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# SunLine Transit Agency Hydrogen-Powered Transit Buses: Third Evaluation Report — Appendices

*Technical Report*
NREL/TP-560-43741-2
June 2008

Kevin Chandler, Battelle
Leslie Eudy, National Renewable Energy Laboratory

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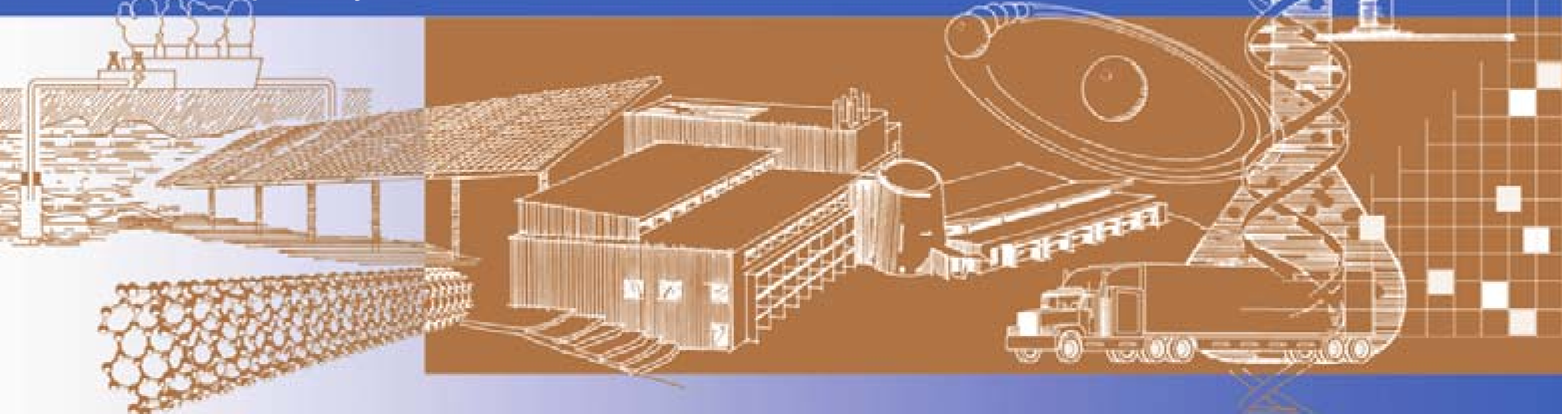

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# Contents

## Introduction to the Appendices

NREL has reported evaluation results for fuel cell buses since 2003. These reports include a broad range of background on the transit property, the buses, infrastructure, and overall experience operating fuel cell buses. Several reports are planned for each evaluation site. The first data report typically includes extensive background material plus an analysis of the first round of data. Update reports follow the initial publication, focusing on the newest data analysis and lessons learned since the previous report. The authors would like to provide more focus on the data, without depriving new readers of the background and context on the transit property and the technology. These appendices, referenced in the main report, are designed to provide the full background for the evaluation. They will be updated as new information is collected, but will contain the original background material from the first report. Both parts are downloaded separately. A Web link is provided on the cover to allow the reader to download the main report.

All NREL publications on hydrogen and fuel cell buses are available at:
http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html

## Appendix A: SunLine Description

### Host Site Profile

SunLine[1] is located in the Palm Springs/Coachella Valley, Calif., area and serves an area greater than 1,100 square miles (Figure A-1). The Coachella Valley is a desert valley 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.

Transit bus operations started in 1977 with 22 vehicles. SunLine provides bus service from two locations in the Valley – one in Thousand Palms, which serves as headquarters, and another in Indio (both locations shown in Figure A-2). In fiscal year 2006, ridership was reported as approximately 3.5 million passengers, the fleet operated 2.8 million miles, and SunLine had an operating budget of $18.2 million.

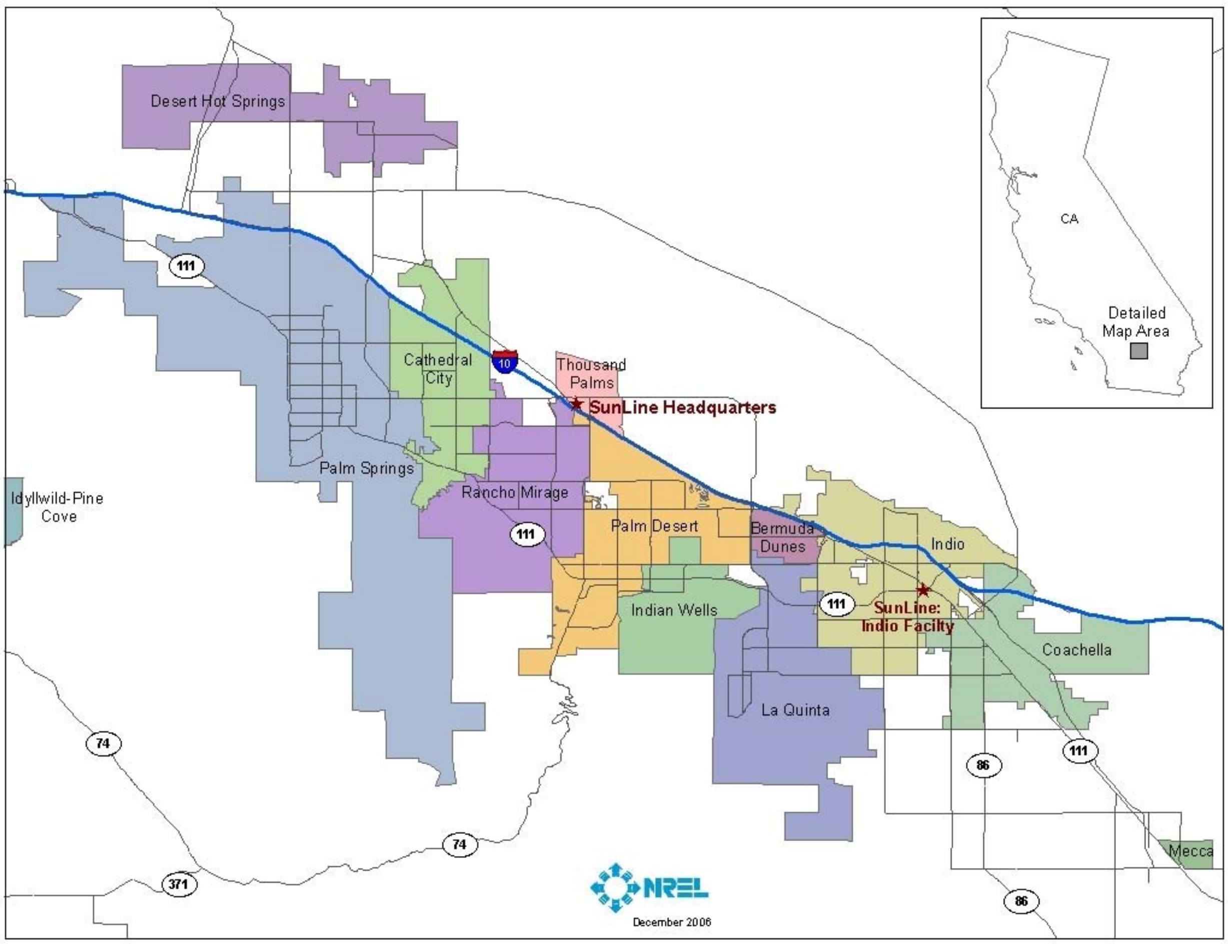


**Figure A-1. SunLine operating area in the Coachella Valley, California**

[1] SunLine Transit Agency Web site: www.sunline.org/


**Figure A-2. SunLine headquarters in Thousand Palms (left) and Indio bus garage (right)**

SunLine is a Joint Powers Authority (JPA) created by its nine member cities as well as the county (Riverside). Each member city and the county have an appointed member on the SunLine board.

- Desert Hot Springs
- Palm Springs
- Cathedral City
- Rancho Mirage
- Palm Desert
- Indian Wells
- La Quinta
- Indio
- Coachella
- Additional board member from Riverside County

SunLine operates 12 fixed routes (SunBus) and provides paratransit services (SunDial). The current bus fleet includes 48 full size transit buses (40 foot) including 46 compressed natural gas (CNG) buses, one New Flyer hybrid hydrogen internal combustion engine (HHICE) bus, and one Van Hool fuel cell bus. The fleet also includes 23 CNG paratransit vehicles and 35 light- and medium-duty CNG vehicles.

