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SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Second Results Report – Appendices

Leslie Eudy
National Renewable Energy Laboratory

Kevin Chandler
Battelle

[Link to main report](#)

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5600-52349-2
October 2011

Contract No. DE-AC36-08GO28308

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Prepared under Task No. H270.8150

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Introduction to the Appendices

The National Renewable Energy Laboratory (NREL) has reported evaluation results for fuel cell buses since 2003. These reports include a broad range of background on the transit property, 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 new 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 can be 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.

Acronyms and Abbreviations

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

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Appendix A. NREL Transit Bus Evaluation Activities

Under funding from the U.S. 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. NREL uses a standard data collection and evaluation protocol that was established early in the process. This protocol has evolved over time but is still based on the original effort.

Since its first evaluation of hydrogen-fueled transit buses in 2000, NREL has published reports on fuel cell bus (FCB) performance and fleet experience for several transit agencies in the United States. Funding for these evaluations comes from DOE and FTA.

- DOE – the Technology Validation activity within DOE's Fuel Cell Technologies (FCT) Program[1] is focused on addressing the technical challenges and accelerating the development and successful market introduction of hydrogen technologies. 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 and analysis and report results of existing FCB projects under this activity.

- FTA – the National Fuel Cell Bus Program (NFCBP) is a cooperative research, development, and demonstration program to facilitate commercialization of fuel cell bus technology for the transit industry. The program is conducted in close partnership with industry and includes a portfolio of development and demonstration projects, component projects, and analysis and coordination efforts. 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. In November 2010, NREL published *Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*, which outlines the methodology for these evaluations.[2] Table A-1 provides an overview of all the FCB evaluation projects planned under both DOE and FTA funding. This is the estimated timing for NREL's data collection and evaluation and does not reflect the early design, development, and construction phase for the buses. The plans for upcoming evaluations are subject to change as each project progresses. The projects are separated by funding agency. Table A-2 provides more details and status for the evaluation sites funded solely by DOE. Additional details on the NFCBP demonstration sites funded by FTA are listed in Table A-3.

[1] DOE FCT website: www1.eere.energy.gov/hydrogenandfuelcells/.
[2] Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/TP-560-49342-1, November 2010, www.nrel.gov/hydrogen/pdfs/49342-1.pdf.

Table A-1. Summary of NREL Evaluations for DOE and FTA[3]

<table>
<tr><th colspan="20">NREL Hydrogen Evaluations for DOE and FTA</th></tr>
<tr><th rowspan="2">Site/Locations</th><th rowspan="2">State</th><th rowspan="2">No. Buses</th><th rowspan="2">Eval. Funding</th><th colspan="4">2010</th><th colspan="4">2011</th><th colspan="4">2012</th><th colspan="4">2013</th></tr>
<tr><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><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>AC Transit /SF Bay Area</td><td>CA</td><td>12</td><td rowspan="3">DOE Technology Validation</td><td></td><td></td><td colspan="10">ZEBA Demo</td><td></td><td></td><td></td><td></td></tr>
<tr><td>SunLine /Thousand Palms</td><td>CA</td><td>1</td><td></td><td colspan="8">Advanced FCB Project</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>City of Burbank/Burbank</td><td>CA</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">Burbank FCB</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>SunLine /Thousand Palms</td><td>CA</td><td>1</td><td rowspan="10">FTA National Fuel Cell Bus Program</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="7">American FCB Demo</td><td></td></tr>
<tr><td>CTTRANSIT /Hartford</td><td>CT</td><td>4</td><td></td><td></td><td colspan="8">Nutmeg Hybrid FCB Demo</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>USC, CMRTA /Columbia
UT, Cap Metro/Austin</td><td>SC
TX</td><td>1</td><td colspan="4">Hybrid FCB</td><td></td><td></td><td colspan="4">Demo Site 2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Logan Airport /Boston</td><td>MA</td><td>1</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><td></td><td></td></tr>
<tr><td>Albany /NY</td><td>NY</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">Light-wt FCB</td><td></td><td></td><td></td><td></td></tr>
<tr><td>SFMTA /San Francisco</td><td>CA</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">FC APU Hybrid</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CTA/ Chicago</td><td>IL</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">Chicago FCB</td><td></td><td></td></tr>
<tr><td>BJCTA/Birmingham</td><td>AL</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="6">Birmingham FCB</td></tr>
<tr><td>Ohio State/Columbus</td><td>OH</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="8">EcoSaver IV Hybrid FCB</td></tr>
<tr><td>USC, CMRTA /Columbia</td><td>SC</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="8">Advanced Composite FCB</td></tr>
</table>

