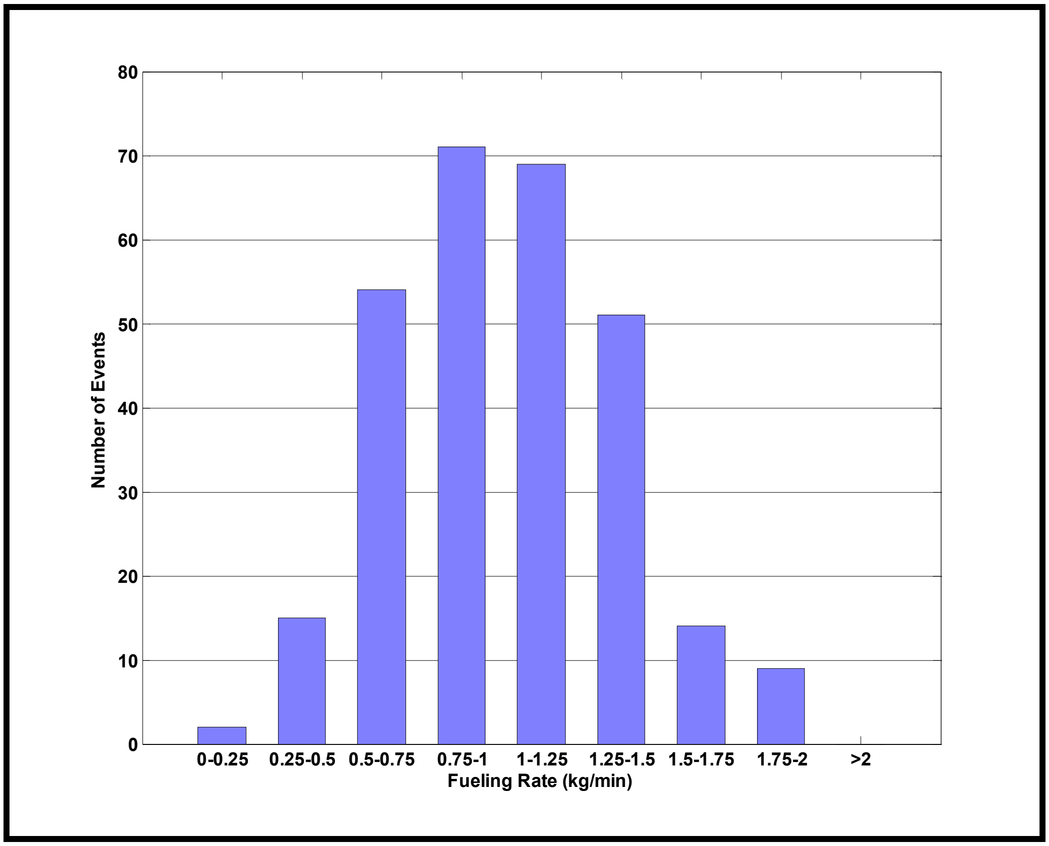

Figure 6. Cumulative fueling rate histogram

Hydrogen fuel costs at SunLine are made up of the cost of natural gas for the reformer, maintenance of the station equipment, and capital costs amortization. The maintenance of the station is performed by SunLine and includes parts and labor. The average cost for hydrogen during the evaluation period was $17.21 per kg. This average cost was so high because of the low volume use of hydrogen while the HHICE bus was out of service (most of June 2007 through March 2008) and while the fuel cell bus was reduced to minimal service (October 2007 through January 2008). 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.

SunLine supplies CNG fuel to users in its area and the fueling station allows public fueling. The high volume of natural gas use has allowed SunLine to command a low cost as a commodity user. During the evaluation period for the CNG buses (July 2006 to March 2008), the CNG price at the dispenser for SunLine (not the public price) was $1.34 per GGE. This price includes all costs – natural gas, maintenance, and station amortization.

Evaluation Results

The evaluation period presented in this report for the fuel cell and HHICE buses is January 2006 through March 2008. The CNG buses went into service near the end of June 2006, and the evaluation period is July 1, 2006 through March 2008.

In this third evaluation report, both the fuel cell and HHICE buses are considered to be prototype technology that is in the process of being commercialized. The analysis and comparison discussions with standard/new CNG buses were done to help baseline the status and progress of these two hydrogen propulsion technologies. The intent of this analysis is to determine the status of this implementation and document the improvements that have been made over time at SunLine. There is no intent to consider this implementation of fuel cell or HHICE buses as commercial (or full revenue transit service). The evaluation focuses on documenting progress and opportunities for improving the vehicles, infrastructure, and procedures.