**Alternative Fuels.** SunLine started looking for a defining position on clean bus operations in 1991. At that time, a decision was made to convert the entire SunLine fleet (buses and support vehicles) to CNG in order to maximize the impact of potential emissions reductions and economic benefits. This decision was made at a very early stage in CNG bus development and deployment in the United States. For context, in 1991 approximately 25 heavy CNG buses had just been placed into service in this country, with another 70 on order.

As background for SunLine's interest in alternative fuels, the State of California has identified some severe air quality challenges, especially in the Los Angeles metropolitan area. The

Coachella Valley, including Palm Springs, is located in Riverside County, which is one of the four counties (Los Angeles, Orange, Riverside, and San Bernardino counties) included in the Los Angeles metropolitan area. Starting in the late 1980s and early 1990s, the California Air Resources Board (CARB) began to strongly encourage alternative fuels for vehicles to help with emissions reductions. The South Coast Air Quality Management District (SCAQMD) launched several incentive programs for converting vehicles in the district to alternative fuels. One of these incentive programs focused on transit buses because of the potential significant emissions impact in urban areas.

The SunLine board of directors approved a 100% alternative fuels approach in 1992 and took advantage of local and state incentives for purchasing alternative fuel vehicles. Natural gas vehicle training programs were developed at the College of the Desert's Energy Technology Training Center, and the SunLine mechanics were the first "graduates" of that training. All SunLine employees received some natural gas vehicle safety familiarization training. SunLine was the nation's first fleet to change to 100% CNG bus operations, which occurred essentially overnight in May 1994. An NREL report documenting SunLine's first 10 years of CNG operations experience is available[2]. Since May 1994, SunLine has remained fully committed to operating its entire fleet on alternative fuels and continues that commitment to this day with CNG and hydrogen-fueled transit buses.

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

Table A-1 provides a summary of several hydrogen-related projects at SunLine since the installation of onsite hydrogen production and dispensing in 2000. The Ballard P4 fuel cell bus (ZEBus) was demonstrated during 2000 and 2001 (shown in Figure A-3), but was not used in actual revenue service[3]. The next major project was a development project with NREL and Cummins Westport, Inc. (CWI) to develop and demonstrate a natural gas engine capable of using hydrogen and CNG blended fuel[4]. The second fuel cell bus demonstrated at SunLine was the ISE integrated ThunderPower bus powered by UTC Power's 60 kW fuel cell power system (shown in Figure A-4) in 2002 through 2003[5]. This fuel cell bus went on to be demonstrated in several locations, including AC Transit.

[2] NREL, 2006, "Ten Years of Compressed Natural Gas Operations at SunLine Transit Agency," http://www.nrel.gov/vehiclesandfuels/ngvtf/pdfs/39180.pdf

[3] Ballard/Xcellsis, 2001, "Customer Report of ZEBus at SunLine Transit," http://www.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/sunline_project_reports2.pdf

[4] NREL, 2005, "Development and Demonstration of Hydrogen and Compressed Natural Gas Blend Transit Buses," http://www.nrel.gov/vehiclesandfuels/ngvtf/pdfs/38707.pdf

[5] NREL, 2003, "Fuel Cell Transit Buses, ThunderPower Bus Evaluation at SunLine Transit Agency," http://www.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/sunline_report.pdf

SunLine and HyRadix[6] worked together in 2004 to install a natural gas reformer to produce high purity hydrogen for use by vehicles. The testing of this HyRadix reformer was completed in 2006 and a commercial design was released for purchase. The SunLine unit was replaced with the new/commercial design and placed back into service in August 2006.

The ISE/New Flyer HHICE bus was introduced into service in late 2004. Soon after arriving at SunLine, the HHICE bus was shipped to Manitoba, Canada for cold weather testing in February and March 2005[7]. In December 2005, SunLine received its third fuel cell bus; this one was developed by ISE, Van Hool, and UTC Power. The HHICE and Van Hool fuel cell bus are currently in operation and preliminary evaluation results are provided in this report.


**Figure A-3. Ballard P4 ZEBus fuel cell bus**

**Figure A-4. ThunderPower fuel cell bus**

**Table A-1. Hydrogen-Related Activities at SunLine**

| Timeframe | Activity | Description |
|---|---|---|
| 2000-2004 | Addition of hydrogen dispensing | A Stuart Energy electrolyzer was installed for testing and used to produce hydrogen; decommissioned and removed in 2004 |
| 2000-2001 | Ballard P4 Fuel Cell Bus Demonstration (ZEbus) | Demonstration of the Ballard phase 4 fuel cell bus from July 2000 through June 2001; still on site as a static display |
| 2002-2004 | Development and testing of a hydrogen and CNG blend engine | Support for development and testing of a Cummins natural gas engine to operate on a hydrogen CNG fuel blend. Buses in service during 10/2003 and 6/2004; buses retired in 2005. |
| 2002-2003 | Demonstration of ThunderPower fuel cell bus | Demonstration of a small transit bus integrated by ISE, power plant from UTC Power; bus demonstrated in other locations; currently static display at ISE |
| 2004-2006 | Addition of HyRadix natural gas reformer | Prototype HyRadix natural gas reformer was installed to produce high pressure hydrogen for use with the HHICE bus and other vehicles using hydrogen. Unit was replaced with commercial design in 2006. |
| 2004-present | Demonstration of HHICE bus | Demonstration of ISE/New Flyer HHICE bus started in December 2004. The bus was tested in Manitoba, Canada during February and March 2005, and then returned to SunLine for operation. |
| 2005-present | Demonstration of fuel cell bus | Demonstration of Van Hool/ISE/UTC Power fuel cell bus started in December 2005 |
| 2006-present | Upgrade of HyRadix natural gas reformer to commercial product | HyRadix has introduced its natural gas reformer as a commercial product; the unit at SunLine was replaced with the commercial product design; on November 16, 2006 SunLine announced the availability of public hydrogen fueling at its Thousand Palms facility |
| 2006-present | FTA National Fuel Cell Bus Program announcement | SunLine received $2.8 million to develop a new fuel cell bus plus inclusion into other fuel cell bus studies |

[6] HyRadix Web site: www.hyradix.com
[7] Manitoba Energy Science and Technology, 2005, "Cold Weather Demonstration in Winnipeg, Manitoba, Canada"

## Route Descriptions

SunLine operates 12 fixed routes in the Coachella Valley along State Highway 111 and Interstate 10. Table A-2 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 A-2. 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** |

# Appendix B: Evaluation Bus Technology Descriptions

## Fuel Cell, Hydrogen Engine, and CNG Buses

Table B-1 provides bus system descriptions for the fuel cell, hybrid hydrogen internal combustion engine (HHICE), and compressed natural gas (CNG) buses included in the SunLine transit bus evaluation. The prototype fuel cell bus in service at SunLine was developed in collaboration between ISE Corporation[1], UTC Power[2], and Van Hool[3]. 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 Federal Transit Administration/ South Coast Air Quality Management District (FTA/SCAQMD) project in 2004. The bus went into service in December 2004. Soon after the HHICE bus started operation at SunLine, it was sent to Winnipeg, Manitoba, Canada for cold weather testing in February and March 2005, and then resumed operation at SunLine. A single new HHICE bus is estimated (by ISE Corp.) to cost between $1 million and $2 million to purchase today, depending on the number of buses purchased.

**Table B-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<br>Low floor | New Flyer TB-40<br>Low floor | Orion V<br>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<br>15 standing | 39 seated or 33 seated and two wheelchairs<br>13 standing | 44 seated or 38 seated and two wheelchairs<br>21 standing |
| Engine Manufacturer and Model | UTC Power<br>PureMotion 120 Fuel Cell Power System | Ford 6.8 liter<br>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<br>Regenerative braking | Gearbox/Flenders<br>Regenerative braking | ZF 5HP592<br>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 |

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. The

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[1] ISE Corporation Web site: www.isecorp.com
[2] UTC Power Web site: www.utcpower.com
[3] Van Hool Web site: www.abc-companies.com/sales_vh.htm

purchase price reported for these CNG buses ($375,000 each) includes all preparation for SunLine service, such as the radio and farebox.