Demonstration sites color coded by geographic area: Northern California, Northeast, South, Southern California, Southeast, Midwest

Table A-2. DOE/NREL Heavy Vehicle Fuel Cell Bus Evaluations

Fleet	Vehicle/Technology	Number	Evaluation Status
SunLine Transit Agency (Thousand Palms, CA)	New Flyer/Ballard/Bluways fuel cell hybrid bus	1	Bus in operation; in process
City of Burbank, CA	Proterra battery-dominant, plug-in hybrid bus using two Hydrogenics fuel cells	1	Bus delivered; in process
Bay Area Transit Consortia led by AC Transit (Oakland, CA)	Van Hool/UTC Power fuel cell hybrid	12	In process; 9 of 12 buses delivered
Completed Evaluations			
Connecticut Transit (Hartford, CT)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	Complete; results reported in Oct 2008, May 2009, and Jan 2010
SunLine Transit Agency (Thousand Palms, CA)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	Complete; results reported in Feb 2007, Sep 2007, June 2008, Jan 2009, and Aug 2009
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

[3] For current version of the summary table, see link: www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

Table A-3. Summary of FTA NFCBP Demonstration Projects

Project Title	Description
American Fuel Cell Bus Program (CALSTART) Status: In development, scheduled for late 2011 delivery	One new El Dorado bus to be operated at SunLine Transit Agency. This 40-foot bus is equipped with a hybrid propulsion system from BAE Systems, lithium ion batteries, and a fuel cell power system from Ballard (FCvelocity HD6).
Compound Fuel Cell Hybrid Bus 2010 (CALSTART) Status: On-going, bus delivered Nov 2010	One new Orion bus to be operated at San Francisco MTA. This 40-foot bus is equipped with a diesel hybrid propulsion system from BAE Systems, lithium ion batteries, and electric accessories to be driven by an APU consisting of two fuel cell systems from Hydrogenics.
AC Transit HyRoad: Commercialization of Fuel Cells for Public Transit (CALSTART) Status: Project complete	Three existing Van Hool buses to continue operation at AC Transit. These 40-foot buses are equipped with a Siemens ELFA hybrid electric propulsion system integrated by ISE with UTC Power PureMotion fuel cell power system and ZEBRA sodium nickel chloride high-temperature batteries. The project focused on maximizing operation of the buses to study failure modes and determine improvements.
Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing (CTE) Status: On-going, bus moved to second demonstration site	One newly designed Proterra bus to be operated in Columbia, SC, and Austin, TX. This 35-foot bus is a plug-in/battery dominant hybrid propulsion design integrated by Proterra with two Hydrogenics fuel cell power systems, and includes lithium titanate batteries for energy storage.
Nutmeg Project (NAVC) Status: On-going, buses in service	Four next-generation Van Hool 40-foot buses operating in Hartford, CT, at CTTRANSIT. These buses were purchased by UTC Power and are leased for transit operation. These 40-foot buses are equipped with a Siemens ELFA hybrid electric propulsion system integrated by Van Hool with a UTC Power PureMotion fuel cell power system. This design includes lithium ion batteries for energy storage.
Lightweight Battery Dominant Hybrid Fuel Cell Bus (NAVC) Status: In development	GE-led project for one development/testing bus and one new fuel cell bus. The testing vehicle includes a Hydrogenics fuel cell power system and has been used to support development activities of the new fuel cell bus, which will use a Ballard fuel cell power system.
Massachusetts Hydrogen Fuel Cell Powered Bus Program (NAVC) Status: In development	One new fuel cell bus to be operated at the Boston-area Logan International Airport. This will be a plug-in/battery dominant hybrid propulsion system. This design is planned with a Nuvera/Fiat fuel cell power system and lithium ion batteries for energy storage.
Chicago Transit Authority FCB Demo (CALSTART) Status: In development	Develop a next generation, 'Buy America' compliant fuel cell bus and test in the Chicago Transit Authority fleet. Project goals include proving the fuel cell system in a cold climate, exploring the potential of larger FCB fleet deployments, and reducing overall FCB cost to $1M. Partners: BAE Systems, ElDorado, Ballard.
Adv. Composite FCB Demo (CTE) Status: In development	Develop a 35-foot, highly efficient, battery-dominant FCB with an enhanced version fuel cell and fast charging capability. Demonstrate the bus in revenue service. Partners: Proterra, Ballard.
Birmingham FCB Demo (CTE) Status: In development	Develop and demonstrate a 30-foot battery dominant FCB with advanced lithium ion battery technology. Project goals include improved range, acceleration, and fuel economy. Partners: EV America, Ballard. (Continuation of an existing program originally funded outside the NFCBP.)
ECO Saver IV Hybrid Electric FCB Demo (CTE) Status: In development	Develop an advanced, battery-dominant FCB by integrating a Ballard fuel cell into an existing hybrid electric bus platform. Demonstrate in a campus shuttle route. Partners: DesignLine, Ballard.

