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SunLine Transit Agency

Hydrogen-Powered Transit Buses: Evaluation Results Update

Kevin Chandler, Battelle
Leslie Eudy, National Renewable Energy Laboratory

Technical Report
NREL/TP-560-42080
October 2007

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Executive Summary

In early 2007, the National Renewable Energy Laboratory (NREL) published a preliminary evaluation results report[1] (January 2006 through November 2006) on hydrogen- and CNG-fueled buses operating at SunLine Transit Agency (SunLine) in Thousand Palms, California (Palm Springs Coachella Valley area). This report provides an update to the previous report and includes results and experience from December 2006 through June 2007. The evaluation covers one prototype fuel cell bus, one prototype hydrogen hybrid internal combustion engine (HHICE) bus, and five new CNG baseline buses operating from the same SunLine bus depot. The evaluation periods presented in this report are as follows:

- **Fuel Cell Bus** – January 2006 through June 2007 (18 months of operation)
- **HHICE Bus** – January 2006 through June 2007 (18 months of operation)
- **New CNG Buses** – July 2006 through June 2007 (12 months of operation)

The fuel cell bus was manufactured by Van Hool and ISE Corp. and features an electric hybrid drive system with a UTC Power PureMotion[2] 120 Fuel Cell Power System and ZEBRA batteries for energy storage. The HHICE bus from New Flyer has essentially the same electric hybrid drive system from ISE Corp. but with ultracapacitors for energy storage and a Ford V10 Triton engine customized to operate on hydrogen fuel. The new CNG buses from Orion Bus Industries use Cummins Westport C Gas Plus natural gas engines.

This evaluation of prototype fuel cell and HHICE transit buses at SunLine is a part of the U.S. Department of Energy's (DOE) Hydrogen, Fuel Cells & Infrastructure Technologies Program (HFCIT). This program integrates activities in hydrogen production, storage, and delivery with transportation and stationary fuel cell applications. This evaluation focuses on documenting progress and opportunities for improving the vehicles, infrastructure, and procedures. **There is no intent to consider the implementation of these hydrogen-fueled transit buses as commercial (or full revenue transit service).**

Hydrogen Fueling Experience – Update

During the evaluation period (January 2006 through June 2007), SunLine dispensed a total of 13,771 kg of hydrogen. The station was used at least once per day to fill at least one of the two hydrogen buses for 83% of the calendar days during the period. The overall average daily usage was 30.5 kg per day. The two buses were filled a total of 726 times during the evaluation period, with an average fill amount of 19.0 kg. The HHICE bus fuelings averaged 20.4 kg, while the fuel cell bus averaged 17.0 kg. During the March through June 2007 time period, the average fueling rate was 0.97 kg/min based on 111 fueling events for a total of 2,358 kg.

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

[2] PureMotion is a trademark of UTC Power

One major incident occurred with SunLine's hydrogen reformer. On April 4, 2007, the hydrogen reformer had a component failure in the hydrogen purification subsystem. The fault was automatically detected and the unit was shutdown, but not before some amount of contaminants broke through to the downstream low pressure hydrogen storage. This fuel quality issue was not a concern for the HHICE bus, but was potentially a significant concern with the fuel cell bus. The hydrogen storage for the fuel station and for the two buses was purged and replaced with "clean" hydrogen. It did appear that the fuel cell bus received some of the lower quality hydrogen fuel, which had a direct impact on the fuel cell system. The fuel cell system showed a degraded power output, but UTC Power reported that the contaminants did not appear to cause any permanent damage (the fuel cell system power output recovered with the use of "clean" hydrogen). This issue has been resolved and the buses were up and running at normal levels before the end of the evaluation period. The reformer incident was resolved within 24 hours and the unit was producing high purity hydrogen.

Bus Experience – Update

In the preliminary evaluation results report for SunLine, there were several issues described for each of the study bus groups (fuel cell, HHICE, and CNG). The following descriptions update those issues and provide additional issues and descriptions, if necessary.

Fuel Cell Bus. As mentioned in the preliminary report, the fuel cell bus experienced several issues that affected performance and availability. The three primary issues were the ZEBRA batteries, the AC system, and the fuel cell power system (cell stack assembly [CSA]). An update on the status of these problems follows.

- **ZEBRA batteries** – These batteries have had significant problems in this application. The main challenges have been accommodating cell failures and optimizing the state of charge (SOC) algorithm. The issues with using the three ZEBRA batteries have continued, but experience and planning has helped alleviate the extreme problems of trying to keep the fuel cell bus available for service. ISE has been able to make more of the batteries available, and a battery is always kept up to temperature and charge for quick replacement when needed.
- **Air Conditioning** – SunLine's summer operation exposes buses to extreme heat conditions, with average high temperatures reaching the 110-120° F range. Also, the hybrid design is unique because the air conditioning (A/C) unit is driven electrically instead of mechanically (by belt) like most vehicles. During the summer of 2006, the A/C system experienced problems with failed evaporator and condenser motors. SunLine worked with the A/C manufacturer to replace the failing motors with a newer design. The new motor is working well and the problem has not resurfaced. The bus had not experienced any A/C issues as of June of 2007; even though the temperature reached as high as 113° F (monthly average high temperature was 105° F).
- **UTC Power PureMotion 120 Fuel Cell Power System** – As reported in the preliminary evaluation results report, the CSAs for the fuel cell bus were replaced with an improved design CSA toward the end of September 2006. However, the power degradation issue reappeared after only a few months of operation. SunLine and UTC Power agreed to perform accelerated testing of the fuel cell power system, and in January 2007, SunLine operated the fuel cell bus for 5,125 miles. After this accelerated testing, UTC Power

determined that the power degradation problem was not resolved and the CSAs were again replaced in March 2007 (with the same design as those installed in September 2006). The current plans are to operate the fuel cell bus for eight hours/day and five days per week until the currently planned end of demonstration (and warranty period) around the end of November or sometime in December 2007.

HHICE bus. From January 2006 through May 2007, the HHICE bus performed well, experiencing only a few problems in performance. However, in late May, the bus was road called for a broken fan belt. The engine had continued to run without the belt, causing the engine to overheat, which resulted in a blown head gasket. There was no software mode that would protect the engine from this condition; however, that situation has now been corrected. The bus was down for repair during May and June.

CNG buses. This bus order has had one significant problem so far. There has been an isolation issue between the exhaust and the wiring and panels in the bus. Work has been done to develop a better thermal blanket and reposition some of the exhaust stack and wiring.

Evaluation Results – Update

Table ES-1 provides a summary of results for many of the categories presented in this report. Note that fuel economy for the hydrogen-fueled buses are shown in miles per kilogram of hydrogen and the CNG buses are shown in miles per gasoline gallon equivalent (GGE). These units are essentially the same and comparable.

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell	HHICE	CNG
Number of Buses	1	1	5
Data Period	1/06-6/07	1/06-6/07	7/06-6/07
Number of Months	18	18	12
Total Mileage in Period	37,005	38,853	265,107
Average Monthly Mileage per Bus	2,056	2,159	4,418
Availability (85% is target)	65%	77%	87%
Fuel Economy (Miles/kg or GGE)	7.37	4.39	2.95
Miles between Roadcalls (MBRC) – All	1,194	2,428	10,604
MBRC – Propulsion Only	1,322	2,775	37,872
Total Maintenance, $/mile	0.46	0.58	0.27
Maintenance – Propulsion Only, $/mile	0.24	0.37	0.07

What's Next for This Demonstration?

This report covers SunLine operation of the fuel cell, HHICE, and CNG buses through June 2007. The next evaluation report for this site will include operational data through December 2007 and is planned for release around March 2008.

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. Figure 1 shows the service area covered by the agency. 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.