Table B-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 B-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 |

## Fuel Cell Bus Propulsion System Description

The fuel cell bus uses the PureMotion[4] 120 Fuel Cell Power System manufactured by UTC Power in a hybrid electric drive system designed by ISE. The Van Hool A330 transit bus chassis was redesigned to integrate the fuel cell system. The bus has a low floor from front to back and three doors for easy passenger boarding.

ISE's hybrid system (shown in Figure B-1) is a series configuration, meaning the fuel cell power system is not mechanically coupled to the drive axle. The fuel cell power system and energy storage system work together to provide power to two electric drive motors, which are coupled to the driveline through a combining gearbox. When the bus needs extra power, the fuel cell power system and energy storage provide power to the drive motors. When the power requirements of the bus are low, the fuel cell power system provides power and recharges the energy storage system.

The hybrid system is also capable of regenerative braking, which captures the energy typically expended during braking and uses it to recharge the energy storage system. Each component of the propulsion system is carefully controlled through an ISE-developed operating system.

ISE designed the system to be flexible. Depending on a client's needs, a variety of powerplants and energy storage options can be integrated into the system. The bus at SunLine has a fuel cell powerplant and three ZEBRA (sodium/nickel chloride) batteries[5] as the energy storage system.

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[4] PureMotion is a registered trademark of UTC Power.
[5] Web site: www.betard.co.uk/

The powerplant, which is the primary power source for the hybrid system is UTC Power's PureMotion 120 Fuel Cell Power System which produces 120 kW from its proton exchange membrane (PEM) fuel cell stacks. UTC Power's fuel cells operate at near-ambient pressure, which eliminates the need for a compressor. This not only increases the efficiency of the system, but also results in very quiet operation.

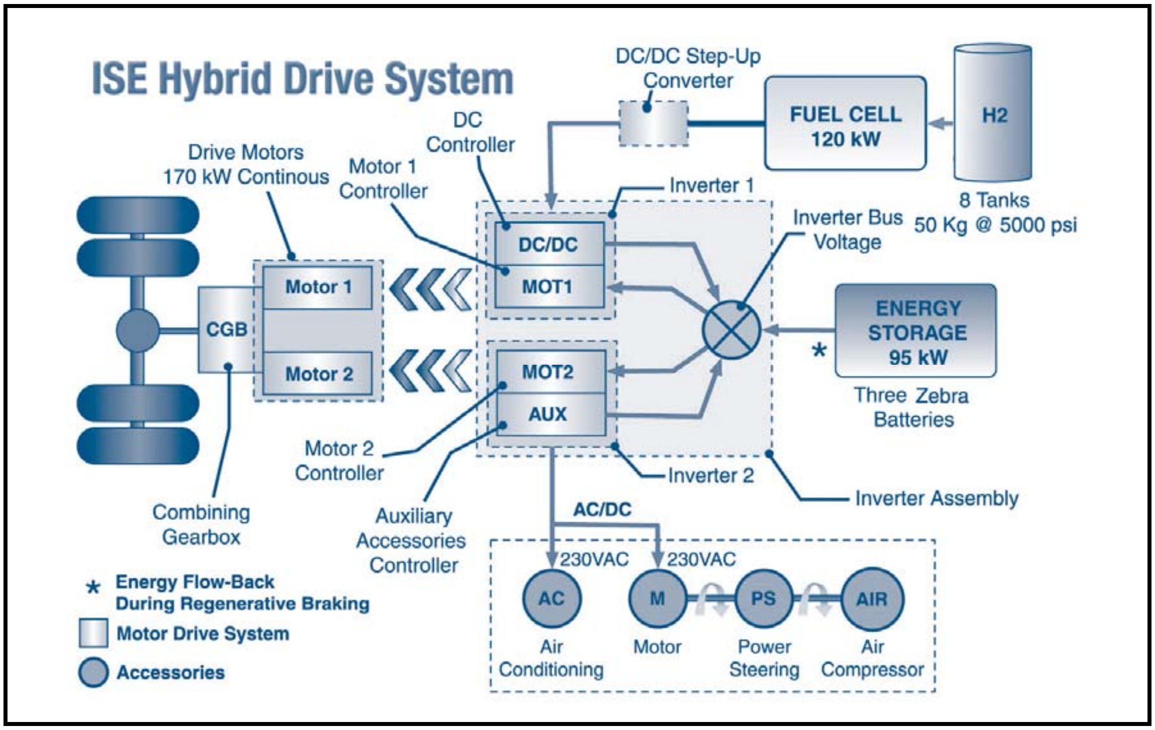


**Figure B-1. ISE's hybrid propulsion system**

## HHICE Bus Propulsion System Description

The HHICE bus was developed by ISE Corporation with cooperation and support from New Flyer[6]. The major systems are shown in Figure B-2. New Flyer delivered the bus to ISE as a "glider" without the power train. The HHICE bus features ISE's ThunderVolt hybrid drive system (essentially the same hybrid system as described above for the fuel cell bus at SunLine) and Ford Motor Company's Triton V10 engine, which is optimized to run on hydrogen. ISE's hybrid system is a series configuration, meaning that the powerplant is not mechanically coupled to the drive axle. The powerplant and energy storage system work together to provide power to two electric drive motors that are connected to the driveline through a combining gearbox.

As with the fuel cell bus, the hybrid system in the HHICE bus uses regenerative braking to recharge the energy storage system. The energy storage system on the HHICE bus consists of two packs of Maxwell[7] ultracapacitors. The benefit of using ultracapacitors over batteries is the speed at which energy can be stored and retrieved from the capacitors; the challenge with ultracapacitors is having enough energy density onboard a vehicle to enable efficient use of the

[6] New Flyer Web site: www.newflyer.com
[7] Maxwell Web site: www.maxwell.com

energy storage system. Each component of the propulsion system is carefully controlled through an ISE-developed operating system.

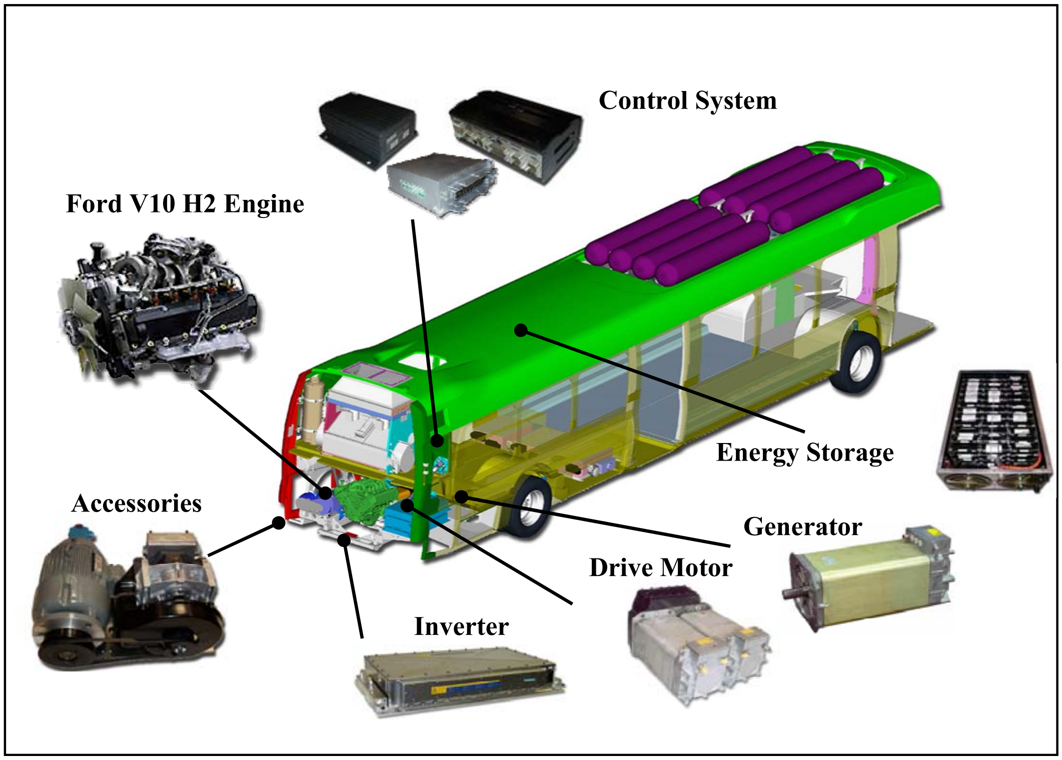


**Figure B-2. Propulsion system for HHICE bus (courtesy of ISE Corp.)**

## CNG Bus Propulsion System Description

SunLine is in the process of replacing its existing fleet of model year 1994 Orion V CNG buses. In June 2006, SunLine received 15 new CNG Orion V buses with Cummins Westport, Inc.[8] (CWI) C Gas Plus engines (engine shown in Figure B-3). Development of the "Plus" version of the engine (modifications for better fuel and emission control) was supported by DOE and NREL[9]. Orion Bus Industries[10] is located in Mississauga, Ontario, Canada and Oriskany, N.Y. Both the CNG engine and Orion V models are established, commercial products in the transit bus industry.