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 they available and appropriate. Baseline vehicles are typically diesel buses or occasionally compressed natural gas (CNG) buses. 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 B: SunLine Description

Host Site Profile

SunLine[4] is located in the Palm Springs/Coachella Valley, California, and serves an area greater than 1,100 square miles (Figure B-1). Transit bus operations started in 1977 with 22 vehicles. SunLine provides bus service from two locations in the valley—one in Thousand Palms (shown in Figure B-2), which serves as headquarters, and another in Indio. In fiscal year 2009, ridership was reported as approximately 3.6 million passengers, the fleet operated 3.2 million revenue miles, and SunLine had an operating budget of $22.7 million.[5]

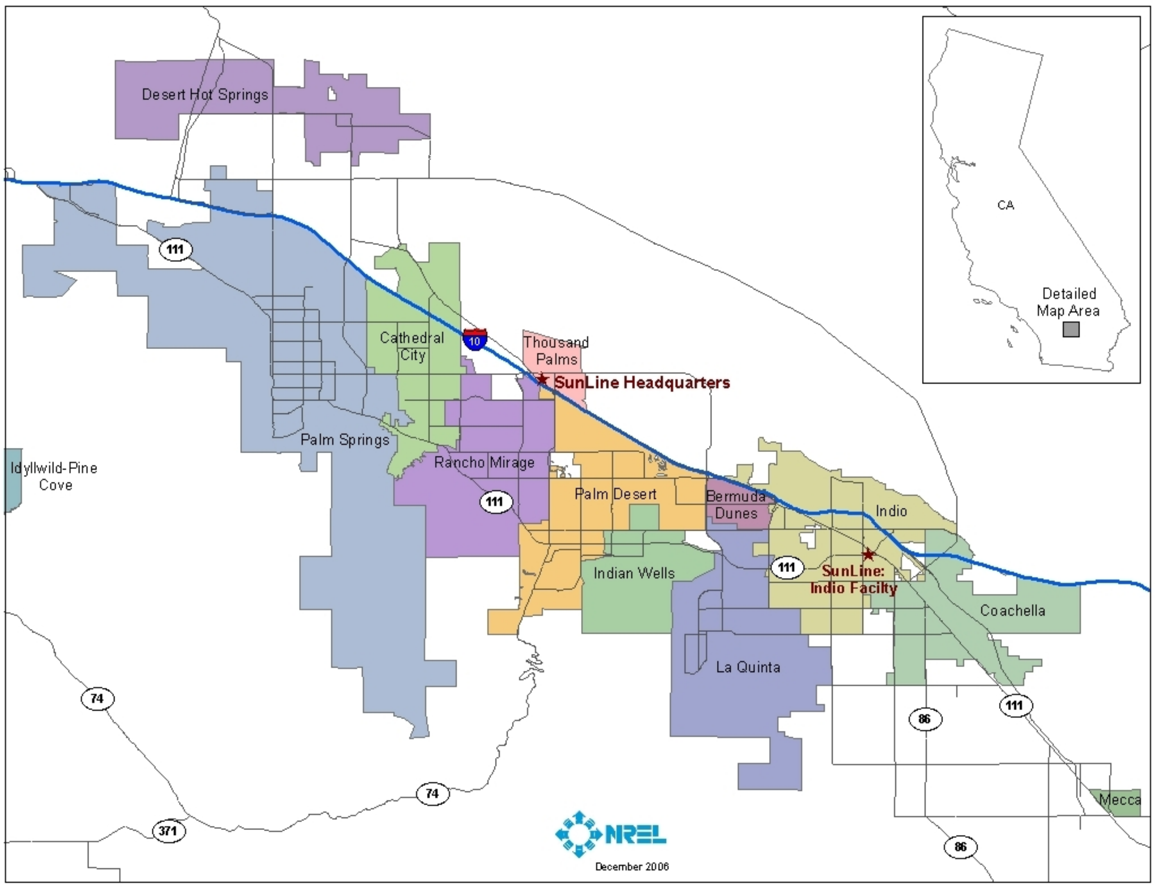

Figure B-1. SunLine operating area in the Coachella Valley, California

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. SunLine operates 11 fixed routes (SunBus) and provides paratransit services (SunDial). Table B-1 outlines SunLine's current bus fleet including the newest fuel cell bus. In addition to the 69 fixed-route buses, the agency's fleet includes 31 CNG paratransit vehicles. Its non-revenue vehicle fleet consists of 39 light- and medium-duty CNG vehicles and one hybrid light-duty vehicle.