Route Assignments

Buses at the two SunLine operating locations are generally dispatched randomly. The overall system average operating speed at SunLine is 13.2 mph. The HHICE bus has been used almost exclusively on Line 50 (operated 323 days, average speed of 14.1 mph), except for a few days on Line 30 and Line 31 (operated 6 days total on these two routes) in January 2006. The fuel cell bus has been used on Line 50 (operated 328 days) and Line 111 (operated 35 days, average speed of 14.3 mph). In-service data for the fuel cell bus indicate an average operating speed of 12.8 mph based on mileage and fuel cell system operating hours. The new CNG buses have been randomly dispatched, with heavy use on the Line 111 and Line 14 (average speed of 14.7 mph), which are SunLine's top two routes.

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage may indicate downtime for maintenance or purposeful reduction of planned work for the buses. This section provides a summary of bus usage and availability for the three study groups of buses.

For the fuel cell bus, total mileage accumulation for the evaluation period was 50,931 miles (13,926 miles since the last evaluation report), and the fuel cell system accumulated 3,918 hours (1,096 hours since the last evaluation report). These numbers indicate an overall average speed of operation at 12.8 mph (average of 12.7 mph since the last evaluation report), which is a little lower than the overall SunLine operation speed of 13.2 mph.

Table 1 summarizes the average monthly mileage accumulation by bus and study group for the evaluation periods. Using the CNG buses as the baseline, the fuel cell bus had an average monthly mileage that was 43% that of the CNG buses and the HHICE bus had average monthly mileage 37% that of the CNG buses. This is consistent in that the fuel cell and HHICE buses have planned service at about half of the CNG buses and both of the hydrogen buses had significant downtime during the evaluation period.

Table 1. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average
FC1	**2,865**	**50,965**	**50,931**	**27**	**1,886**
550 HHICE	**17,481**	**61,009**	**43,528**	**27**	**1,612**
563 CNG	4,916	89,320	84,404	21	4,019
565 CNG	7,637	110,370	102,733	21	4,892
566 CNG	5,576	91,523	85,947	21	4,093
567 CNG	7,104	90,552	83,448	21	3,974
568 CNG	6,388	107,510	101,122	21	4,815
Total CNG			**457,654**	**105**	**4,359**

Another measure of reliability is availability – the percent of time that the buses are planned for operation compared to the time the buses are actually available for that planned operation. Figure 7 shows the monthly average availability for each of the three study bus groups. As shown on the chart, the availability goal is 85% for all buses.