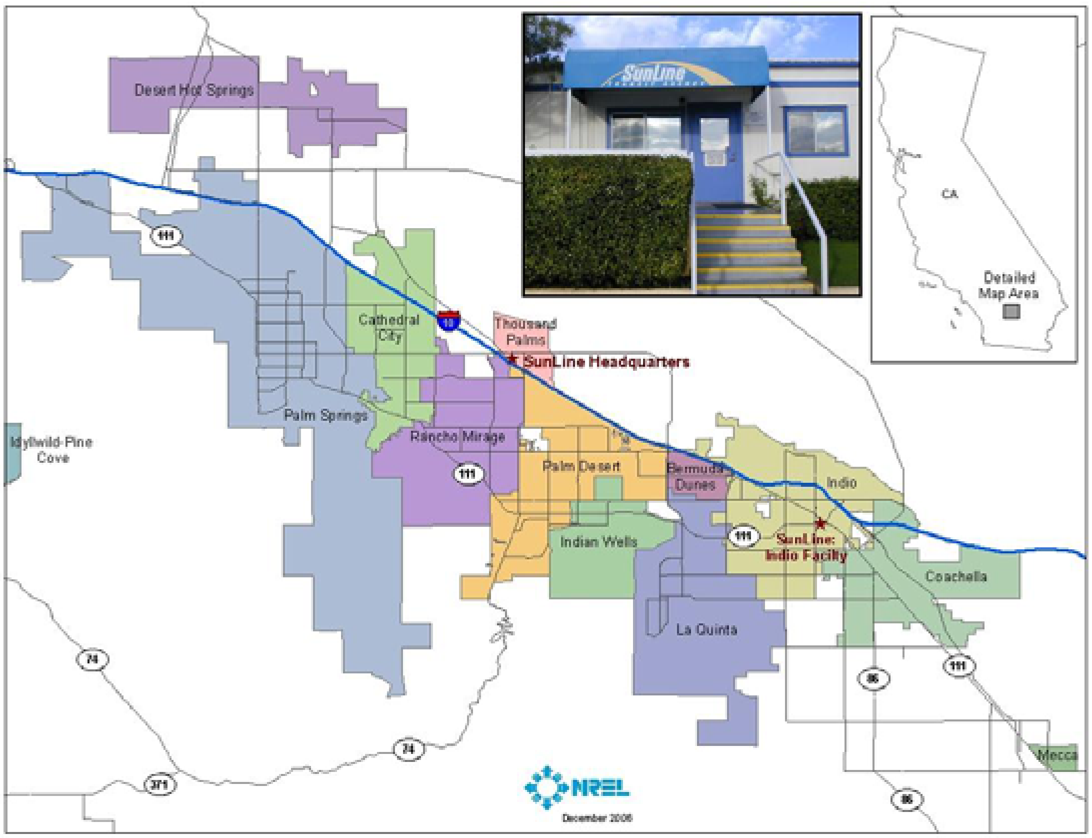


Figure 1. SunLine service area in the Coachella Valley, California

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 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. This HHICE bus has been in operation 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. The buses are pictured in Figure 2.

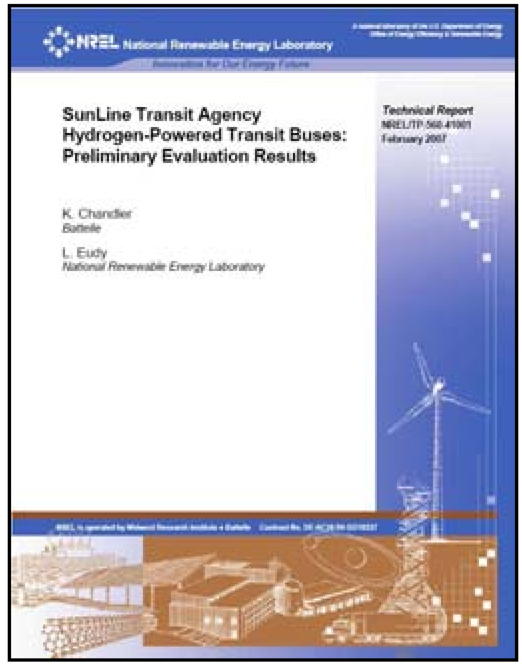
Figure 2. Fuel cell (top) and HHICE (bottom) transit buses at SunLine

These buses are operated in the Coachella Valley, which is a desert region with annual rainfall around five inches per year. Average high temperatures are typically above 80° F for eight months of the year, and can get as high as 120° F. These conditions make the area an excellent location for investigating the effects of heat and low humidity on advanced propulsions systems. SunLine is working closely with UTC Power and ISE on the project. These demonstrations are critical to understanding how these prototype systems and components perform in the field. The manufacturers use the data collected to verify the results from controlled laboratory tests and to further optimize and improve their advanced propulsion systems for commercialization.

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 (Figure 3).

Figure 3. New 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. A preliminary data report was published in February 2007.[3] This report included descriptions of the propulsion and fueling technologies, details on the early experiences, lessons learned, and 11 months of preliminary operations data on the hydrogen-fueled buses. Evaluation results were also provided for new CNG transit buses as a baseline comparison to the prototype hydrogen-fueled transit buses.



This update report provides results and experience from December 2006 through June 2007, which is in addition to those provided in the preliminary evaluation results report. This report includes data on one prototype fuel cell bus, one prototype HHICE bus, and five new CNG baseline buses operating from the same SunLine bus depot. The evaluation periods presented in this report are as follows:

- **Fuel Cell Bus** – January 2006 through June 2007 (18 months of operation)
- **HHICE Bus** – January 2006 through June 2007 (18 months of operation)
- **New CNG Buses** – July 2006 through June 2007 (12 months of operation)

Infrastructure and Facilities

Fueling facilities at SunLine include private and public access for CNG, liquefied natural gas (LNG), compressed hydrogen, and a blend of hydrogen and CNG. SunLine produces hydrogen on site using a natural gas reformer. The HyRadix Adéo (Figure 4) is a commercial product that uses a proprietary catalytic auto-thermal reforming technology. The new unit was installed at SunLine in August of 2006, and is capable of producing 9 kg of hydrogen per hour. SunLine typically operates the unit at 4.5 kg per hour due to current hydrogen consumption. Figure 5 shows the fuel cell bus at the SunLine hydrogen fueling dispenser.

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

Figure 4. SunLine's HyRadix Adéo commercial reformer

Figure 5. SunLine's fuel cell bus during fueling

Hydrogen Fueling Experience – Update

Figure 6 shows total monthly hydrogen dispensed into the two hydrogen-fueled buses for January 2006 through June 2007. 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 83% of the calendar days during the period. The overall average daily usage was 30.5 kg per day. During this period, SunLine dispensed a total of 13,771 kg of hydrogen.

The highest daily hydrogen usage was during January 2007, because the fuel cell bus was operated more than 5,000 miles in one month and the HHICE bus was operated at its normal level at the same time. The daily fuel usage decreased during April and May 2007 because of a hydrogen production quality incident and the subsequent purging process that followed (over a three week period). Hydrogen use also decreased toward the end of May 2007 and during all of June 2007 because the HHICE bus was out of service.

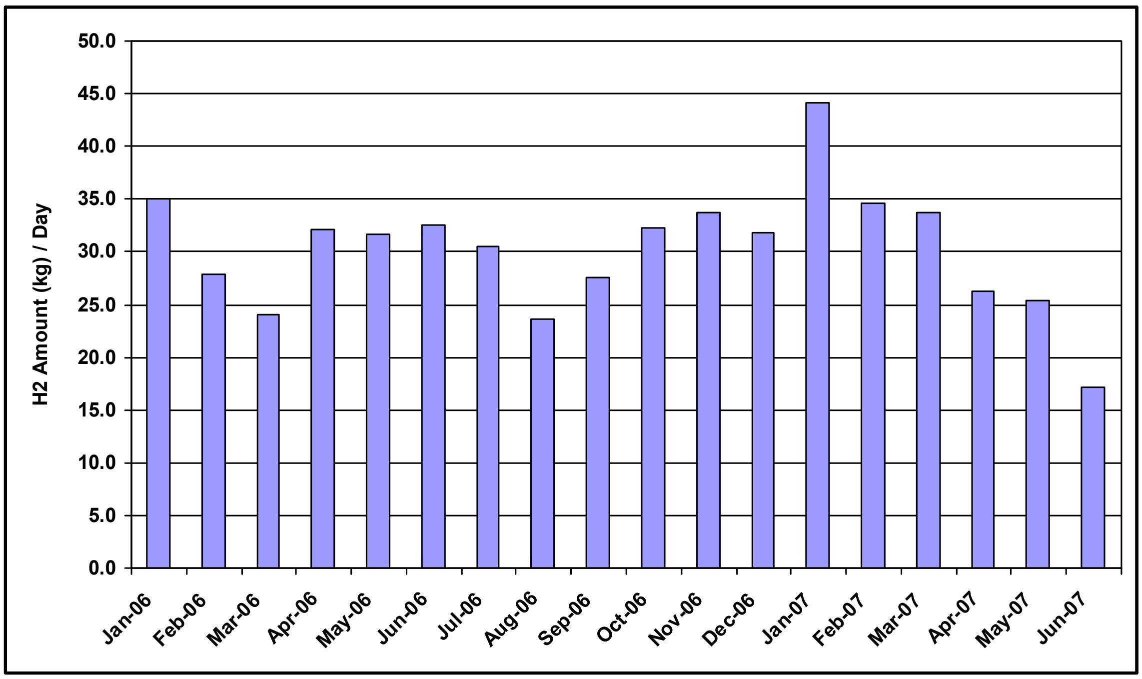


Figure 6. Average hydrogen dispensed per day (excluding 0 kg days)

Figure 7 shows the distribution of hydrogen amounts per fill. The two buses were filled a total of 726 times during the evaluation period, with an average fill amount of 19.0 kg. The HHICE bus fuelings averaged 20.4 kg, while the fuel cell bus averaged 17.0 kg.