[4] SunLine Transit Agency website: www.sunline.org.
[5] SunLine Transit Agency FY 2008 Annual Report: www.sunline.org/annual-report.

Figure B-2. SunLine headquarters in Thousand Palms

Table B-1. SunLine Fixed-Route Bus Fleet

Number	Description
41	New Flyer 40-ft, low floor, CNG
15	Orion V 40-ft, CNG
10	ElDorado 30-ft, CNG
1	New Flyer Hybrid Hydrogen ICE (HHICE)
1	Van Hool 40-ft, Fuel Cell Bus
1	New Flyer 40-ft, Advanced Technology Fuel Cell Bus
69	**Total Bus Fleet**

Route Descriptions

SunLine's fixed routes in the Coachella Valley operate along State Highway 111 and Interstate 10. In 2009, SunLine conducted a Comprehensive Operational Analysis[6] to better understand the existing and future transit market in the area and to develop a plan for optimizing service to cost-effectively meet those needs. The Preferred Service Plan outlined in the study recommended a variety of modifications to the route structure to increase ridership and lower operational costs. The changes included realignment of select routes, establishment of new routes, and increased frequencies and spans on most routes. SunLine began implementing this plan during 2010. Table B-2 shows a weekly summary of the updated bus use at SunLine and indicates that bus service operates at an average of 13.9 mph on the weekends and 14.0 mph during the week for an overall average of 13.9 mph.

TableB-2. Summary of Total Weekly Bus Use at SunLine

Day of Week	Total Miles	Hours	Average Speed
Weekday	42,993.0	3,080.8	14.0
Weekend	11,388.6	820.9	13.9
Total	**54,381.6**	**3,901.7**	**13.9**

The weather in SunLine's service area can have an effect on vehicle performance. The Coachella Valley is a hot, desert climate with an annual rainfall between 2 and 4 inches. Average high

[6] Link to SunLine's Comprehensive Operational Analysis: http://www.sunline.org/pub/pdfs/COA_July2009.pdf.

temperatures are usually over 80°F for eight months of the year and can get as high as 120°F. This 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.

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-duty 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) 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 fuel vehicles. 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 essentially occurred overnight in May 1994. An NREL report documenting SunLine's first 10 years of CNG operations experience is available.[7] 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's experience with hydrogen spans more than a decade of development and demonstration projects. SunLine has successfully used its unique capabilities with gaseous fuels, its small size, and its 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. A timeline of SunLine's hydrogen fueled bus demonstrations is shown in Figure B-3.

[7] NREL, 2006, "Ten Years of Compressed Natural Gas Operations at SunLine Transit Agency," http://www.eere.energy.gov/afdc/pdfs/39180.pdf.