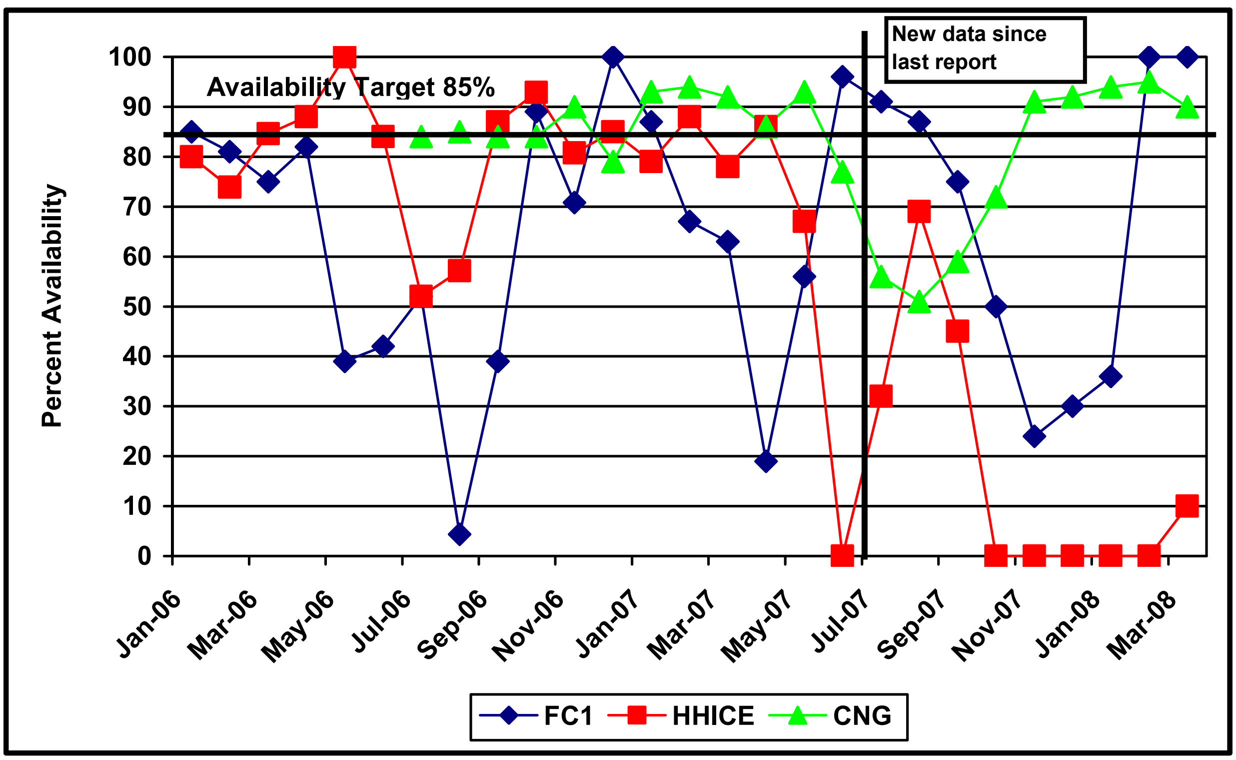

Figure 7. Availability for all three study bus groups

The **fuel cell bus** availability has suffered because of issues with the energy storage batteries (ZEBRA) and replacements of the fuel cell power system. Overall, the availability for the fuel cell bus has averaged 66% (for the July 2007-March 2008 data period, availability averaged 68%).

- **Battery Issues** – The ZEBRA batteries have had significant problems in this application. Battery voltage mismatches have been a problem. Just as big a problem has been the availability of replacement batteries and having them ready to install into buses.

- **Fuel Cell System Issues** – The fuel cell system in this bus was replaced during the summer of 2006 because of degradation of power, and placed back into full service in September 2006. UTC Power has set a power degradation point below which the power system is no longer viable for revenue bus service. The new power system was replaced again in March 2007 for the same type of degradation issue. Toward the end of the originally planned end of the demonstration (December 2007), UTC Power determined that the power system would not be capable of completing the required 4,000 hours of warranty operation. In early February, 2008, UTC Power replaced the fuel cell power system with a unit taken from one of AC Transit's fuel cell buses in order to complete the warranty operation at SunLine. This fuel cell bus recently completed the 4,000 hours of warranty operation and was replaced in April, 2008, with a newer/upgraded version of the power system for additional fuel cell bus testing. The new power system is expected to be much more durable than the previous versions. The additional testing will be performed via a new agreement between SunLine, FTA, UTC Power, and ISE Corp. This new operation will be discussed in the last section of this report (What's Next for SunLine?).

The **HHICE bus** was out of service for nearly all of the July 2007 –March 2008 data period and this lowered the availability considerably (average 59%).

- **Engine Issues** – On May 22, 2007, the bus had a broken fan belt and overheated. This incident caused a need to rebuild the engine. The same incident occurred again on July 20, 2007 when the belt broke, allowing the engine to overheat. The engine was again rebuilt. Another, more significant incident occurred on September 12, 2007 when the bus experienced a fire at the engine. ISE Corp. determined that each of these incidents should have been preventable if the engine were better instrumented. After the incident in September 2007, the bus was sent back to ISE Corp. to repair the engine compartment as well as to add better instrumentation (and engine shutdown capabilities) and rebuild the engine. The bus returned to SunLine in mid-March 2008 after significant testing at ISE Corp. (approximately 435 miles of testing of the engine and instrumentation). SunLine plans ongoing operation and demonstration of this prototype bus in revenue service.