[8] Cummins-Westport Web site: www.cumminswesport.com
[9] "On-Road Development of the C-Gas Plus Engine in Heavy-Duty Vehicles," 2003, NREL/FS-540-32871; "An Emission and Performance Comparison of the Natural Gas C-Gas Plus Engine in Heavy-Duty Trucks," 2003, NREL/SR-540-32863. Visit www.eere.energy.gov/afdc to obtain these publications.
[10] Daimler Buses Web site: www.orionbus.com

**Figure B-3. CWI C Gas Plus engine**

# Appendix C: Evaluation Infrastructure Description

## Infrastructure and Facilities

SunLine's gaseous fuel experience began in the early 1990s when the agency switched its fleet to compressed natural gas (CNG). Protecting the air quality in the Coachella Valley was the primary reason the agency chose to abandon diesel for natural gas. To accomplish this conversion, SunLine sought out various partners. College of the Desert, a local community college, created a training program for alternative fuels. SunLine partnered with the local natural gas provider, Southern California Gas Company (SoCal Gas), to build the fueling infrastructure. The CNG station was completed and ready for operation by the end of 1993. The most unusual aspect of the station, from a transit perspective, is the fact that it is open to the public. SunLine recently took over full ownership of the station, and now benefits fully from the sale of fuel. In addition to CNG, the station offers liquefied natural gas (LNG), a blend of CNG and hydrogen, and pure hydrogen. Diesel and gasoline are not available at SunLine.

### *Natural Gas Fueling*

SunLine has two bus operations sites, and both locations have a CNG fueling station for the bus fleet and for public fueling. As mentioned in Appendix A, SunLine and SoCal Gas built the original CNG fast fill station at the Thousand Palms facility with construction starting in 1993. In 1997, Clean Energy purchased the SoCal Gas portion of the fueling station and operation. The station has a public filling station on the outside of the facility at Thousand Palms (Figure C-1) and piping is run underground to SunLine's private bus filling station (Figure C-2). The public and private stations provide CNG at 3,000 psi. SunLine has recently upgraded this CNG fueling station to provide 3,600 psi fueling. LNG was added to this fueling station in 2001.


Photo courtesy of SunLine

**Figure C-1. Public fueling at SunLine's Thousand Palms CNG fueling station**

**Figure C-2. CNG fueling lane and bus wash (Thousand Palms)**

The CNG fueling station at Thousand Palms includes two 400 hp natural gas compressors from Wilson Technologies (shown in Figure C-3) and provides a 10-minute CNG fill for a transit bus. The station design includes six American Society of Mechanical Engineers (ASME) tubes for a buffer to help start the fast fill.


**Figure C-3. CNG compressor station (Thousand Palms)**

In 1995, SunLine opened a second operating location in Indio called the Clean Air Center, which now operates approximately 40% of SunLine's service. A CNG fueling station was added at this location in 1995. This station includes both public and private fueling, with higher speed fueling behind the fence of the facility. One Sulzer and one IMW Industries natural gas compressor along with three ASME tubes for a buffer were installed at Indio (Figure C-4). Fueling times range from 12 minutes up to 20 minutes, depending on demand. Some trucks and support vehicles are also fueled at this location from the public side of the station.


**Figure C-4. CNG fueling equipment (Indio)**

### *Hydrogen Fueling*

SunLine has been providing hydrogen fuel for various vehicles on site since 2000. Acting as a "test bed" for advanced technologies, SunLine has partnered with various organizations to test and optimize hydrogen production technologies. The fleet has demonstrated hydrogen production methods, including electrolyzers from two different manufacturers (using energy from solar and wind) and natural gas reformers.

In 2004, HyRadix was selected to demonstrate its prototype natural gas reformer at SunLine under a project funded by the U.S. Department of Energy (DOE) and the South Coast Air Quality Management District (SCAQMD). The objectives of the project included demonstrating the unit in real-world conditions, evaluating the fill rates for vehicles, and evaluating the cost of hydrogen production compared to DOE targets. During the demonstration, the reformer provided high purity hydrogen to SunLine and gave HyRadix the opportunity to fully test the unit's capabilities for transit applications. Lessons learned during the demonstration have been used to optimize the system for commercialization. For more information on the results of the demonstration, refer to the 2005 DOE Annual Merit Review Proceedings[1] and the Annual Progress Report[2].

In June, 2006 SunLine awarded a contract to HyRadix to replace the existing unit with its commercial reformer, the Adéo. The cost of a new Adéo reformer from HyRadix starts around $750,000. This is the first HyRadix commercial unit to be installed in North America. The installation was completed and the unit went into service in August 2006. Funding for the new reformer was provided by SCAQMD and the Federal Transit Administration (FTA). SunLine also purchased a six-year service contract from HyRadix for operating and maintaining the reformer ($300,000 total).

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[1] J. Harness, *Auto-Thermal Reforming Based Refueling Station at SunLine*, DOE 2005 Annual Merit Review, May 24, 2005, Arlington, VA, www.hydrogen.energy.gov/pdfs/review05/tvp_6_harness.pdf

[2] J. Harness, *Auto-Thermal Reforming Based Refueling Station at SunLine Services*, DOE Hydrogen Program FY2005 Progress Report, VIII.3.C, www.hydrogen.energy.gov/pdfs/progress05/viii_c_3_harness.pdf.

On November 16, 2006, SunLine and HyRadix announced the opening of the first hydrogen fueling station available to the public. The SunLine public fueling station provides CNG, LNG, hydrogen, and blended hydrogen (20%) and CNG (80%) fuel to the public. SunLine estimates that this hydrogen fueling infrastructure can produce enough hydrogen to comfortably operate five full-size transit buses without running out of fuel for the small hydrogen vehicles expected to be fueled at this station.


The HyRadix Adéo[3] is a natural gas reformer that uses a proprietary catalytic auto-thermal reforming technology. The reformer generates hydrogen in four steps (as shown in Figure C-5):

1. **Sulfur removal** – The natural gas is fed through an ambient temperature sulfur adsorption device to remove specific impurities, such as the odorant added for leak detection. These compounds can affect the performance of the catalysts used in the reforming process.
2. **Reforming** – The natural gas is converted into a hydrogen-rich product stream through auto-thermal reforming, which uses a bi-functional catalyst that promotes two reactions (partial oxidation reaction and steam reforming reaction) in the same catalyst bed.
3. **Heat integration** – To increase overall efficiency, heat recovered during the process is used to pre-heat the feed into the reactor and generate steam for the reforming reaction.
4. **Purification** – Pressure swing adsorption (PSA) technology is used to purify the hydrogen.

The resulting purified hydrogen is compressed to 6,000 psi for storage prior to dispensing into the buses. The reformer is capable of producing 9 kg of hydrogen per hour. SunLine typically operates the unit at 4.5 kg per hour to meet current hydrogen demand. The HyRadix reformer unit is shown in Figure C-6. Onsite storage of hydrogen is approximately 180 kg of hydrogen in nine ASME tubes and a tube trailer with another 16 ASME tubes (shown in Figure C-7). Figure C-8 shows the hydrogen dispenser, which provides hydrogen to vehicles at a pressure up to 5,000 psi. Figure C-9 shows the fuel cell bus during fueling.