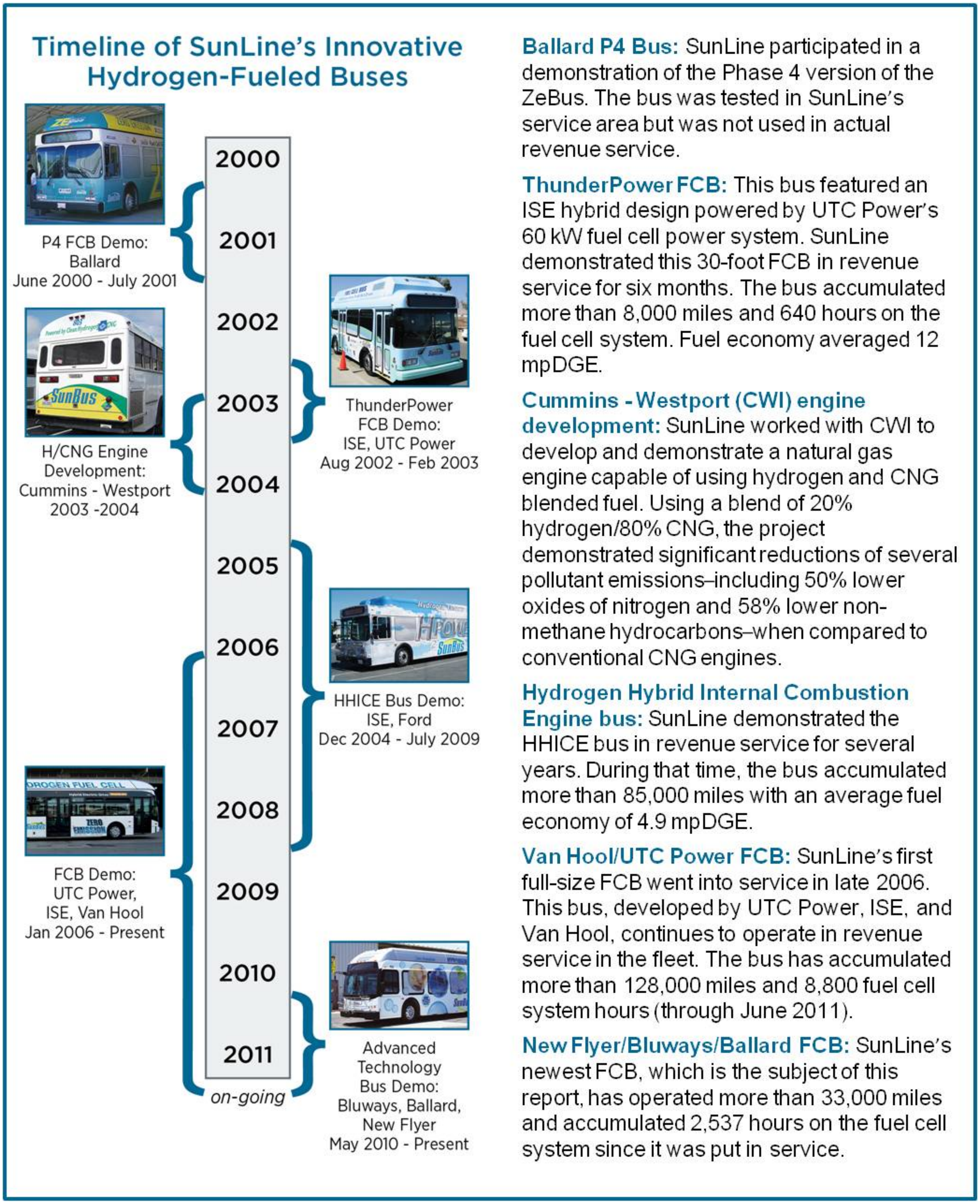

Figure B-3. Timeline of SunLine's hydrogen fueled bus demonstrations

Appendix C: Evaluation Bus Technology Descriptions

Table C-1 provides bus system descriptions for the AT fuel cell bus and CNG buses that were studied in this evaluation. The AT bus is a low floor, 40-foot New Flyer model with the latest advances designed to improve performance, reliability, and durability. Five compressed natural gas (CNG) buses operating from the same SunLine location are being used as a baseline comparison. These buses are 2008 model year New Flyer CNG buses with Cummins Westport ISL G natural gas engines that are designed to meet 2010 emission regulations.

Table C-1. Fuel Cell and CNG Bus System Descriptions

Vehicle System	AT Fuel Cell Bus	CNG Bus
Number of buses	1	5
Bus manufacturer and model	New Flyer, H40LFR	New Flyer
Model year	2009	2008
Length/width/height	40 ft/102 in./137 in.	40 ft/102 in./130.8 in.
Gross vehicle weight rating	44,530 lb	42,540 lb
Passenger capacity	37 seated with no wheelchairs	39 seated with no wheelchairs
Hybrid system	Bluways hybrid-electric drive system incorporating Siemens ELFA components	N/A
Fuel cell or engine	Ballard Power Systems FCvelocity HD6, 150 kW	Cummins Westport ISL G, 280 hp @ 2,200 rpm
Propulsion motor	Two Siemens AC induction motors, 85 kW each	N/A
Energy storage	Valence, phosphate based lithium ion batteries, rated energy: 47 kWh	N/A
Accessories	Electric	Mechanical
Fuel/storage	Gaseous hydrogen, 43 kg at 5,000 psi, 6 Dynetek, Type 3 tanks	125 diesel gallon equivalent
Bus purchase cost	$1,200,000[8]	$402,900

Advanced Technology Fuel Cell Bus

This AT fuel cell bus was designed in collaboration between Bluways,[9] Ballard, and New Flyer. The bus was originally developed as the pilot for an order of 20 buses to be operated in British Columbia, Canada, beginning with the 2010 Winter Olympic Games. The transit operator, BC Transit, put the bus through a series of acceptance tests over a period of about six months. The data results from those tests enabled the manufacturers to make changes and optimize the design prior to building the larger fleet. Once this bus completed its pilot testing in Canada, it was returned to Bluways where it was upgraded to match the final design of the rest of the BC Transit fleet. With funding from California and federal government agencies, SunLine was able to purchase the bus for operation in its service area. The bus is pictured in Figure C-1.