The chart shows that the **CNG buses** are essentially right on the availability goal (average of 83%). During the period of June through October 2007, three of the five CNG buses had significant downtime for repairs. Bus 563 had an exhaust and engine problem that kept the bus out of service for nearly all of June through October 2007. Bus 566 missed service for most of August 2007 for warranty body repairs. Bus 567 was involved in a significant accident in June 2007 and was not retuned to service until almost the middle of October 2007. This reduced availability was coincidence and significant because of the small sample size of five buses. This was not a fleet-wide issue. Table 2 provides a summary of the availability and unavailability reasons for each of the three study bus groups. Overall during the evaluation periods, the average availability for the fuel cell bus was 66%, the HHICE bus was 59%, and the CNG buses was 83%. Issues that kept the fuel cell bus out of service included problems with the air conditioning (16%), fuel cell system (43%), and ZEBRA batteries (16%). Issues that kept the HHICE bus out of service included problems with the drive system, mostly engine (85%); lack of hydrogen fuel (12%); and general maintenance activities (3%). Issues that kept the CNG buses out of service included general maintenance and some air conditioning repairs.

Table 2. Summary of Reasons for Availability and Unavailability of Buses for Service

Category	Fuel Cell Bus		HHICE Bus		CNG Buses	
	Number	Percent	Number	Percent	Number	Percent
Planned Work Days	653		667		2,929	
Days Available	432	66	396	59	2,444	83
Available	**432**	**100**	**396**	**100**	**2,444**	**100**
On-Route	412	95	373	94	2,426	99
Event/Demonstration	13	3	6	2	5	0
Training	6	1	13	3	0	0
Not Used	2	1	4	1	13	1
Unavailable	**221**	**100**	**271**	**100**	**485**	**100**
Fuel Cell Propulsion	95	43				
ISE Propulsion	16	7	231	85		
ZEBRA Battery	35	16				
Air Conditioning	35	16	0	0	27	6
Headsign	7	3				
SunLine Maintenance	1	1	9	3	458	94
Fueling Unavailable	31	14	31	12		

During the October 2007 through January 2008 period, the fuel cell bus had reduced service due to power degradation of the fuel cell power system. During this timeframe, the bus was unavailable for service for 48 days in order to ensure that the fuel cell bus would be available for special limited service and events while waiting for a replacement fuel cell system. If those 48 days were removed from the availability calculation, the overall availability would have been 71%.

Between May 2007 and March 2008, the HHICE bus was mostly out of service because of issues with the engines. The problems, as described above, included two engine overheating incidents and an engine fire. These incidents caused the bus to be out of service 190 days during this time frame. If these days were removed from the availability calculation, the HHICE bus would have an availability of 83%.

During the evaluation period, three of the CNG buses had significant and long-term downtime for specific maintenance issues as discussed above. These long-term downtime issues caused these three buses to be unavailable from service for 184 days. If these issues were removed from the availability calculation, the new CNG-bus availability number would be 89%.

Fuel Economy and Cost

Table 3 shows hydrogen and CNG fuel consumption and fuel economy for the three study bus groups during the evaluation period. Using the GGE fuel economy and the CNG buses as the baseline, the fuel cell bus had a fuel economy 2.4 times higher than the CNG buses and the HHICE bus had a fuel economy 44% higher than the CNG buses. The fuel cell bus had a fuel economy 66% higher than the HHICE bus. Figure 8 shows average fuel economies for each of the three study groups of buses. Fuel economies were calculated as a moving two-month average so that any significant fluctuations could be smoothed out and the cyclical pattern based on higher temperatures causing lower fuel economies and vice versa could be clearly shown. However, the two lowest points shown on the chart for the fuel cell bus are affected more by the power degradation issue of the fuel cell power system than the ambient temperatures.

Table 3. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg) or CNG (GGE)	Miles per kg or GGE	Diesel Equivalent Amount (Gallon)	Miles per Gallon (DGE)
FC1	**50,391**	**7,079.0**	**7.19**	**6,264.6**	**8.13**
550 HHICE	**42,523**	**9,807.2**	**4.34**	**8,678.9**	**4.90**
563 CNG	83,579	28,038.1	2.98	25,094.1	3.33
565 CNG	101,493	33,977.5	2.99	30,409.9	3.34
566 CNG	85,680	28,608.8	2.99	25,604.9	3.35
567 CNG	82,806	26,767.8	3.09	23,957.2	3.46
568 CNG	101,122	33,404.8	3.03	29,897.3	3.38
CNG Total	**454,680**	**150,797.1**	**3.02**	**134,963.4**	**3.37**