Figure 8 shows the cumulative fueling rate histogram for the SunLine station from March through June 2007. (Prior to March, this data was not available.) During this time, there were 111 fueling events for a total of 2,358 kg. The overall average fueling rate was 0.97 kg/min.

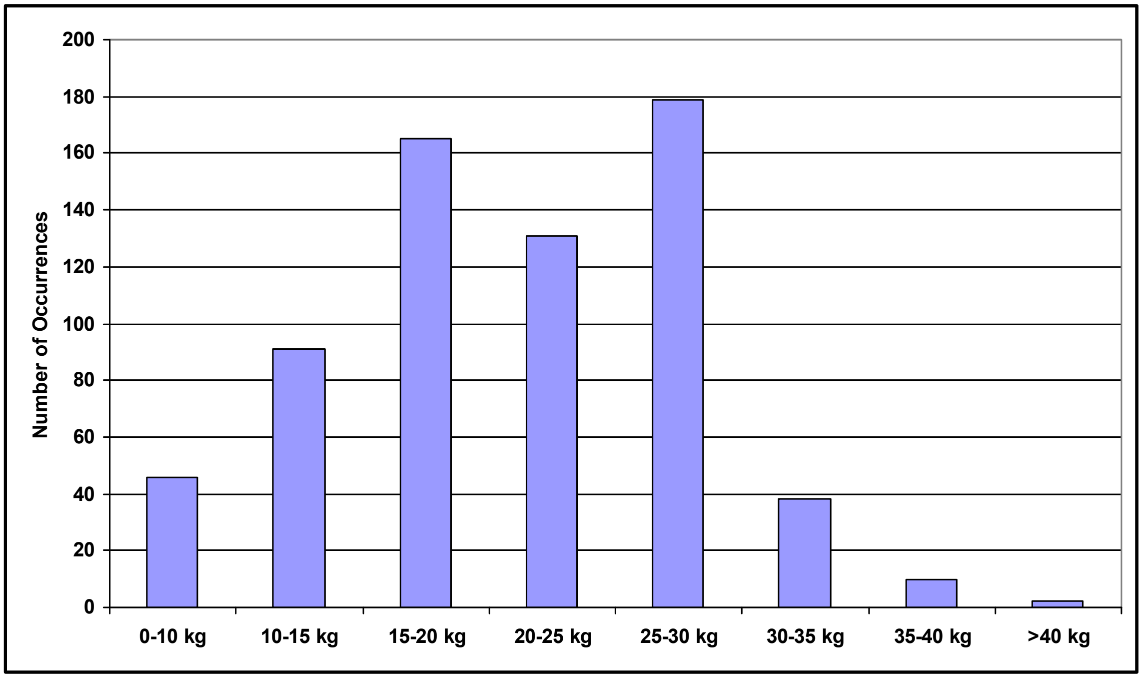


Figure 7. Distribution of fueling amounts

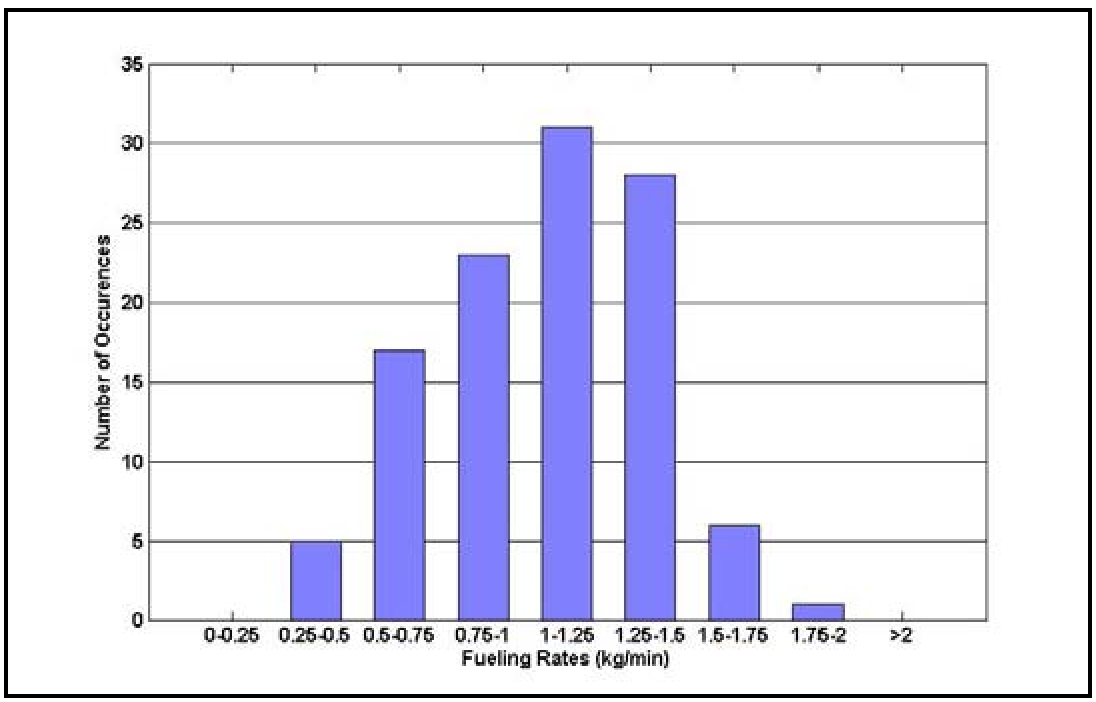


Figure 8. Cumulative fueling rate histogram

Hydrogen fuel quality issue – On April 4, 2007, the Adéo hydrogen reformer suffered a component failure in the hydrogen purification subsystem (PSA system). The fault was automatically detected and the Adéo unit was shutdown, but not before some amount of contaminants broke through to the downstream low pressure hydrogen storage.

SunLine staff immediately isolated and purged the low pressure storage to remove the contaminants before resuming fueling operations. Later, sampling revealed that the purging had not been sufficient and some of the contaminants had made their way into the storage tank of the fuel cell bus. By proceeding cautiously, SunLine personnel were able to correct this without serious damage to the fuel cell power system although this resulted in several extra days out of service for the bus.

The root cause was traced to an isolated failure of an electrical component. While this failure also exposed some software bugs that allowed the system to export off-spec hydrogen, it did not represent a chronic failure of the system – in particular the PSA adsorbent was not damaged. The repair and recovery were quick and the system was back up and producing high purity hydrogen within 24 hours of the failure.

Subsequently, the software bugs have been further isolated and fixed. Among the lessons learned are that a more conservative approach should be taken when purging contaminants from the storage system. Additional gas samples are important in helping to determine if all the contaminants have been purged from the system.

Fuel Cell, Hydrogen Engine, and CNG Buses

Table 1 provides bus system descriptions for the fuel cell, HHICE, and new CNG buses included in this evaluation. The prototype fuel cell bus in service at SunLine was developed in collaboration between ISE Corporation, UTC Power, and Van Hool. The bus uses the PureMotion 120 Fuel Cell Power System manufactured by UTC Power in a hybrid electric drive system designed by ISE. This fuel cell bus started revenue service at SunLine in late December, 2005.

The ISE Corp./New Flyer HHICE bus was purchased by SunLine as part of a joint FTA/SCAQMD project in 2004. The bus went into service in December 2004. The new CNG buses from Orion were purchased in 2005 and were delivered in June 2006. For this evaluation, five buses from an order of 15 new Orion V CNG buses were selected for a baseline comparison to the fuel cell and HHICE buses at SunLine. These CNG buses, as well as the two hydrogen-fueled buses, are operated from the Thousand Palms operating depot.

Table 2 provides descriptions of some of the electric propulsion systems for the fuel cell and HHICE buses. The electric propulsion systems for these two buses are nearly identical except for the energy storage and slightly greater hydrogen storage on the HHICE bus. Note that the CNG buses are not a hybrid configuration and do not have regenerative braking or energy storage for the drive system. The bus systems were described in detail in the preliminary evaluation report, published in February, 2007.