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

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

Figure C-1. SunLine's AT fuel cell bus at a transit stop

Hybrid Fuel Cell System

The design is a next-generation system based on experiences with early hybrid and fuel cell bus demonstrations conducted by the manufacturers. Each partner brings a unique perspective and set of experiences to creating a fuel cell bus designed to compete in the market. For Ballard, the new fuel cell module included improvements and upgrades based on lessons learned with projects such as the CUTE and HyFLEET:CUTE programs. As part of these and other demonstrations, Ballard gathered data from fuel cell buses operating for more than 1.2 million miles of revenue service. The data collected during these demonstrations were used to refine and optimize the fuel cell and system components for higher efficiency and increased durability. Ballard now offers a 5-year, 12,000-hour warranty on the HD6 fuel cell module.

The Bluways hybrid system was designed as a plug-and-play architecture, which enables a variety of power sources or energy storage solutions to be easily incorporated. For this AT bus, Bluways integrated Ballard's 150-kW fuel cell module and lithium-ion batteries from Valence. The hybrid electric propulsion system is based on the Siemens ELFA system. The company's experience with early version fuel cell buses and a fleet of gasoline hybrid buses provided in-service data to aid in the development process.

Appendix D: 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 has full ownership of the station and benefits fully from the sale of fuel. In addition to CNG, the station offers a blend of CNG and hydrogen, and pure hydrogen. Diesel and gasoline are not available at SunLine.

Natural Gas Fueling

SunLine has two bus operation sites, and both locations have a CNG fueling station for the bus fleet and for public fueling. The station has a public fueling station on the outside of the facility at Thousand Palms (Figure D-1), and piping is run underground to SunLine's private bus fueling station (Figure D-2). The public and private stations provide CNG at 3,600 psi.

Figure D-1. Public fueling at SunLine's Thousand Palms CNG fueling station (left) and a CNG dispenser (right)

Figure D-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 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.

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. Fueling times range from 12 minutes to 20 minutes, depending on demand. Some trucks and support vehicles are also fueled at this location from the public side of the station.

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.

SunLine currently produces hydrogen with a HyRadix reformer. 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). The HyRadix Adéo[10] 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 D-3):

- **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.
- **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.

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

- **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.
- **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. Onsite storage of hydrogen is approximately 180 kg of hydrogen in 9 ASME tubes and a tube trailer with another 16 ASME tubes. The hydrogen dispenser provides hydrogen to vehicles at a pressure up to 5,000 psi. Figure D-4 shows the hydrogen storage, natural gas reformer, and dispenser at the SunLine fueling station.