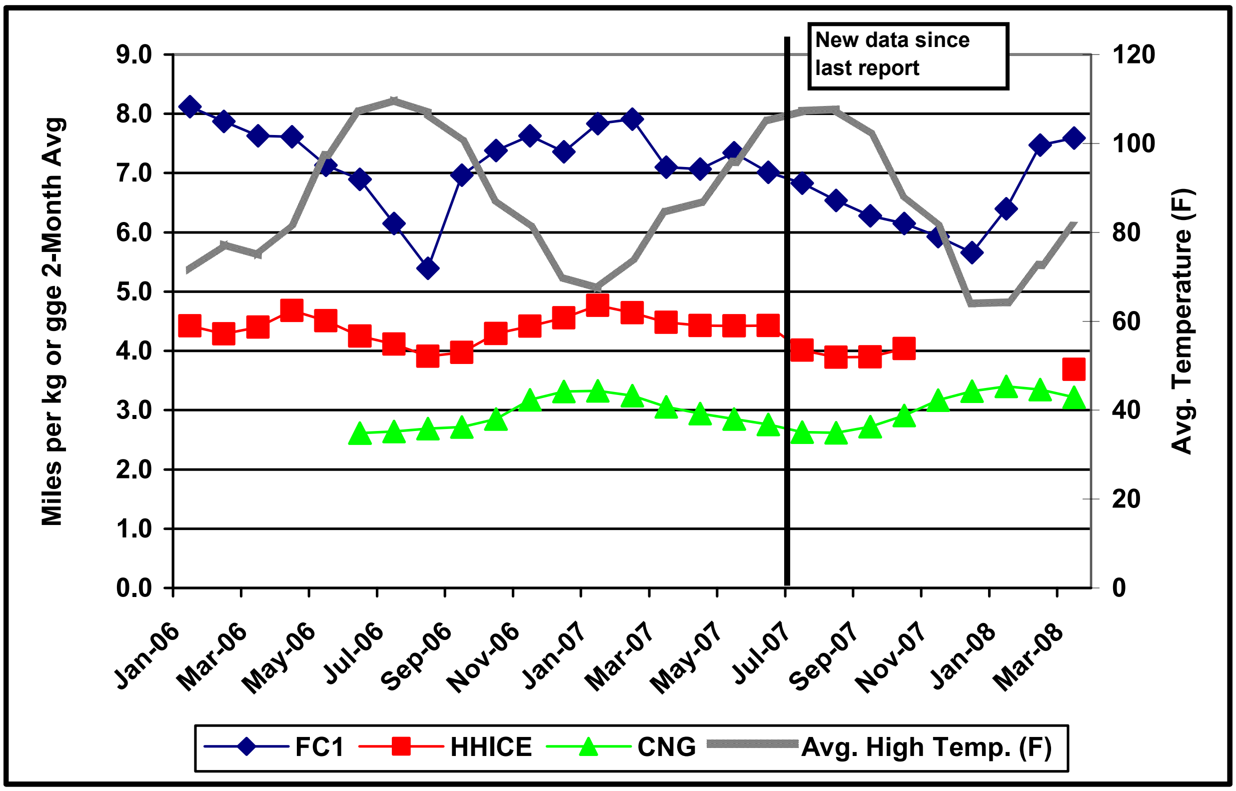

Figure 8. Two-month average fuel economy (miles per kg or GGE)

The fuel costs per mile for the three study groups of buses for the evaluation period were $1.11 per mile for the fuel cell bus; $1.85 per mile for the HHICE bus; and $0.44 for the CNG buses. The fuel cost for CNG has been much lower than the cost for hydrogen production.

Maintenance Analysis

The maintenance cost analysis in this section is only for the evaluation period (fuel cell bus and HHICE: January 2006 through March 2008; CNG: July 2006 through March 2008). Warranty costs are generally <u>not</u> included in the cost-per-mile calculations. All work orders for the study buses were collected and analyzed for this evaluation. For consistency, the maintenance labor rate was kept at a constant $50 per hour; this does not reflect an average rate for SunLine. This section first covers total maintenance costs, then maintenance costs broken down 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 4 shows total maintenance costs for the fuel cell, HHICE, and CNG buses. The CNG buses have the lowest total maintenance cost per mile of the three study bus groups. The per mile maintenance costs for the fuel cell and HHICE buses are 47% higher and 2.0 times higher, respectively, than the baseline/CNG buses. All three study bus groups were under warranty during the entire evaluation period. Although the HHICE bus is still under warranty, it has higher costs than the fuel cell bus because the SunLine mechanics do much more of the work on the HHICE bus than the fuel cell bus. The fuel cell bus maintenance is done almost exclusively by ISE Corp. and UTC Power, except for routine and non-drivetrain maintenance.