[3] HyRadix specifications two-page handout, http://www.hyradix.com/common/documents/adeo_specs.pdf

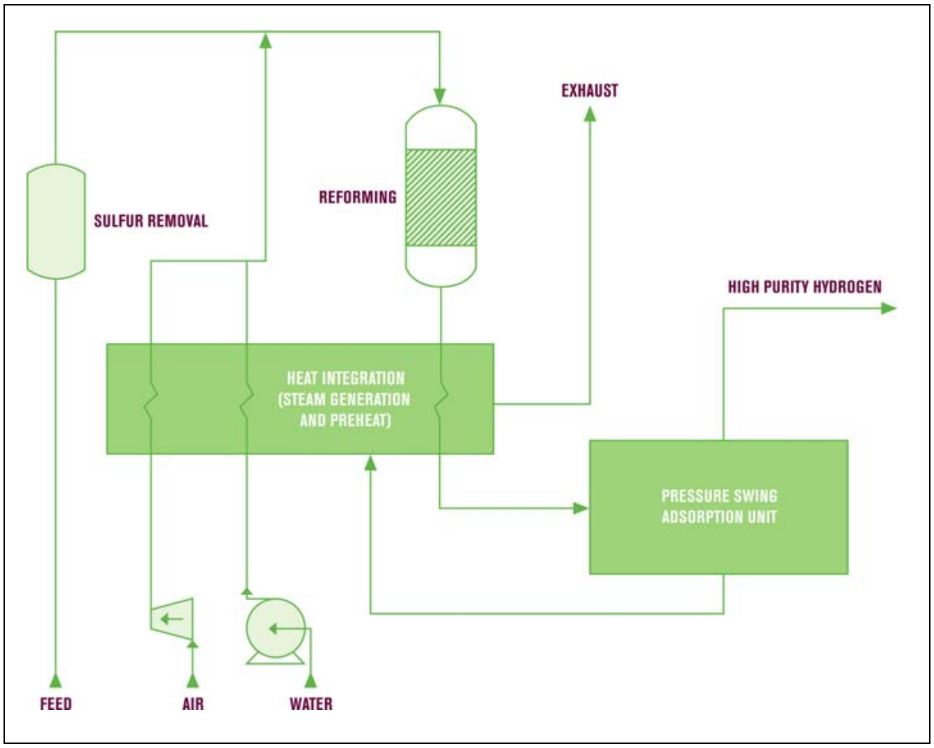


**Figure C-5. HyRadix hydrogen production process (Courtesy of HyRadix)**


**Figure C-6. SunLine's HyRadix Adéo commercial reformer**

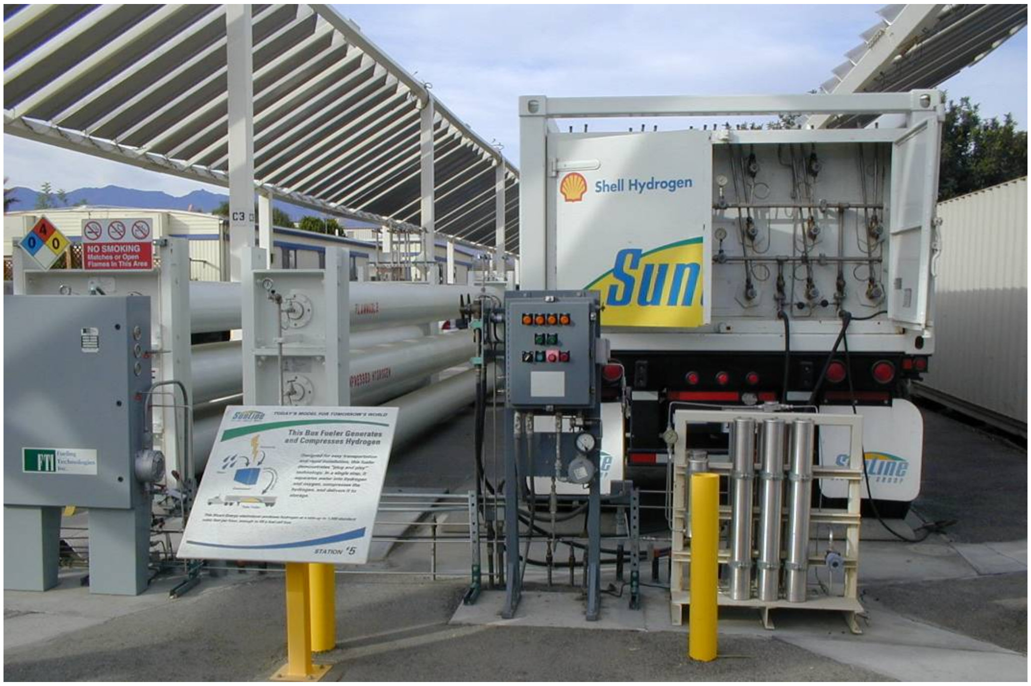


**Figure C-7. Hydrogen storage at SunLine**


**Figure C-8. Hydrogen dispenser at SunLine**


**Figure C-9. SunLine's fuel cell bus during fueling**

## Maintenance Facilities

In order to support operations and maintenance of CNG buses, SunLine made some modifications and upgrades to the maintenance facility in 1995. These included the addition of combustible gas detectors and the upgrade of some of the electrical conduit, lighting, and ventilation in the maintenance bays. The fueling station and maintenance facility upgrade costs at the Thousand Palms location were reported to be $1.47 million in 1995. Figure C-10 shows the maintenance facility at Thousand Palms. There were no additional costs for the outside bus parking areas.

The combustible gas sensors and alarms in the maintenance facility are required by building codes for indoor maintenance of CNG vehicles. The combustible gas detection system is designed to alarm at a 20% lower flammability limit (LFL) in air with a siren and lights. At 40% LFL the siren and lights latch on, power in the building is turned off, and the vents are opened in the roof of the building. The proper operation of this system is tested quarterly and the combustible gas detectors are calibrated every six months.

**Figure C-10. CNG maintenance facility in Thousand Palms**

When SunLine first began testing hydrogen buses, it built a special onsite facility for maintenance (shown in Figure C-11). Located behind the CNG bus maintenance building, the facility is essentially a tent designed to vent hydrogen through its roof. It consists of an aluminum frame covered with fireproof canvas, which is ventilated along the ridgeline with an 18-inch gap and a 6-inch raised "rain cap" to allow hydrogen gas to safely escape if it is inadvertently released from the vehicle. All lighting within the tent structure and adjacent maintenance bay is rated Class 1, Division 1. The building is also equipped with sensors that sound an alarm if a hydrogen leak is detected. Construction of the building cost approximately $50,000 ($21,000 for the building, doors, and ventilation system, and $29,000 for the fire and combustible gas sensors and the alarm system). This type of structure can provide a low-cost option to an agency in warmer climates, such as SunLine.

There have been no reported hydrogen leaks in the hydrogen maintenance facility, and no alarms have occurred. The system and sensors are checked and calibrated twice a year.

**Figure C-11. Hydrogen maintenance building**

# Appendix D: NREL Transit Bus Evaluation Activities

Under funding from the Department of Energy (DOE) and in coordination with the Federal Transit Administration (FTA), the National Renewable Energy Laboratory (NREL) has been evaluating alternative fuel transit buses since the early 1990s. In 1996, DOE and NREL completed an evaluation of transit buses at eight transit agencies that included six different alternative fuels. As part of this alternative fuel transit bus evaluation, NREL and Battelle (NREL's contractor for this effort) developed a customized data collection and evaluation protocol. This protocol has evolved over time, but is still based on the original effort.

NREL first began evaluating hydrogen-fueled transit buses in 2000 with SunLine Transit Agency. Since that time, NREL has published reports on fuel cell bus (FCB) performance and fleet experience for several transit agencies in the United States. These evaluations were funded under the DOE's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program[1], which is focused on addressing the technical challenges and accelerating the development and successful market introduction of hydrogen technologies. Technology validation is one of the key elements of this program.[2] NREL supports DOE's Technology Validation activity by evaluating hydrogen and fuel cell vehicles in parallel with hydrogen infrastructure to determine the current status of the technology and assess the progress toward technology readiness.