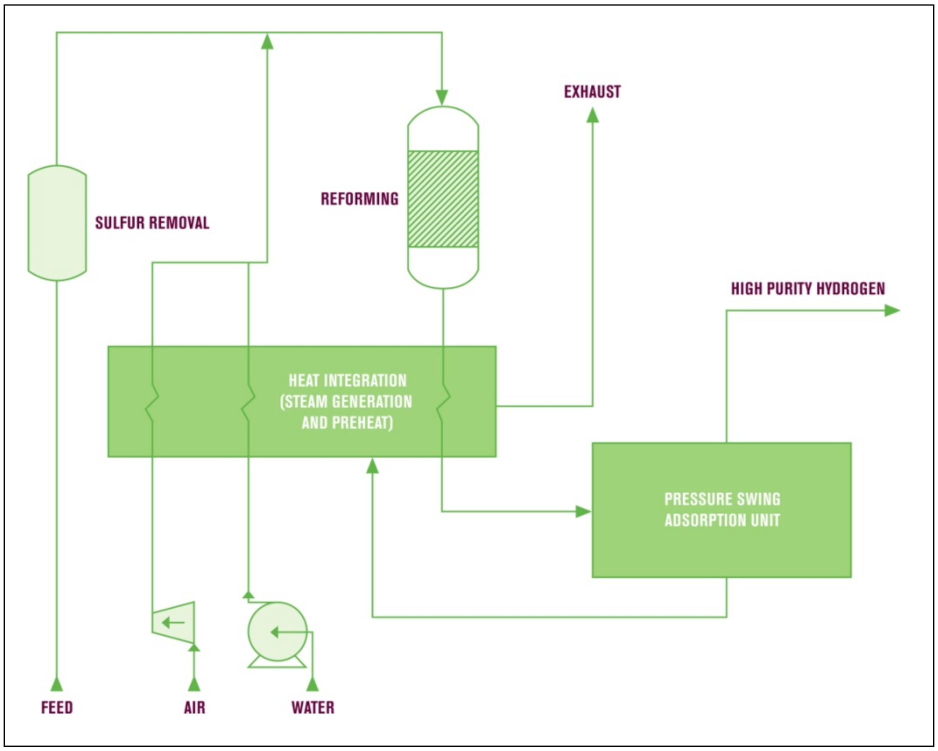

Figure D-3. HyRadix hydrogen production process (Courtesy of HyRadix)

The SunLine public fueling station provides CNG, 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.

Figure D-4. SunLine's hydrogen storage (top left), HyRadix Adéo commercial reformer (bottom left), and hydrogen dispenser (right)

Maintenance Facilities

To support operation 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. 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 a 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.

When SunLine first began testing hydrogen buses, it built a special on-site facility for maintenance. 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 located in a warmer climate, such as SunLine. The CNG and hydrogen maintenance facilities are pictured in Figure D-5.

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 D-5. CNG maintenance facility in Thousand Palms (top) and hydrogen maintenance building (bottom)

Appendix E: Fleet Summary Statistics

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

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Number of vehicles	1	1	5	5
Period used for fuel and oil op analysis	5/10–6/11	12/10–6/11	5/10–6/11	12/10–6/11
Total number of months in period	14	7	14	7
Fuel and oil analysis base fleet mileage	20,744	11,164	320,005	161,833
Period used for maintenance op analysis	5/10–6/11	12/10–6/11	5/10–6/11	12/10–6/11
Total number of months in period	14	7	14	7
Maintenance analysis base fleet mileage	20,851	11,164	320,005	161,833
Average monthly mileage per vehicle	1,489	1,595	4,572	4,624
Availability	62%	64%	89%	88%
Fleet fuel usage in CNG GGE/H_2 kg	3,472	1,807	108,250	53,254
Roadcalls	4	2	24	17
RCs MBRC	5,213	5,582	13,334	9,520
Propulsion roadcalls	4	2	13	10
Propulsion MBRC	5,213	5,582	24,616	16,183
Fleet miles/kg hydrogen or CNG GGE	5.98	6.18	2.96	3.04
(1.13 kg H_2/gal diesel fuel)				
Representative fleet MPG (energy equiv)	6.75	6.98	3.30	3.40
Hydrogen cost per kg	8.00	8.00		
GGE cost			0.90	0.97
Fuel cost per mile	**1.34**	**1.29**	**0.30**	**0.32**
Total scheduled repair cost per mile	0.16	0.20	0.13	0.13
Total unscheduled repair cost per mile	0.68	0.96	0.28	0.31
Total maintenance cost per mile	**0.84**	**1.16**	**0.41**	**0.44**
Total operating cost per mile	**2.18**	**2.45**	**0.71**	**0.76**

Maintenance Costs

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Fleet mileage	20,851	11,164	320,005	161,833
Total parts cost	1,949.22	1,796.00	44,240.48	25,858.95
Total labor hours	310.5	222.5	1739.3	908.5
Average labor cost (@ $50.00 per hour)	15,525.00	11,125.00	86,965.00	45,425.00
Total maintenance cost	17,474.22	12,921.00	131,205.48	71,283.95
Total maintenance cost per bus	17,474.22	12,921.00	26,241.10	14,256.79
Total maintenance cost per mile	**0.84**	**1.16**	**0.41**	**0.44**