Table 1. Fuel Cell, HHICE, and CNG Bus System Descriptions

Vehicle System	Operation from Thousand Palms Depot		
	Fuel Cell Bus	HHICE Bus	CNG Bus
Number of Buses	1	1	5
Bus Manufacturer and Model	Van Hool A330 Low floor	New Flyer TB-40 Low floor	Orion V High floor
Model Year	2005	2004	2006
Length/Width/Height	40 ft/102 in/139 in	40 ft/102 in/137 in	40 ft/102 in/135 in
GVWR/Curb Weight	43,240 lb/36,000 lb	40,000 lb/32,032 lb	40,600 lb/29,600 lb
Wheelbase	228 in	293 in	280 in
Passenger Capacity	30 seated or 26 seated and two wheelchairs 15 standing	39 seated or 33 seated and two wheelchairs 13 standing	44 seated or 38 seated and two wheelchairs 21 standing
Engine Manufacturer and Model	UTC Power PureMotion 120 Fuel Cell Power System	Ford 6.8 liter Triton V10 hydrogen	Cummins C Gas Plus
Drive Motor Rated Power	170 kW	150 kW @ 3100 rpm	280 hp @ 2400 rpm
Accessories	Electrical	Electrical	Mechanical
Emissions Equipment	None	None	Catalytic converter
Transmission/Retarder	Gearbox/Flenders Regenerative braking	Gearbox/Flenders Regenerative braking	ZF 5HP592 Integrated retarder
Fuel Capacity	50 kg hydrogen	58 kg hydrogen	125 DGE
Bus Purchase Cost	$3.1 million	$1 million to $2 million	$375,000

Table 2. Additional Electric Propulsion System Descriptions

Propulsion Systems	Fuel Cell Bus	HHICE Bus
Manufacturer/Integrator	ISE Corporation	ISE Corporation
Hybrid Type	Series, charge sustaining	Series, charge sustaining
Drive System	Siemens ELFA/ISE	Siemens ELFA/ISE
Propulsion Motor	2-AC induction, 85 kW each	2-AC induction, 85 kW each
Energy Storage	Battery – 3 modules/216 cells sodium/nickel chloride ZEBRA®; 53 kWh capacity	Ultracapacitors – 2 packs/144 modules each; Maxwell; 0.6 kWh capacity
Fuel Storage	Eight, roof mounted, SCI, type 3 tanks; 5,000 psi rated	Eight, roof mounted, SCI, type 3 tanks; 5,000 psi rated
Regenerative Braking	Yes	Yes

Bus Experience – Update

In the preliminary evaluation results report for SunLine, there were several issues described for each of the study bus groups (fuel cell, HHICE, and CNG). The following descriptions update those issues and provide additional issues and descriptions, if necessary.

Fuel Cell Bus: As mentioned in the preliminary report, the fuel cell bus experienced several issues that affected performance and availability. The three primary issues were the ZEBRA batteries, the AC system, and the fuel cell power system (CSA). An update to the status of these problems follows.

- **ZEBRA batteries** – These batteries have had significant problems in this application. The main challenges have been accommodating cell failures and optimizing the state of charge (SOC) algorithm. The issues with using the three ZEBRA batteries have continued, but experience and planning has helped alleviate the extreme problems of trying to keep the fuel cell bus available for service. ISE has been able to make more of the batteries available, and a battery is always kept up to temperature and charge for quick replacement when needed.
- **Air Conditioning** – SunLine's summer operation exposes buses to extreme heat conditions, with average high temperatures reaching the 110-120° F range. Also, this hybrid design is unique because the air conditioning (A/C) unit is driven electrically instead of mechanically (by belt) like most vehicles. During the summer of 2006, the A/C system experienced problems with failed evaporator and condenser motors. SunLine worked with the A/C manufacturer to replace the failing motors with a newer design. The new motor is working well and the problem has not resurfaced. The bus has not experienced any A/C issues through June of 2007, even though the temperature reached as high as 113° F (monthly average high temperature was 105° F).
- **UTC Power PureMotion 120 Fuel Cell Power System** – As reported in the Preliminary Evaluation Results report, the CSAs for the fuel cell bus were replaced with an improved CSA toward the end of September, 2006. However, the power degradation issue reappeared after only a few months of operation. SunLine and UTC Power agreed to conduct accelerated testing of the fuel cell power system, and in January 2007, SunLine operated the fuel cell bus for 5,125 miles. After this accelerated testing, UTC Power determined that the power degradation problem was not resolved, and the CSAs were again replaced in March 2007 (with the same design as those installed in September 2006). The current plans are to operate the fuel cell bus for eight hours/day and five days per week until the currently planned end of demonstration (and warranty period) around the end of November or sometime in December 2007.
- **Charging** – The fuel cell bus is plugged into a charge port overnight to balance the charge between batteries, top off the charge, and provide heat for the batteries and fuel cell.

HHICE Bus: From January 2006 through May 2007, the HHICE bus performed well, experiencing only a few problems in performance. However, in late May, the bus was road called for a broken fan belt. The engine had continued to run without the belt, causing the engine to overheat, which resulted in a blown head gasket. There was no software mode that would protect the engine from this condition. This engine was replaced and the software for the engine now includes redundant, fail safe protection for issues such as this.

The bus was down for repair during May and June. The engine was torn down for inspection. There was clearly less wear on this engine compared to the previous engine that was replaced back in December 2005. One addition for the new installation will be a 10 micron coalescing filter for the fuel. The bus was not yet back into service by the end of the evaluation period covered in this report.

CNG Buses: This bus order has had one significant problem so far. There has been an isolation issue between the exhaust and the wiring and panels in the bus. Work has been done to develop a better thermal blanket and reposition some of the exhaust stack and wiring.

Evaluation Results

Both the fuel cell and HHICE buses were in service during a portion of December 2005, but this is not included in the evaluation because of low bus use during the month. This also helps remove some of the start-up issues at the very beginning of operation. This has also been done for the new CNG buses. These buses went into service near the end of June 2006, and the evaluation period started on July 1, 2006.

In this evaluation results update report, both the fuel cell and HHICE buses are considered 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 Descriptions

SunLine operates 12 fixed routes in the Coachella Valley along State Highway 111 and Interstate 10. Table 3 shows a weekly summary of bus usage at SunLine, and indicates that bus service operates at an average of 12.7 mph on the weekends and 13.4 mph during the week for an overall average of 13.2 mph. The weather plays a role in how the SunLine buses are operated. During the eight months in the year when the average high temperature is above 80° F, drivers typically idle on the shorter layovers to keep the buses cool for passengers. This causes the bus average speed to go down and the air conditioning load to go up, both of which have a significant impact on fuel efficiency.

Table 3. Summary of Total Weekly Bus Usage at SunLine

Day of Week	Total Miles	Hours	Average Speed
Weekday	30,534.5	2,278.5	13.4
Weekend	8,777.4	693.8	12.7
Total	**39,311.9**	**2,972.3**	**13.2**

Buses at the two SunLine operating locations are generally dispatched randomly. However, the HHICE bus has been used almost exclusively on Line 50 (average speed of 14.1 mph), except for a few days on Line 30 and Line 31 in January 2006. The fuel cell bus has been used on Line 50 (operated 112 days) and Line 111 (operated 37 days, average speed of 14.3 mph). In-service data indicate an average operating speed of 13.1 mph based on mileage and fuel cell system operating hours. The new CNG buses have been randomly dispatched.

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.

Figure 9 shows mileage and fuel cell system operating hour accumulation for the fuel cell bus during the evaluation period (January 2006 through June 2007). Total mileage accumulation for the evaluation period was 37,005 miles (17,797 miles since the last evaluation report), and the fuel cell system accumulated 2,822 hours (1,335 hours since the last evaluation report). These numbers indicate an overall average speed of operation at 13.1 mph (average of 13.3 mph since the last evaluation report), which is nearly the same as the overall SunLine operation speed of 13.2 mph.