Table 4. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Cost ($) per Mile
Fuel Cell	**50,931**	**719.60**	**425.3**	**0.44**
HHICE	**43,528**	**4,389.76**	**425.3**	**0.59**
563 CNG	84,404	5,974.03	372.1	0.29
565 CNG	102,733	8,213.54	470.0	0.31
566 CNG	85,947	8,403.22	345.5	0.30
567 CNG	83,448	6,081.67	367.3	0.29
568 CNG	101,122	7,568.43	424.0	0.28
Total CNG	**457,654**	**36,240.89**	**1,978.8**	**0.30**
Avg. per Bus	**91,531**	**7,248.18**	**395.8**	**--**

Maintenance Costs Broken Down by System – Table 5 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**

The systems with the highest percentage of maintenance costs for all three study groups were propulsion-related, PMI, and cab, body, and accessories with some variation in the rank order.

Table 5. Breakdown of Vehicle System Maintenance Cost per Mile (Evaluation Period)

System	Fuel Cell		HHICE		CNG	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Cab, Body, and Accessories	0.06	14	0.05	9	0.07	24
Propulsion-Related	0.22	50	0.39	66	0.09	30
PMI	0.08	18	0.09	15	0.09	30
Brakes	0.01	2	0.00	0	0.00	0
Frame, Steering, and Suspension	0.02	5	0.00	0	0.01	3
HVAC	0.05	11	0.01	2	0.02	7
Lighting	0.00	0	0.02	3	0.01	3
Axles, Wheels, and Drive Shaft	0.00	0	0.00	0	0.00	0
Tires	0.00	0	0.03	5	0.01	3
Total	**0.44**	**100**	**0.59**	**100**	**0.30**	**100**

The cab, body, and accessories category had similar costs/mile for each of the three study bus groups, although the percent of totals were significantly different. The propulsion-related maintenance costs were high for the HHICE and fuel cell buses compared with the CNG buses, with the HHICE bus having the highest cost per mile. For the PMI category, all three bus groups had similar costs per mile. This is different from the last evaluation report in that the fuel cell bus PMI cost has gone up to match the other two study groups. SunLine's mechanics are participating more in the fuel cell bus maintenance.

The only other system maintenance category of note is the HVAC system for the fuel cell bus. The air conditioning on the fuel cell bus has required significant maintenance attention and has caused significant unavailability of the bus for service. The problem was with the evaporator and condenser motors, which were failing on a regular basis during the summer of 2006. SunLine was having difficulty keeping replacement motors in stock to keep the bus available for service. A redesign of the motors was implemented in September 2006, after the heat of the summer had passed. This problem appears to be resolved.

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 6 categorizes the propulsion-related system repairs for the three study bus groups during the evaluation period (no warranty). Each of the three study groups of buses was under warranty during the entire evaluation period. Also, the fuel cell and HHICE buses were maintained by the UTC Power and ISE technicians when significant repairs to the fuel cell power system or drive system were required. In most cases, the only costs captured here are for support by the SunLine mechanics to the manufacturer technicians. However, the new data included in this evaluation report indicate that the SunLine mechanics are getting more involved in repairs of the fuel cell bus.

- **Total propulsion-related** – The HHICE bus had the highest maintenance costs for these systems, followed by the fuel cell bus. The CNG buses had very low maintenance costs for these systems (as expected because the buses were new and featured fully commercial technology).
- **Exhaust** – There were few or no costs for this system for the three study groups of buses.
- **Fuel** – The fuel cell bus had the highest maintenance costs. The HHICE bus and CNG buses were nearly the same.
- **Powerplant and electric propulsion** – The fuel cell bus maintenance reported here involved almost exclusively SunLine mechanics supporting UTC Power and ISE technicians' work on the bus. One significant issue involved the ZEBRA batteries and the number of problems and changeouts of the three battery packs. The HHICE bus had issues with injectors and the turbocharger, which were repaired under warranty with support from SunLine. The only other repairs were for preventive maintenance. The preventive maintenance for the CNG buses was almost exclusively in the powerplant category (and none for electric propulsion).
- **Non-lighting electrical (charging, cranking, and ignition)** – The fuel cell bus had some costs in this category relating to 12-volt batteries and no-start maintenance. The HHICE bus had significant repairs with the standard batteries on the bus (nine changeouts and four roadcalls). Other maintenance costs included two sets of spark plugs and two sets of coils as well as injector replacements. The CNG buses mostly had preventive maintenance repairs in this category for spark plugs (23 sets of six) at the 18,000 preventive maintenance cycle for each bus. Other repairs in this category included changeout of coils, one starter under warranty, one voltage regulator under warranty, and four sets of batteries.
- **Air intake** – The fuel cell bus costs in this category were just for support by SunLine mechanics. The HHICE and CNG buses only had air filter changeouts in this category. The costs per mile for all three groups of buses were low and essentially the same.
- **Cooling** – The fuel cell bus had the highest cost per mile in this category. The HHICE bus required maintenance for problems with the low coolant sensor (replaced three times and caused two roadcalls). The CNG buses only had shake down issues for new buses for securing coolant lines and alarms.
- **Transmission** – Only the CNG buses had costs in this category for filters under preventive maintenance.