While DOE has not funded the direct development of fuel cell buses, it has provided funding to NREL to conduct data collection, analysis, and reporting of existing FCB project evaluation results under its Technology Validation activity. The current hydrogen transit bus evaluations include four active projects and two that were completed in the last few years.

In 2006, FTA initiated its newest development program, the National Fuel Cell Bus Program (NFCBP)[3]. The NFCBP was established as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: a Legacy for Users (SAFETEA-LU) transportation authorization. The NFCBP program designates $49 million in funding for 2006 through 2009 to help develop commercially viable fuel cell buses and technologies. The FTA competitively selected three nonprofit organizations—the Center for Transportation and the Environment (CTE), the Northeast Advanced Vehicle Consortium (NAVC), and WestStart-CALSTART—to administer projects under the program. The FTA selected 14 separate projects in all, including eight planned demonstration projects.

The FTA is collaborating with DOE and NREL to ensure that data are collected on all fuel cell bus demonstrations under the program. FTA has tasked NREL with evaluating the fuel cell bus demonstrations for the NFCBP. NREL uses the standard data collection and analysis protocol established for DOE heavy-duty vehicle evaluations as described in this plan. In May 2008, NREL published *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*, which outlines the

[1] DOE HFCIT Web site: www1.eere.energy.gov/hydrogenandfuelcells/
[2] DOE Multi-Year Research, Development and Demonstration Plan, www1.eere.energy.gov/hydrogenandfuelcells/mypp/
[3] FTA Bus Research and Testing Web site: http://www.fta.dot.gov/assistance/technology/research_4578.html

methodology for these evaluations[4]. Table D-1 provides an overview of all the FCB evaluation projects planned under both DOE and FTA funding. The projects are separated by funding agency, however for the NFCBP evaluation sites, any detailed data collection and analysis of the fuel cell system or infrastructure will be funded by DOE. Table D-2 provides more details and status for the evaluation sites funded solely by DOE. Additional details on the eight NFCBP demonstrations sites funded by FTA are listed in Table D-3. FTA is also considering additional funding for one or two sites beyond the NFCBP sites, but that has not been determined.

**Table D-1. Summary of Hydrogen Evaluations for DOE and FTA[5]**

<table>
<tr><th rowspan="2">Site/Locations</th><th rowspan="2">State</th><th rowspan="2">Eval. Funding</th><th colspan="2">2007</th><th colspan="4">2008</th><th colspan="4">2009</th><th colspan="4">2010</th></tr>
<tr><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>AC Transit /Oakland</td><td>CA</td><td rowspan="8">DOE Tech. Validation</td><td colspan="2">HyRoad</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>AC Transit /Oakland</td><td>CA</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="8">AC Transit CA ZEB 2009</td></tr>
<tr><td>SunLine /Thousand Palms</td><td>CA</td><td colspan="3">FCB/HHICE</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>SunLine /Thousand Palms</td><td>CA</td><td></td><td></td><td colspan="5">FCB Ext. Service</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>SunLine /Thousand Palms</td><td>CA</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="8">Advanced FCB Project</td></tr>
<tr><td>CTTRANSIT /Hartford</td><td>CT</td><td colspan="8">CTTRANSIT FCB Demo</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Hickam AFB /Honolulu</td><td>HI</td><td colspan="6">Air Force FCV Demo</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>VTA /San Jose</td><td>CA</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="8">VTA CA ZEB 2009</td></tr>
<tr><td>AC Transit /Oakland</td><td>CA</td><td rowspan="8">FTA National Fuel Cell Bus Program*</td><td></td><td colspan="5">Accelerated Testing</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>SunLine /Thousand Palms</td><td>CA</td><td></td><td></td><td></td><td></td><td></td><td colspan="9">American FCB Demo</td></tr>
<tr><td>CTTRANSIT /Hartford</td><td>CT</td><td></td><td></td><td></td><td></td><td></td><td colspan="9">CT Hybrid FCB Demo</td></tr>
<tr><td>Columbia /Site 2/ CTTRANSIT</td><td>SC/CT</td><td></td><td></td><td></td><td></td><td colspan="10">Dual Variable Output Hybrid FCB</td></tr>
<tr><td>Logan Airport /Boston</td><td>MA</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="6">MA H2 FCB Fleet</td></tr>
<tr><td>TBD/NY</td><td>NY</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="8">Lightweight FCB Demo</td></tr>
<tr><td>TBD/NY</td><td>NY</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="7">Hydroelectric H2 Powered FCB</td></tr>
<tr><td>SFMTA /San Francisco</td><td>CA</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">FC APU Hybrid</td></tr>
</table>

Color coded by geographic area * Detailed data collection and analysis funded by DOE

**Table D-2. DOE/NREL Heavy Vehicle Fuel Cell/Hydrogen Evaluations**

| Fleet | Vehicle/Technology | Number | Evaluation Status |
|---|---|---|---|
| SunLine Transit Agency (Thousand Palms, CA) | Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp. | 1 | Extended testing with updated fuel cell system, In process |
| Connecticut Transit (Hartford, CT) | Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp. | 1 | Bus in operation; data collection started |
| U.S. Air Force/Hickam Air Force Base (Honolulu, HI) | Shuttle bus: Hydrogenics and Enova, battery-dominant fuel cell hybrid | 1 | Shuttle bus in operation; data collection started |
| | Delivery van: Hydrogenics and Enova, fuel cell hybrid | 1 | Van in operation; data collection started |
| **Completed Evaluations** | | | |
| SunLine Transit Agency (Thousand Palms, CA) | New Flyer/ISE Corp. hydrogen internal combustion engine transit bus | 1 | Complete; results reported in Feb. 2007, Sep. 2007, and May 2008 |
| | Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp. | 1 | |
| Alameda-Contra Costa Transit District (Oakland, CA) | Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp. | 3 | Complete; results reported in Mar. 2007, Oct. 2007, and June 2008 |
| Santa Clara VTA, (San Jose, CA) and San Mateo (San Carlos, CA) | Gillig/Ballard fuel cell transit bus | 3 | Complete and reported in 2006 |
| SunLine Transit Agency (Thousand Palms, CA) | ISE Corp./ UTC Power ThunderPower hybrid fuel cell transit bus | 1 | Complete and reported in 2003 |

[4] Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-560-42781, May 2008.
[5] For current version of the summary table, see link: http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html

**Table D-3. Summary of FTA NFCBP Demonstration Projects**

| Project | Description |
|---|---|
| **Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing** (CTE) | Proterra will develop a battery-dominant 35-ft plug-in hybrid fuel cell bus (Hydrogenics) and demonstrate in Columbia, SC, and cities in CT |
| **Connecticut Fuel Cell Bus Demonstration** (NAVC) | UTC Power is leading a team to develop and demonstrate an advanced version hybrid 40-ft fuel cell buses; enhanced UTC Power 120 kW PEM fuel cell with upgraded seals, catalysts, bipolar plates, balance of plant |
| **Lightweight Fuel Cell Hybrid Bus** (NAVC) | GE led team to develop an advanced propulsion system integrated with a lightweight bus platform for field evaluation focused on advanced battery technologies for lower cost |
| **Massachusetts Hydrogen Fuel Cell Powered Bus Fleet** (NAVC) | Advanced bus development and in-service demonstration; integrate Nuvera 82 kW fuel cell with drive system from ISE Corp. and advanced energy storage; demonstration effort includes Nuvera's novel PowerTap fueling infrastructure |
| **Hydroelectric Hydrogen Powered FCB Program** (NAVC) | The project team led by the New York Power Authority will develop and demonstrate two 40-ft buses for operation in upstate New York for up to 2 years; Next-generation Ballard HD6 fuel cell module (150 kW) in hybrid configuration with ISE drive and ultracapacitors or batteries |
| **American Advanced Fuel Cell Bus Program** (WestStart-CALSTART) | A team led by SunLine will design and demonstrate 40-ft fuel cell bus with design improvements that meets FTA buy America requirements (New Flyer chassis, ISE hybrid drive system, and UTC Power fuel cell system); in-service evaluation in hot desert climate |
| **Compound Fuel Cell Hybrid Bus for 2010** (WestStart-CALSTART) | A team led by BAE will develop 40-ft hybrid bus with fuel cell auxiliary power unit coupled with diesel engine; demonstrate for one year at San Francisco MTA; small Hydrogenics PEM fuel cell (12 kW twin or 16 kW), BAE Systems drive, electrically driven accessories, advanced energy storage |
| **AC Transit HyRoad: Commercialization of Fuel Cells for Public Transit** (WestStart-CALSTART) | Accelerated testing to failure of existing fuel cell buses; Team includes Van Hool (bus chassis), ISE (hybrid drive system), and UTC Power (fuel cell system) |

## Overall Evaluation Objectives

The objectives of the DOE and FTA evaluations are to provide comprehensive, unbiased evaluation results of fuel cell and hydrogen bus development and performance compared to conventional baseline vehicles when available and appropriate. Baseline vehicles are typically diesel buses or occasionally compressed natural gas (CNG). These evaluations also include information on the development and performance of hydrogen infrastructure, and descriptions of the facility modifications required for safe operation of hydrogen-fueled vehicles.