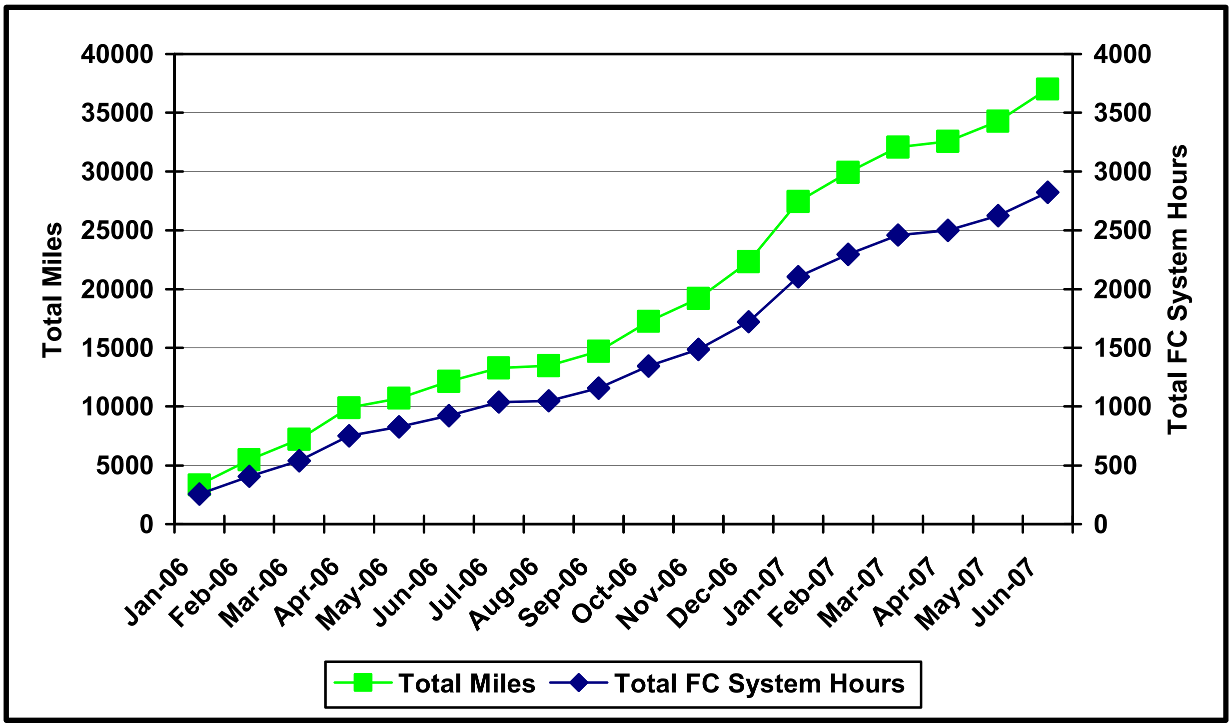


Figure 9. Cumulative mileage and fuel cell hours for one fuel cell bus

Table 4 summarizes 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 average monthly mileage 47% of CNG operation and the HHICE bus had average monthly mileage 49% of CNG operation. This is consistent in that the fuel cell and HHICE buses are being used at half the rate of the baseline CNG buses.

Table 4. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average
FC1	**2,865**	**39,870**	**37,005**	**18**	**2,056**
550 HHICE	**17,481**	**56,334**	**38,853**	**18**	**2,159**
563 CNG	4,916	59,855	54,939	12	4,578
565 CNG	7,637	64,738	57,101	12	4,758
566 CNG	5,576	48,240	42,644	12	3,554
567 CNG	7,104	60,522	53,418	12	4,452
568 CNG	6,388	63,373	56,985	12	4,749
Total CNG			**265,107**	**60**	**4,418**

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 10 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. The chart shows that the CNG buses are essentially right on the goal (average of 87%). The HHICE bus was at or above the availability target except for July-August 2006 and May-June 2007 (average 77%). During this timeframe, the HHICE bus was out of service because of a lack of hydrogen availability during the installation of the new HyRadix reformer unit and during the more recent period, the bus was out of service for engine failure and replacement.

The fuel cell bus availability was much lower than the availability target during May through September 2006 because of problems with the A/C and the fuel cell systems, as discussed above in the experience update section. The fuel cell bus also had more downtime during February 2007 through May 2007 to have the fuel cell CSAs replaced again, for ongoing battery problems, and because of a lack of fuel availability.

Table 5 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 65%, the HHICE bus was 77%, and the CNG buses were 87%. Issues that kept the fuel cell bus out of service included problems with the air conditioning (22%), fuel cell system (29%), and ZEBRA batteries (19%). Issues that kept the HHICE bus out of service included problems with the drive system (63%), lack of hydrogen fuel (29%), and general maintenance activities (8%). Issues that kept the CNG buses out of service included general maintenance and some air conditioning repairs.

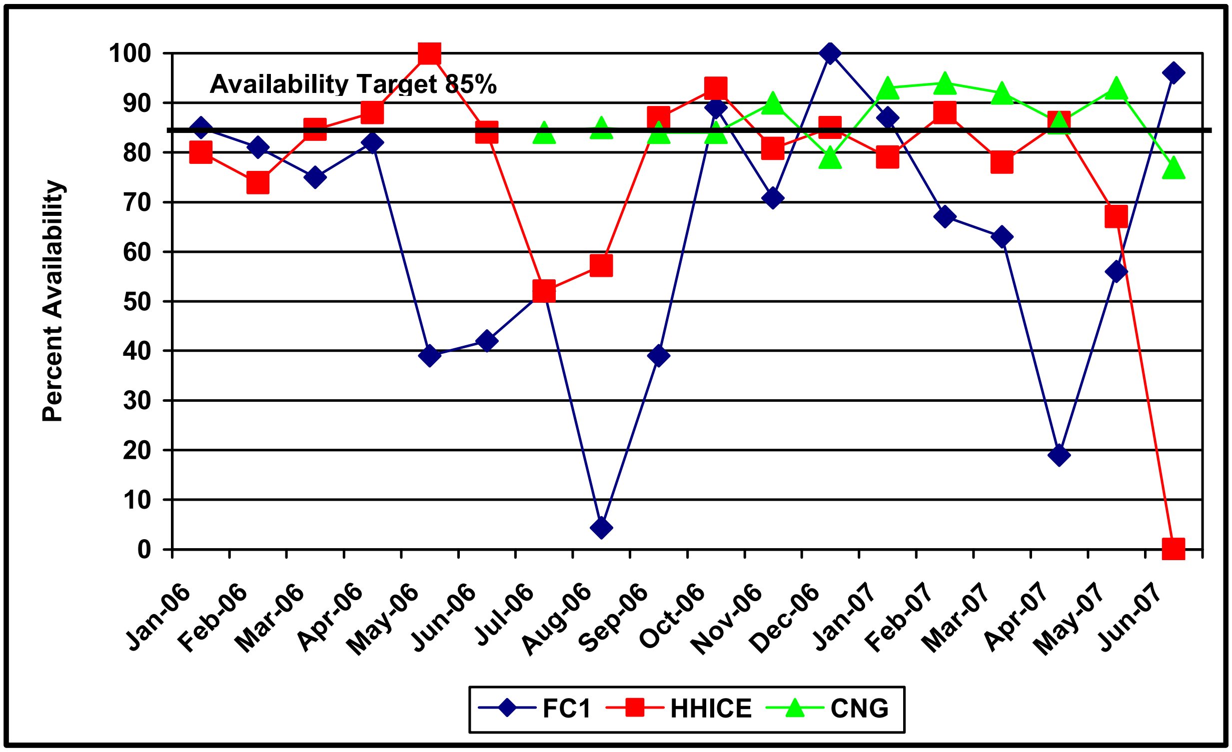


Figure 10. Availability for all three study bus groups

Table 5. 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	449		465		1,697	
Days Available	293	65	357	77	1,475	87
Available	**293**	**100**	**357**	**100**	**1,475**	**100**
On-Route	283	97	334	93	1,462	99
Event/Demonstration	3	1	6	2	5	0
Training	6	2	13	4	0	0
Not Used	2	0	4	1	8	1
Unavailable	**156**	**100**	**108**	**100**	**222**	**100**
Fuel Cell Propulsion	45	29				
ISE Propulsion	9	6	68	63		
ZEBRA Battery	29	19				
Air Conditioning	35	22	0	0	18	8
Headsign	7	4				
SunLine Maintenance	0	0	9	8	204	92
Fueling Unavailable	31	20	31	29		

Fuel Economy and Cost

Hydrogen fuel is supplied at SunLine by a HyRadix natural gas reformer for compression up to 5,000 psi into vehicles. CNG is brought into the SunLine property via a high-pressure natural gas line and then compressed up to 3,000 psi for delivery into the vehicles. SunLine has approved funding to upgrade the Thousand Palms natural gas fueling infrastructure to dispense CNG up to 3,600 psi. This upgrade is expected to be completed around April to June 2008.

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 for state fuel sales regulations. In the case of hydrogen, the unit used is typically kilograms (kg), which is essentially the same energy equivalent 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 in Appendix A.

Table 6 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 2.5 times higher than the CNG buses and the HHICE bus had a fuel economy 49% higher than the CNG buses. The fuel cell bus had a fuel economy 68% higher than the HHICE bus. Figure 11 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.