Table 6. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	HHICE	CNG
Mileage	50,931	43,528	457,654
Total Propulsion-Related Systems (Roll-up)			
Parts cost ($)	355.90	4,019.32	20,331.47
Labor hours	215.3	258.5	364.0
Total cost ($)	11,118.40	16,944.32	38,531.47
Total cost ($) per mile	**0.22**	**0.39**	**0.08**
Exhaust System Repairs			
Parts cost ($)	0.00	0.00	0.00
Labor hours	0.0	0.0	9.5
Total cost ($)	0.00	0.00	475.0
Total cost ($) per mile	**0.00**	**0.00**	**0.00**
Fuel System Repairs			
Parts cost ($)	0.00	12.04	1,006.59
Labor hours	8.0	24.5	32.5
Total cost ($)	400.00	1,237.04	2,631.59
Total cost ($) per mile	**0.01**	**0.03**	**0.01**
Powerplant System Repairs			
Parts cost ($)	0.00	314.23	8,810.54
Labor hours	64.5	149.5	213.8
Total cost ($)	3,235.01	7,789.23	19,498.04
Total cost ($) per mile	**0.06**	**0.18**	**0.04**
Electric Propulsion System Repairs			
Parts cost ($)	0.00	0.00	0.00
Labor hours	115.0	1.8	0.0
Total cost ($)	5,750.00	87.50	0.00
Total cost ($) per mile	**0.11**	**0.00**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)			
Parts cost ($)	335.90	3,396.76	7,465.67
Labor hours	2.0	62.0	49.8
Total cost ($)	455.90	6,496.76	9,953.17
Total cost ($) per mile	**0.01**	**0.15**	**0.02**
Air Intake System Repairs			
Parts cost ($)	0.00	235.66	2,138.88
Labor hours	7.0	2.5	3.5
Total cost ($)	350.00	360.66	2,313.88
Total cost ($) per mile	**0.01**	**0.01**	**0.01**
Cooling System Repairs			
Parts cost ($)	0.00	60.63	142.96
Labor hours	15.0	17.8	45.0
Total cost ($)	750.00	948.13	2,392.96
Total cost ($) per mile	**0.02**	**0.02**	**0.01**
Transmission System Repairs			
Parts cost ($)	0.00	0.00	766.83
Labor hours	0.3	0.5	10.0
Total cost ($)	12.50	25.00	1,266.83
Total cost ($) per mile	**0.00**	**0.00**	**0.00**

Roadcall Analysis

A roadcall (RC) or revenue vehicle system failure (as named in the National Transit Database[4]) 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 schedule is kept, this is not considered a RC. The analysis provided here only includes RCs that were 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), engine problems, etc. They do not include RCs for things such as radios, HVAC, or destination signs.

Table 7 shows the RCs and miles between roadcalls (MBRC) for each study bus in two categories: all RCs and propulsion-related-only RCs. The fuel cell and HHICE buses have had several RCs and low vehicle usage, which is indicative of the prototype nature of these two buses. Compared to the fuel cell bus, the HHICE bus has slightly higher MBRC rates for both the all-roadcalls category and the propulsion-only category. For the fuel cell buses, 20 of the total RCs were directly related to the ZEBRA batteries, and seven were due to the fuel cell powerplant. (The fuel cell powerplant RCs include both fuel cell and balance of plant components.) If the ZEBRA battery RCs were removed, the rates would be 3,395 MBRC for all roadcalls and 4,244 MBRC for propulsion only. The MBRC specific to the fuel cell powerplant equate to 7,276.