The DOE and FTA demonstration and evaluation programs have two major goals:

- Provide credible data analysis results to the transit bus and fuel cell industries that go beyond "proof of concept" for fuel cell transit buses and infrastructure.

- Provide results focused on performance and use including progress over time and experience from integrating vehicle systems, operations, and facilities for the fuel cell transit buses and supporting infrastructure.

DOE and FTA have both cited the lack of data and analysis results in real-world service as a challenge for moving the technology forward. These evaluations have proved useful for a variety of groups including transit operators considering the technology for future procurements, manufacturers needing to understand the status of the technology for transit applications, and government agencies making policy decisions or determining future research needs.

# Appendix E: Fleet Summary Statistics

**Fleet Summary Statistics: SunLine Transit Agency**
**Fuel Cell Bus (FCB), Hybrid Hydrogen Internal Combustion Engine (HHICE), and Compressed Natural Gas (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 | 1/06-3/08 | 1/06-3/08 | 7/06-3/08 |
| Total Number of Months in Period | 27 | 27 | 21 |
| Fuel and Oil Analysis Base Fleet Mileage | 50,931 | 42,523 | 454,680 |
| Period Used for Maintenance Op Analysis | 1/06-3/08 | 1/06-3/08 | 7/06-3/08 |
| Total Number of Months in Period | 27 | 27 | 21 |
| Maintenance Analysis Base Fleet Mileage | 50,931 | 43,528 | 457,654 |
| Average Monthly Mileage per Vehicle | 1,886 | 1,612 | 4,359 |
| Availability | 66% | 59% | 83% |
| Fleet Fuel Usage in CNG GGE/H2 kg | 7,079 | 9,807 | 150,797 |
| Roadcalls | 35 | 21 | 46 |
| RCs MBRC | 1,455 | 2,073 | 9,949 |
| Propulsion Roadcalls | 32 | 19 | 15 |
| Propulsion MBRC | 1,592 | 2,291 | 30,510 |
| | | | |
| Fleet Miles/kg Hydrogen or CNG GGE | 7.19 | 4.34 | 3.02 |
| (1.13 kg H2/gal Diesel Fuel) | | | |
| Representative Fleet MPG (energy equiv.) | 8.13 | 4.90 | 3.37 |
| | | | |
| Hydrogen Cost per kg | 8.00 | 8.00 | |
| Cost per Gasoline Gallon Equivalent | | | 1.34 |
| Fuel Cost per Mile | **1.11** | **1.85** | **0.44** |
| | | | |
| Total Scheduled Repair Cost per Mile | 0.09 | 0.11 | 0.15 |
| Total Unscheduled Repair Cost per Mile | 0.35 | 0.48 | 0.15 |
| Total Maintenance Cost per Mile | **0.44** | **0.59** | **0.30** |
| | | | |
| **Total Operating Cost per Mile** | **1.55** | **2.43** | **0.74** |

### Maintenance Costs

| | Fuel Cell | HHICE | CNG |
|---|---|---|---|
| Fleet Mileage | 50,931 | 43,528 | 457,654 |
| | | | |
| Total Parts Cost | 719.60 | 4,389.76 | 36,240.89 |
| Total Labor Hours | 428.3 | 425.3 | 1,978.8 |
| Average Labor Cost (@ $50.00 per hour) | 21,412.50 | 21,262.50 | 98,940.00 |
| | | | |
| Total Maintenance Cost | 22,132.10 | 25,652.26 | 135,180.89 |
| Total Maintenance Cost per Bus | 22,132.10 | 25,652.26 | 27,036.18 |
| **Total Maintenance Cost per Mile** | **0.44** | **0.59** | **0.30** |