SunLine has tracked the utility (electricity, natural gas, and water) costs along with the costs to maintain the HyRadix reformer since the prototype unit was placed into service. They report that hydrogen production has cost $4.26 per kg since the reformer started operation to present. This hydrogen fuel cost for production indicates that the fuel cell bus fuel cost is $0.58 per mile and the HHICE bus fuel cost is $0.97 per mile.

Table 6. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg) or CNG (GGE)	Miles per kg or GGE	Diesel Equivalent Amount (Gallon)	Miles per Gallon (DGE)
FC1	**37,005**	**5,019.2**	**7.37**	**4,441.8**	**8.33**
550 HHICE	**38,283**	**8,722.5**	**4.39**	**7,819.0**	**4.96**
563 CNG	54,114	19,042.2	2.84	17,042.8	3.18
565 CNG	55,861	19,140.2	2.92	17,130.5	3.26
566 CNG	42,397	14,217.9	2.98	12,725.0	3.33
567 CNG	52,776	17,709.7	2.98	15,850.2	3.33
568 CNG	56,985	18.868.0	3.02	16,886.9	3.37
CNG Total	**262,133**	**88,977.9**	**2.95**	**79,635.2**	**3.29**

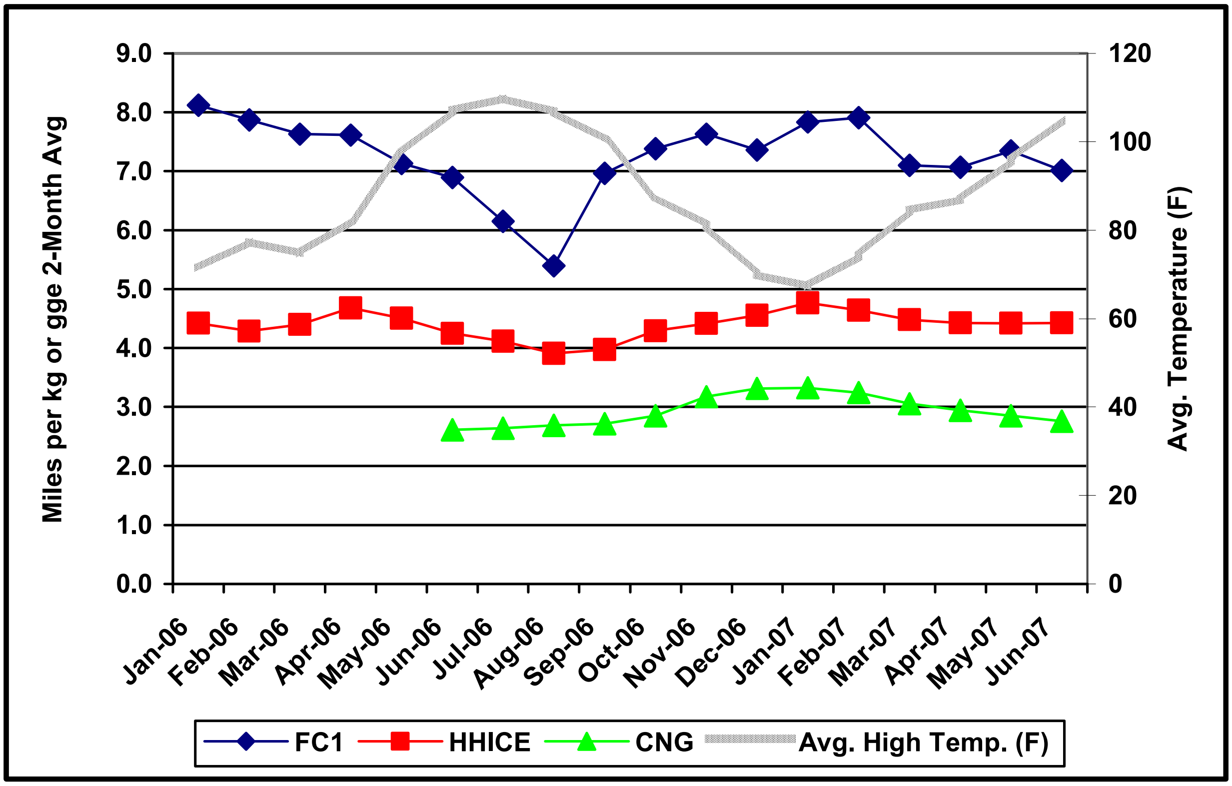


Figure 11. Two-month average fuel economy (miles per kg or GGE)

SunLine provides CNG fuel for its entire bus operation and sells CNG to the public. This large volume of CNG allows SunLine to provide CNG at a reasonable price compared to diesel fuel cost. During the evaluation period, the average price of CNG was $1.36 per GGE. This CNG cost indicates that the CNG buses have a fuel cost of $0.46 per mile. The fuel cell bus hydrogen cost per mile has been 25% higher, and the HHICE hydrogen cost per mile has been two times higher than for the CNG buses.

Maintenance Analysis

The maintenance cost analysis in this section is only for the evaluation period (FC1 and HHICE: January 2006 through June 2007; CNG: July 2006 through June 2007). We do <u>not</u> intend to include warranty costs in the cost-per-mile calculations. More work is required for collecting warranty maintenance costs and ensuring that all these warranty-covered costs have been removed from the analysis. This will be a high priority for the final evaluation report for this site.

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 7 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 70% higher and 2.1 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 and UTC Power, except for routine and non-drivetrain maintenance.

Table 7. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Cost ($) per Mile
FC1	**37,005**	**613.34**	**330.0**	**0.46**
550 HHICE	**38,853**	**4,348.03**	**361.8**	**0.58**
563 CNG	54,939	3,197.17	236.8	0.27
565 CNG	57,101	3,459.63	250.8	0.28
566 CNG	42,664	3,621.75	192.5	0.31
567 CNG	53,418	3,049.63	210.3	0.25
568 CNG	56,985	2,981.26	212.0	0.24
Total CNG	**265,107**	**16,309.44**	**1,102.3**	**0.27**
Avg. per Bus	**53,021**	**3,261.89**	**220.5**	**--**

Maintenance Costs Broken Down by System – Table 8 shows maintenance costs by vehicle system and bus study group (without warranty costs included). The vehicle systems shown in the table include the following:

- **Cab, Body, and Accessories**: Includes body, glass, and paint repairs following accidents; cab and sheet metal repairs on seats and doors; and accessory repairs such as hubodometers and radios.
- **Propulsion-Related Systems**: Repairs for exhaust, fuel, engine, electric motors, fuel cell modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, and transmission.
- **Preventive Maintenance Inspections (PMI)**: Labor for inspections during preventive maintenance.
- **Brakes**
- **Frame, Steering, and Suspension**
- **Heating, Ventilation, and Air Conditioning (HVAC)**

- **Lighting**
- **Air System, General**
- **Axles, Wheels, and Drive Shaft**
- **Tires**

The systems with the highest percentage of maintenance costs for the fuel cell bus were propulsion-related, HVAC, and cab, body, and accessories. For the HHICE bus, the three highest cost systems were propulsion-related, PMI, and cab, body, and accessories. The CNG buses had the same three systems as the HHICE bus, but in a slightly different ranking.

Table 8. 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	0.07	15	0.05	9	0.07	26
Propulsion-Related	0.24	53	0.37	64	0.07	26
PMI	0.06	13	0.09	15	0.08	29
Brakes	0.01	2	0.00	0	0.00	0
Frame, Steering, and Suspension	0.01	2	0.00	0	0.01	4
HVAC	0.07	15	0.01	2	0.02	7
Lighting	0.00	0	0.02	3	0.01	4
Axles, Wheels, and Drive Shaft	0.00	0	0.01	2	0.00	0
Tires	0.00	0	0.03	5	0.01	4
Total	**0.46**	**100**	**0.58**	**100**	**0.27**	**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, the HHICE and CNG buses had similar costs per mile. The fuel cell bus had significantly lower PMI than the other two study bus groups. This was most likely caused by much of the PMI being done under warranty by the UTC Power and ISE technicians and not the SunLine mechanics.

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. Based on maintenance data through June 2007, it appears that the A/C motor issue has been 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 9 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.