Table 7. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC
Fuel Cell	**50,931**	**35**	**1,455**	**32**	**1,592**
HHICE	**43,528**	**21**	**2,073**	**19**	**2,291**
563 CNG	84,404	9	9,378	5	16,881
565 CNG	102,733	11	9,339	5	20,547
566 CNG	85,947	6	14,325	0	
567 CNG	83,448	13	6,419	2	41,724
568 CNG	101,122	7	14,446	3	33,707
Total CNG	**457,654**	**46**	**9,949**	**15**	**30,510**

[4] Federal Transit Administration's National Transit Database Web site: www.ntdprogram.gov/ntdprogram/

What's Next for SunLine?

This report covers SunLine operation of the fuel cell, HHICE, and CNG buses through March 2008. SunLine, FTA, UTC Power, and ISE Corp. have entered into a new agreement to operate a new fuel cell power system for another two year period. The new power system is expected to be much more durable than the previous versions. This fuel cell power system was installed in April 2008 and the bus has re-started normal eight-hour service seven days per week. This service may be increased up to 16 hours per day depending on the availability of replacement ZEBRA batteries. The next report, expected near the end of 2008, will describe all of this new service and experience. NREL expects to continue to track the fuel cell bus and CNG buses in this evaluation through the next two years. In addition, NREL will track the following two new fuel cell bus projects.

Advanced Fuel Cell Bus Project: In 2002, SunLine tested an early prototype hybrid fuel cell bus in service for six months. The system was designed by ISE on a 30-foot Thor bus chassis. SunLine plans to demonstrate this bus with a new hybrid FC powertrain under funding from CARB, AQMD, and FTA. ISE Corporation is leading the design effort, and will include the newest design fuel cell from Ballard and advanced lithium batteries. The bus is expected to be ready for service in fall of 2008 and will operate for at least two years.

American Fuel Cell Bus Project: Funded under the FTA's National Fuel Cell Bus Program, SunLine is leading a team to develop a purpose-built fuel cell bus that meets "Buy America" requirements. The design features a number of advancements that are expected to result in a highly efficient bus. Elements include:

- Lightweight, U.S. built, bus body
- Advanced windows to reduce interior heat
- Advanced energy storage and new power electronics
- High efficiency accessories
- Newest generation fuel cell

Project partners include ISE Corporation for the hybrid system and integration, UTC Power for the fuel cell power system, and New Flyer for the advanced design bus chassis. The demonstration is part of the portfolio of projects for the Pasadena-based consortia, WestStart-CALSTART.

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Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
CARB	California Air Resources Board
CNG	compressed natural gas
CTA	Center for Transportation and the Environment
CWI	Cummins Westport Inc.
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
FCB	fuel cell bus
ft	feet
FTA	Federal Transit Administration
GGE	gasoline gallon equivalent
HFCIT	Hydrogen, Fuel Cells, and Infrastructure Technology
HHICE	hydrogen hybrid internal combustion engine
hp	horsepower
HVAC	heating, ventilation, and air conditioning
ICE	internal combustion engine
in	inches
kg	kilogram
kW	kilowatts
lb	pounds
LFL	lower flammability limit
LNG	liquefied natural gas
MBRC	miles between roadcalls
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
NAVC	Northeast Advanced Vehicle Consortium
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
PSA	pressure swing adsorption
psi	pounds per square inch
RC	roadcall
rpm	revolutions per minute
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: a Legacy for Users
SCAQMD	South Coast Air Quality Management District

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Hydrogen and fuel cell related: www.nrel.gov/hydrogen/proj_fc_bus_eval.html
Hybrid and other technologies: www.nrel.gov/vehiclesandfuels/fleettest/publications_bus.html

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
June 2008

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
SunLine Transit Agency Hydrogen-Powered Transit Buses: Third Evaluation Report and Appendices

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kevin Chandler, Leslie Eudy

5d. PROJECT NUMBER
NREL/TP-560-43741

5e. TASK NUMBER
H2708200

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-560-43741

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This report describes operations at SunLine Transit Agency for a protoype fuel cell bus, a prototype hydrogen hybrid interal combustion engine bus, and five new compressed natural gas buses.

15. SUBJECT TERMS
fuel cell bus; hybrid; transit; SunLine; bus; HHICE

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(09/2007)