**Breakdown of Maintenance Costs by Vehicle System**

| | Fuel Cell | HHICE | CNG |
|---|---|---|---|
| Fleet Mileage | 50,931 | 43,528 | 457,654 |
| | | | |
| **Total Propulsion-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 65)** | | | |
| Parts Cost | 355.90 | 4,019.32 | 20,331.47 |
| Labor Hours | 215.3 | 258.5 | 364.0 |
| Average Labor Cost | 10,762.50 | 12,925.00 | 18,200.00 |
| Total Cost (for system) | 11,118.40 | 16,944.32 | 38,531.47 |
| Total Cost (for system) per Bus | 11,118.40 | 16,944.32 | 7,706.29 |
| **Total Cost (for system) per Mile** | **0.22** | **0.39** | **0.08** |
| | | | |
| **Exhaust System Repairs (ATA VMRS 43)** | | | |
| Parts Cost | 0.00 | 0.00 | 0.00 |
| Labor Hours | 0.0 | 0.0 | 9.5 |
| Average Labor Cost | 0.00 | 0.00 | 475.00 |
| Total Cost (for system) | 0.00 | 0.00 | 475.00 |
| Total Cost (for system) per Bus | 0.00 | 0.00 | 95.00 |
| **Total Cost (for system) per Mile** | **0.00** | **0.00** | **0.00** |
| | | | |
| **Fuel System Repairs (ATA VMRS 44)** | | | |
| Parts Cost | 0.00 | 12.04 | 1,006.59 |
| Labor Hours | 8.0 | 24.5 | 32.5 |
| Average Labor Cost | 400.00 | 1,225.00 | 1,625.00 |
| Total Cost (for system) | 400.00 | 1,237.04 | 2,631.59 |
| Total Cost (for system) per Bus | 400.00 | 1,237.04 | 526.32 |
| **Total Cost (for system) per Mile** | **0.01** | **0.03** | **0.01** |
| | | | |
| **Powerplant (Engine) Repairs (ATA VMRS 45)** | | | |
| Parts Cost | 0.00 | 314.23 | 8,810.54 |
| Labor Hours | 64.5 | 149.5 | 213.8 |
| Average Labor Cost | 3,225.00 | 7,475.00 | 10,687.50 |
| Total Cost (for system) | 3,225.00 | 7,789.23 | 19,498.04 |
| Total Cost (for system) per Bus | 3,225.00 | 7,789.23 | 3,899.61 |
| **Total Cost (for system) per Mile** | **0.06** | **0.18** | **0.04** |
| | | | |
| **Electric Propulsion Repairs (ATA VMRS 46)** | | | |
| Parts Cost | 0.00 | 0.00 | 0.00 |
| Labor Hours | 115.0 | 1.8 | 0.0 |
| Average Labor Cost | 5,750.00 | 87.50 | 0.00 |
| Total Cost (for system) | 5,750.00 | 87.50 | 0.00 |
| Total Cost (for system) per Bus | 5,750.00 | 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 | 7,465.67 |
| Labor Hours | 2.0 | 62.0 | 49.8 |
| Average Labor Cost | 100.00 | 3,100.00 | 2,487.50 |
| Total Cost (for system) | 455.90 | 6,496.76 | 9,953.17 |
| Total Cost (for system) per Bus | 455.90 | 6,496.76 | 1,990.63 |
| **Total Cost (for system) per Mile** | **0.01** | **0.15** | **0.02** |
| | | | |
| **Air Intake System Repairs (ATA VMRS 41)** | | | |
| Parts Cost | 0.00 | 235.66 | 2,138.88 |
| Labor Hours | 7.0 | 2.5 | 3.5 |
| Average Labor Cost | 350.00 | 125.00 | 175.00 |
| Total Cost (for system) | 350.00 | 360.66 | 2,313.88 |
| Total Cost (for system) per Bus | 350.00 | 360.66 | 462.78 |
| **Total Cost (for system) per Mile** | **0.01** | **0.01** | **0.01** |
| | | | |
| **Cooling System Repairs (ATA VMRS 42)** | | | |
| Parts Cost | 0.00 | 60.63 | 142.96 |
| Labor Hours | 15.0 | 17.8 | 45.0 |
| Average Labor Cost | 750.00 | 887.50 | 2,250.00 |
| Total Cost (for system) | 750.00 | 948.13 | 2,392.96 |
| Total Cost (for system) per Bus | 750.00 | 948.13 | 478.59 |
| **Total Cost (for system) per Mile** | **0.01** | **0.02** | **0.01** |
| | | | |
| **General Air System Repairs (ATA VMRS 10)** | | | |
| Parts Cost | 37.79 | 0.00 | 28.23 |
| Labor Hours | 2.5 | 0.0 | 5.8 |
| Average Labor Cost | 125.00 | 0.00 | 287.50 |
| Total Cost (for system) | 162.79 | 0.00 | 315.73 |
| Total Cost (for system) per Bus | 162.79 | 0.00 | 63.15 |
| **Total Cost (for system) per Mile** | **0.00** | **0.00** | **0.00** |
| | | | |
| **Brake System Repairs (ATA VMRS 13)** | | | |
| Parts Cost | 0.00 | 0.00 | 4.22 |
| Labor Hours | 9.0 | 1.5 | 10.3 |
| Average Labor Cost | 450.00 | 75.00 | 512.50 |
| Total Cost (for system) | 450.00 | 75.00 | 516.72 |
| Total Cost (for system) per Bus | 450.00 | 75.00 | 103.34 |
| **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 | 766.83 |
| Labor Hours | 0.3 | 0.5 | 10.0 |
| Average Labor Cost | 12.50 | 25.00 | 500.00 |
| Total Cost (for system) | 12.50 | 25.00 | 1,266.83 |
| Total Cost (for system) per Bus | 12.50 | 25.00 | 253.37 |
| **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 | 75.8 | 76.5 | 806.5 |
| Average Labor Cost | 3,787.50 | 3,825.00 | 40,325.00 |
| Total Cost (for system) | 3,787.50 | 3,825.00 | 40,325.00 |
| Total Cost (for system) per Bus | 3,787.50 | 3,825.00 | 8,065.00 |
| **Total Cost (for system) per Mile** | **0.07** | **0.09** | **0.09** |
| | | | |
| **HVAC System Repairs (ATA VMRS 01)** | | | |
| Parts Cost | 0.00 | 0.00 | 3,195.34 |
| Labor Hours | 53.3 | 4.0 | 66.5 |
| Average Labor Cost | 2,662.50 | 200.00 | 3,326.50 |
| Total Cost (for system) | 2,662.50 | 200.00 | 6,521.84 |
| Total Cost (for system) per Bus | 2,662.50 | 200.00 | 1,304.37 |
| **Total Cost (for system) per Mile** | **0.05** | **0.01** | **0.01** |
| | | | |
| **Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)** | | | |
| Parts Cost | 165.03 | 149.54 | 8,790.56 |
| Labor Hours | 60.0 | 44.5 | 477.0 |
| Average Labor Cost | 3,000.00 | 2,225.00 | 23,850.00 |
| Total Cost (for system) | 3,165.03 | 2,374.54 | 32,640.56 |
| Total Cost (for system) per Bus | 3,165.03 | 2,374.54 | 6,528.11 |
| **Total Cost (for system) per Mile** | **0.06** | **0.05** | **0.07** |
| | | | |
| **Lighting System Repairs (ATA VMRS 34)** | | | |
| Parts Cost | 18.00 | 220.90 | 1,276.17 |
| Labor Hours | 2.5 | 12.8 | 91.1 |
| Average Labor Cost | 125.00 | 637.50 | 4,552.50 |
| Total Cost (for system) | 143.00 | 858.40 | 5,828.67 |
| Total Cost (for system) per Bus | 143.00 | 858.40 | 1,165.73 |
| **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 | 142.88 | 0.00 | 2,335.95 |
| Labor Hours | 10.0 | 3.5 | 39.5 |
| Average Labor Cost | 500.00 | 175.00 | 1,975.00 |
| Total Cost (for system) | 642.88 | 175.00 | 4,310.95 |
| Total Cost (for system) per Bus | 642.88 | 175.00 | 862.19 |
| **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 | 233.60 |
| Labor Hours | 0.0 | 1.5 | 12.3 |
| Average Labor Cost | 0.00 | 75.00 | 612.50 |
| Total Cost (for system) | 0.00 | 75.00 | 846.10 |
| Total Cost (for system) per Bus | 0.00 | 75.00 | 169.22 |
| **Total Cost (for system) per Mile** | **0.00** | **0.00** | **0.00** |
| | | | |
| **Tire Repairs (ATA VMRS 17)** | | | |
| Parts Cost | 0.00 | 0.00 | 45.34 |
| Labor Hours | 0.0 | 22.5 | 106.0 |
| Average Labor Cost | 0.00 | 1,125.00 | 5,300.00 |
| Total Cost (for system) | 0.00 | 1,125.00 | 5,345.34 |
| Total Cost (for system) per Bus | 0.00 | 1,125.00 | 1,069.07 |
| **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 F: Fleet Summary Statistics – SI Units

**Fleet Summary Statistics: SunLine Transit Agency**
**Fuel Cell Bus (FCB), Hybrid Hydrogen Internal Combustion Engine (HHICE), and Compressed Natural Gas (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 | 1/06-3/08 | 1/06-3/08 | 7/06-3/08 |
| Total Number of Months in Period | 27 | 27 | 21 |
| Fuel and Oil Analysis Base Fleet Kilometers | 81,963 | 68,432 | 731,717 |
| Period Used for Maintenance Op Analysis | 1/06-3/08 | 1/06-3/08 | 7/06-3/08 |
| Total Number of Months in Period | 27 | 27 | 21 |
| Maintenance Analysis Base Fleet Kilometers | 81,963 | 70,050 | 736,503 |
| Average Monthly Kilometers per Vehicle | 3,036 | 2,594 | 7,014 |
| Availability | 66% | 59% | 83% |
| Fleet Fuel Usage in Gasoline L/$H_2$ kg | 7,079 | 9,807 | 570,767 |
| Roadcalls | 35 | 21 | 46 |
| Kilometers between Roadcalls (KBRC) | 2,342 | 3,336 | 16,011 |
| Propulsion Roadcalls | 32 | 19 | 15 |
| Propulsion KBRC | 2,561 | 3,687 | 49,100 |
| | | | |
| Fleet kg Hydrogen/100 km | 8.64 | 14.33 | |
| Representative Fleet MPG (L/100 km) | 28.93 | 48.00 | 69.81 |
| | | | |
| Hydrogen Cost per kg | 8.00 | 8.00 | |
| CNG Cost per Liter (based on GGE) | | | 0.35 |
| Fuel Cost per Kilometer | **0.69** | **1.15** | **0.28** |
| | | | |
| Total Scheduled Repair Cost per Kilometer | 0.05 | 0.07 | 0.09 |
| Total Unscheduled Repair Cost per Kilometer | 0.22 | 0.30 | 0.09 |
| Total Maintenance Cost per Kilometer | **0.27** | **0.37** | **0.18** |
| | | | |
| **Total Operating Cost per Kilometer** | **0.96** | **1.51** | **0.46** |

### Maintenance Costs

| | Fuel Cell | HHICE | CNG |
|---|---|---|---|
| Fleet Kilometers | 81,963 | 70,050 | 736,503 |
| | | | |
| Total Parts Cost | 719.60 | 4,389.76 | 36,240.89 |
| Total Labor Hours | 428.3 | 425.3 | 1,978.8 |
| Average Labor Cost (@ $50.00 per hour) | 21,412.50 | 21,262.50 | 98,940.00 |
| | | | |
| Total Maintenance Cost | 22,132.10 | 25,652.26 | 135,180.89 |
| Total Maintenance Cost per Bus | 22,132.10 | 25,652.26 | 27,036.18 |
| **Total Maintenance Cost per Kilometer** | **0.27** | **0.37** | **0.18** |

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