- **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 only a few hours reported for fuel system maintenance costs. The HHICE bus is older than the fuel cell bus and had some maintenance costs for hydrogen fuel line leaks. The CNG buses had some maintenance for small leaks and rerouting of fuel lines (shakedown issues from the new buses) as well as some filter replacements.
- **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 (8 changeouts and 4 roadcalls). Other maintenance costs included two sets of spark plugs and two sets of coils. The CNG buses mostly had preventive maintenance repairs in this category for spark plugs at the 18,000 preventive maintenance cycle for each bus. Other repairs in this category included changeout of coil boots, one starter under warranty, and one voltage regulator under warranty.
- **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.
- **Cooling** – The fuel cell bus had few costs 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 9. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	HHICE	CNG
Mileage	37,005	38,853	265,107
Total Propulsion-Related Systems (Roll-up)			
Parts cost ($)	365.91	3,987.22	9,251.34
Labor hours	173.0	210.0	181.0
Total cost ($)	9,015.91	14,487.22	18,301.34
Total cost ($) per mile	**0.24**	**0.37**	**0.07**
Exhaust System Repairs			
Parts cost ($)	0.00	0.00	0.00
Labor hours	0.0	0.0	5.3
Total cost ($)	0.00	0.00	262.5
Total cost ($) per mile	**0.00**	**0.00**	**0.00**
Fuel System Repairs			
Parts cost ($)	0.00	4.00	488.14
Labor hours	6.5	22.0	23.0
Total cost ($)	325.00	1,104.00	1,638.14
Total cost ($) per mile	**0.01**	**0.03**	**0.01**
Powerplant System Repairs			
Parts cost ($)	10.01	290.17	4,237.71
Labor hours	64.5	115.5	107.5
Total cost ($)	3,235.01	6,065.17	9,612.71
Total cost ($) per mile	**0.09**	**0.16**	**0.04**
Electric Propulsion System Repairs			
Parts cost ($)	0.00	0.00	0.00
Labor hours	80.5	1.8	0.0
Total cost ($)	4,025.00	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	3,208.48
Labor hours	5.0	52.0	17.0
Total cost ($)	605.90	5,996.76	4,058.48
Total cost ($) per mile	**0.02**	**0.15**	**0.02**
Air Intake System Repairs			
Parts cost ($)	0.00	235.66	847.37
Labor hours	7.0	2.5	3.0
Total cost ($)	350.00	360.66	997.37
Total cost ($) per mile	**0.01**	**0.01**	**0.00**
Cooling System Repairs			
Parts cost ($)	0.00	60.63	78.53
Labor hours	9.5	16.3	20.0
Total cost ($)	475.00	873.13	1,078.53
Total cost ($) per mile	**0.01**	**0.02**	**0.00**
Transmission System Repairs			
Parts cost ($)	0.00	0.00	391.11
Labor hours	0.0	0.0	5.3
Total cost ($)	0.00	0.00	653.61
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 10 shows the RCs and miles between roadcalls (MBRC) for each study bus in two categories: all RCs and propulsion-related-only RCs. The CNG buses have had very few 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, 18 of the RCs were directly related to the ZEBRA batteries. If these RCs were removed, the rates would be 2,847 MBRC for all roadcalls and 3,701 MBRC for propulsion only.

Table 10. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC
FC1	**37,005**	**31**	**1,194**	**28**	**1,322**
550 HHICE	**38,853**	**16**	**2,428**	**14**	**2,775**
563 CNG	54,939	5	10,988	3	18,313
565 CNG	57,101	5	11,420	2	28,551
566 CNG	42,664	5	8,533	0	
567 CNG	53,418	8	6,677	1	53,418
568 CNG	56,985	2	28,493	1	56,985
Total CNG	**265,107**	**25**	**10,604**	**7**	**37,872**

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

What's next for This Demonstration?

This report covers SunLine operation of the fuel cell, HHICE, and CNG buses through June 2007. The next evaluation report for this site will include operational data through December 2007 and is planned for release around March 2008.

SunLine is also a recipient of a grant from the Federal Transit Administration (FTA) for its National Fuel Cell Bus Program (NFCBP). This grant includes $2.8 million to support the development of a new fuel cell bus design and demonstration at SunLine. The partners in this effort are New Flyer Bus, ISE Corp., and UTC Power. FTA, DOE, and NREL plan to work together to continue evaluating the NFCBP and other hydrogen and fuel cell-related transit operations.

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Acronyms and Abbreviations

APTA	American Public Transportation Association
ASME	American Society of Mechanical Engineers
CARB	California Air Resources Board
CNG	compressed natural gas
CSA	cell stack assembly
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
MBRC	miles between roadcalls
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
Nm	Newton meters
NO_x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
PSA	pressure swing adsorption
psi	pounds per square inch
RC	roadcall
rpm	revolutions per minute
SCAQMD	South Coast Air Quality Management District
SOC	state of charge
ZEB	zero emission bus

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Reports from DOE/NREL evaluations can be downloaded via the following Web sites:
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

Appendix A: Fleet Summary Statistics

Fleet Summary Statistics: SunLine Transit Agency
FCB, HHICE, and CNG Study Groups

Fleet Operations and Economics

	Fuel Cell	HHICE	CNG
Number of Vehicles	1	1	5
Period Used for Fuel and Oil Op Analysis	1/06-6/07	1/06-6/07	7/06-6/07
Total Number of Months in Period	18	18	12
Fuel and Oil Analysis Base Fleet Mileage	37,005	38,283	262,133
Period Used for Maintenance Op Analysis	1/06-6/07	1/06-6/07	7/06-6/07
Total Number of Months in Period	18	18	12
Maintenance Analysis Base Fleet Mileage	37,005	38,853	265,107
Average Monthly Mileage per Vehicle	2,056	2,159	4,418
Availability	65%	77%	87%
Fleet Fuel Usage in CNG GGE/H2 kg	5,019	8,723	88,978
Roadcalls	31	16	25
RCs MBRC	1,194	2,428	10,604
Propulsion Roadcalls	28	14	7
Propulsion MBRC	1,322	2,775	37,872
Fleet Miles/kg Hydrogen or CNG GGE	7.37	4.39	2.95
(1.13 kg H2/gal Diesel Fuel)			
Representative Fleet MPG (energy equiv.)	8.33	4.96	3.29
Hydrogen Cost per kg	4.26	4.26	
Cost per Gasoline Gallon Equivalent			1.36
Fuel Cost per Mile	**0.58**	**0.97**	**0.46**
Total Scheduled Repair Cost per Mile	0.08	0.11	0.14
Total Unscheduled Repair Cost per Mile	0.39	0.47	0.13
Total Maintenance Cost per Mile	**0.46**	**0.58**	**0.27**
Total Operating Cost per Mile	**1.04**	**1.55**	**0.73**

Maintenance Costs

	Fuel Cell	HHICE	CNG
Fleet Mileage	37,005	38,853	265107
Total Parts Cost	613.34	4,348.03	16,309.44
Total Labor Hours	330.0	361.8	1102.3
Average Labor Cost (@ $50.00 per hour)	16,500.00	18,087.50	55,114.00
Total Maintenance Cost	17,113.34	22,435.53	71,423.44
Total Maintenance Cost per Bus	17,113.34	22,435.53	14,284.69
Total Maintenance Cost per Mile	**0.46**	**0.58**	**0.27**

Breakdown of Maintenance Costs by Vehicle System

	Fuel Cell	HHICE	CNG
Fleet Mileage	37,005	38,853	265,107
Total Propulsion-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 65)			
Parts Cost	365.91	3,987.22	9,251.34
Labor Hours	173.0	210.00	181.0
Average Labor Cost	8,650.00	10,500.00	9,050.00
Total Cost (for system)	9,015.91	14,487.22	18,301.34
Total Cost (for system) per Bus	9,015.91	14,487.22	3,660.27
Total Cost (for system) per Mile	**0.24**	**0.37**	**0.07**
Exhaust System Repairs (ATA VMRS 43)			
Parts Cost	0.00	0.00	0.00
Labor Hours	0.0	0.0	5.3
Average Labor Cost	0.00	0.00	262.50
Total Cost (for system)	0.00	0.00	262.50
Total Cost (for system) per Bus	0.00	0.00	52.50
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**
Fuel System Repairs (ATA VMRS 44)			
Parts Cost	0.00	4.00	488.14
Labor Hours	6.5	22.0	23.0
Average Labor Cost	325.00	1,100.00	1,150.00
Total Cost (for system)	325.00	1,104.00	1,638.14
Total Cost (for system) per Bus	325.00	1,104.00	327.63
Total Cost (for system) per Mile	**0.01**	**0.03**	**0.01**
Powerplant (Engine) Repairs (ATA VMRS 45)			
Parts Cost	10.01	290.17	4,237.71
Labor Hours	64.5	115.5	107.5
Average Labor Cost	3,225.00	5,775.00	5,375.00
Total Cost (for system)	3,235.01	6,065.17	9,612.71
Total Cost (for system) per Bus	3,235.01	6,065.17	1,922.54
Total Cost (for system) per Mile	**0.09**	**0.16**	**0.04**
Electric Propulsion Repairs (ATA VMRS 46)			
Parts Cost	0.00	0.00	0.00
Labor Hours	80.5	1.8	0.0
Average Labor Cost	4,025.00	87.50	0.00
Total Cost (for system)	4,025.00	87.50	0.00
Total Cost (for system) per Bus	4,025.00	87.50	0.00
Total Cost (for system) per Mile	**0.11**	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	HHICE	CNG
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)			
Parts Cost	355.90	3,396.76	3,208.48
Labor Hours	5.0	52.0	17.0
Average Labor Cost	250.00	2,600.00	850.00
Total Cost (for system)	605.90	5,996.76	4,058.48
Total Cost (for system) per Bus	605.90	5,996.76	811.70
Total Cost (for system) per Mile	**0.02**	**0.15**	**0.02**
Air Intake System Repairs (ATA VMRS 41)			
Parts Cost	0.00	235.66	847.37
Labor Hours	7.0	2.5	3.0
Average Labor Cost	350.00	125.00	150.00
Total Cost (for system)	350.00	360.66	997.37
Total Cost (for system) per Bus	350.00	360.66	199.47
Total Cost (for system) per Mile	**0.01**	**0.01**	**0.00**
Cooling System Repairs (ATA VMRS 42)			
Parts Cost	0.00	60.63	78.53
Labor Hours	9.5	16.3	20.0
Average Labor Cost	475.00	812.50	1,000.00
Total Cost (for system)	475.00	873.13	1,078.53
Total Cost (for system) per Bus	475.00	873.13	215.71
Total Cost (for system) per Mile	**0.01**	**0.02**	**0.00**
General Air System Repairs (ATA VMRS 10)			
Parts Cost	12.38	0.00	10.85
Labor Hours	1.0	0.0	3.8
Average Labor Cost	50.00	0.00	187.50
Total Cost (for system)	62.38	0.00	198.35
Total Cost (for system) per Bus	62.38	0.00	39.67
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**
Brake System Repairs (ATA VMRS 13)			
Parts Cost	0.00	0.00	1.82
Labor Hours	5.5	1.5	5.8
Average Labor Cost	275.00	75.00	287.50
Total Cost (for system)	275.00	75.00	289.32
Total Cost (for system) per Bus	275.00	75.00	57.86
Total Cost (for system) per Mile	**0.01**	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	HHICE	CNG
Transmission Repairs (ATA VMRS 27)			
Parts Cost	0.00	0.00	391.11
Labor Hours	0.0	0.0	5.3
Average Labor Cost	0.00	0.00	262.50
Total Cost (for system)	0.00	0.00	653.61
Total Cost (for system) per Bus	0.00	0.00	130.72
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**
Inspections Only – No Parts Replacements (101)			
Parts Cost	0.00	0.00	0.00
Labor Hours	44.8	71.5	456.8
Average Labor Cost	2,237.50	3,575.00	22,837.50
Total Cost (for system)	2,237.50	3,575.00	22,837.50
Total Cost (for system) per Bus	2,237.50	3,575.00	4,567.50
Total Cost (for system) per Mile	**0.06**	**0.09**	**0.09**
HVAC System Repairs (ATA VMRS 01)			
Parts Cost	0.00	0.00	1,918.89
Labor Hours	53.3	4.0	47.3
Average Labor Cost	2,662.50	200.00	2,364.00
Total Cost (for system)	2,662.50	200.00	4,282.89
Total Cost (for system) per Bus	2,662.50	200.00	856.58
Total Cost (for system) per Mile	**0.07**	**0.01**	**0.02**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)			
Parts Cost	157.05	139.91	3,612.14
Labor Hours	45.5	38.0	295.8
Average Labor Cost	2,275.00	1,900.00	14,787.50
Total Cost (for system)	2,432.05	2,039.91	18,399.64
Total Cost (for system) per Bus	2,432.05	2,039.91	3,679.93
Total Cost (for system) per Mile	**0.07**	**0.05**	**0.07**
Lighting System Repairs (ATA VMRS 34)			
Parts Cost	18.00	220.90	572.27
Labor Hours	2.5	11.8	41.0
Average Labor Cost	125.00	587.50	2,050.00
Total Cost (for system)	143.00	808.40	2,622.27
Total Cost (for system) per Bus	143.00	808.40	524.45
Total Cost (for system) per Mile	**0.00**	**0.02**	**0.01**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	HHICE	CNG
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)			
Parts Cost	60.00	0.00	903.27
Labor Hours	4.5	3.5	11.5
Average Labor Cost	225.00	175.00	575.00
Total Cost (for system)	285.00	175.00	1,478.27
Total Cost (for system) per Bus	285.00	175.00	295.65
Total Cost (for system) per Mile	**0.01**	**0.00**	**0.01**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)			
Parts Cost	0.00	0.00	38.86
Labor Hours	0.0	1.5	4.0
Average Labor Cost	0.00	75.00	200.00
Total Cost (for system)	0.00	75.00	238.86
Total Cost (for system) per Bus	0.00	75.00	47.77
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**
Tire Repairs (ATA VMRS 17)			
Parts Cost	0.00	0.00	0.00
Labor Hours	0.0	20.0	55.5
Average Labor Cost	0.00	1,000.00	2,775.00
Total Cost (for system)	0.00	1,000.00	2,775.00
Total Cost (for system) per Bus	0.00	1,000.00	555.00
Total Cost (for system) per Mile	**0.00**	**0.03**	**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. The general energy conversions are as follows, actual energy content will vary by location:

   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/gallon / 113,628 Btu/kg = 1.13 kg/diesel gallon

   The gasoline LHV or GGE is 115,000 Btu/gal, which is approximately 1% higher than 113,628 Btu/kg for hydrogen; these have been called equivalent for this report.

   Gasoline/Diesel = 115,000 Btu/gallon / 128,400 Btu/gallon = 0.896

2. The propulsion-related systems were chosen to include only those vehicle systems that could be directly impacted by the selection of a fuel/advanced technology.
3. ATA VMRS coding is based on parts that were replaced. If there was no part replaced in a given repair, then the code was chosen by the system being worked on.
4. In general, inspections (with no part replacements) were only included in the overall totals (not by system). 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 represent 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
FCB, HHICE, and CNG Study Groups

Fleet Operations and Economics

	Fuel Cell	HHICE	CNG
Number of Vehicles	1	1	5
Period Used for Fuel and Oil Op Analysis	1/06-6/07	1/06-6/07	7/06-6/07
Total Number of Months in Period	18	18	12
Fuel and Oil Analysis Base Fleet Kilometers	59,552	61,609	421,851
Period Used for Maintenance Op Analysis	1/06-6/07	1/06-6/07	7/06-6/07
Total Number of Months in Period	18	18	12
Maintenance Analysis Base Fleet Kilometers	59,552	62,526	426,637
Average Monthly Kilometers per Vehicle	3,308	3,474	7,111
Availability	65%	77%	87%
Fleet Fuel Usage in Gasoline L/H_2 kg	5,019	8,723	336,781
Roadcalls	31	16	25
Kilometers between Roadcalls (KBRC)	1,921	3,908	17,065
Propulsion Roadcalls	28	14	7
Propulsion KBRC	2,127	4,466	60,948
Fleet kg Hydrogen/100 km	8.43	14.16	
Representative Fleet MPG (L/100 km)	28.23	47.42	71.45
Hydrogen Cost per kg	4.26	4.26	
CNG Cost per Liter (based on GGE)			0.36
Fuel Cost per Kilometer	**0.36**	**0.60**	**0.29**
Total Scheduled Repair Cost per Kilometer	0.05	0.07	0.09
Total Unscheduled Repair Cost per Kilometer	0.24	0.29	0.08
Total Maintenance Cost per Kilometer	**0.29**	**0.36**	**0.17**
Total Operating Cost per Kilometer	**0.65**	**0.96**	**0.45**

Maintenance Costs

	Fuel Cell	HHICE	CNG
Fleet Kilometers	59,552	62,526	426,637
Total Parts Cost	613.34	4,348.03	16,309.44
Total Labor Hours	330.0	361.8	1102.3
Average Labor Cost (@ $50.00 per hour)	16,500.00	18,087.50	55,114.00
Total Maintenance Cost	17,113.34	22,435.53	71,423.44
Total Maintenance Cost per Bus	17,113.34	22,435.53	14,284.69
Total Maintenance Cost per Kilometer	**0.29**	**0.36**	**0.17**

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