Maintenance Costs by Vehicle System

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Fleet mileage	20,851	11,164	320,005	161,833
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	59.64	46.64	22,750.64	13,744.81
Labor hours	122.75	78.00	346.50	217.75
Average labor cost	6,137.50	3,900.00	17,325.00	10,887.50
Total cost (for system)	6,197.14	3,946.64	40,075.64	24,632.31
Total cost (for system) per bus	6,197.14	3,946.64	8,015.13	4,926.46
Total cost (for system) per mile	**0.2972**	**0.3535**	**0.1252**	**0.1522**
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	168.95	168.95
Labor hours	0.0	0.0	2.0	2.0
Average labor cost	0.00	0.00	100.00	100.00
Total cost (for system)	0.00	0.00	268.95	268.95
Total cost (for system) per bus	0.00	0.00	53.79	53.79
Total cost (for system) per mile	**0.0000**	**0.0000**	**0.0008**	**0.0017**
Fuel System Repairs (ATA VMRS 44)				
Parts cost	4.45	4.45	676.26	331.92
Labor hours	1.0	0.0	0.5	0.5
Average labor cost	50.00	0.00	25.00	25.00
Total cost (for system)	54.45	4.45	701.26	356.92
Total cost (for system) per bus	54.45	4.45	140.25	71.38
Total cost (for system) per mile	**0.0026**	**0.0004**	**0.0022**	**0.0022**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	13.00	0.00	9,939.60	7,289.26
Labor hours	58.0	37.5	220.8	156.3
Average labor cost	2,900.00	1,875.00	11,037.50	7,812.50
Total cost (for system)	2,913.00	1,875.00	20,977.10	15,101.76
Total cost (for system) per bus	2,913.00	1,875.00	4,195.42	3,020.35
Total cost (for system) per mile	**0.1397**	**0.1680**	**0.0656**	**0.0933**
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	23.0	9.5	0.0	0.0
Average labor cost	1,150.00	475.00	0.00	0.00
Total cost (for system)	1,150.00	475.00	0.00	0.00
Total cost (for system) per bus	1,150.00	475.00	0.00	0.00
Total cost (for system) per mile	**0.0552**	**0.0425**	**0.0000**	**0.0000**

Maintenance Costs by Vehicle System (continued)

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	0.00	0.00	9,670.14	4,663.98
Labor hours	13.5	9.0	71.0	26.0
Average labor cost	675.00	450.00	3,550.00	1,300.00
Total cost (for system)	675.00	450.00	13,220.14	5,963.98
Total cost (for system) per bus	675.00	450.00	2,644.03	1,192.80
Total cost (for system) per mile	**0.0324**	**0.0403**	**0.0413**	**0.0369**
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	0.00	0.00	751.97	331.62
Labor hours	0.0	0.0	0.0	0.0
Average labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	751.97	331.62
Total cost (for system) per bus	0.00	0.00	150.39	66.32
Total cost (for system) per mile	**0.0000**	**0.0000**	**0.0023**	**0.0020**
Cooling System Repairs (ATA VMRS 42)				
Parts cost	42.19	42.19	840.48	583.32
Labor hours	27.3	22.0	49.8	33.0
Average labor cost	1,362.50	1,100.00	2,487.50	1,650.00
Total cost (for system)	1,404.69	1,142.19	3,327.98	2,233.32
Total cost (for system) per bus	1,404.69	1,142.19	665.60	446.66
Total cost (for system) per mile	**0.0674**	**0.1023**	**0.0104**	**0.0138**
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0.00	0.00	456.79	263.27
Labor hours	0.0	0.0	0.0	0.0
Average labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	456.79	263.27
Total cost (for system) per bus	0.00	0.00	91.36	52.65
Total cost (for system) per mile	**0.0000**	**0.0000**	**0.0014**	**0.0016**
General Air System Repairs (ATA VMRS 10)				
Parts cost	0.00	0.00	15.86	15.86
Labor hours	4.5	3.5	14.0	0.0
Average labor cost	225.00	175.00	700.00	0.00
Total cost (for system)	225.00	175.00	715.86	15.86
Total cost (for system) per bus	225.00	175.00	143.17	3.17
Total cost (for system) per mile	**0.0108**	**0.0157**	**0.0022**	**0.0001**

Maintenance Costs by Vehicle System (continued)

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Brake System Repairs (ATA VMRS 13)				
Parts cost	4.99	4.99	4,720.60	4,688.99
Labor hours	0.0	0.0	85.8	84.3
Average labor cost	0.00	0.00	4,287.50	4,212.50
Total cost (for system)	4.99	4.99	9,008.10	8,901.49
Total cost (for system) per bus	4.99	4.99	1,801.62	1,780.30
Total cost (for system) per mile	**0.0002**	**0.0004**	**0.0281**	**0.0550**
Transmission Repairs (ATA VMRS 27)				
Parts cost	0.00	0.00	246.45	112.49
Labor hours	0.0	0.0	2.5	0.0
Average labor cost	0.00	0.00	125.00	0.00
Total cost (for system)	0.00	0.00	371.45	112.49
Total cost (for system) per bus	0.00	0.00	74.29	22.50
Total cost (for system) per mile	**0.0000**	**0.0000**	**0.0012**	**0.0007**
Inspections Only - No Parts Replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	65.3	44.5	545.8	259.3
Average labor cost	3,262.50	2,225.00	27,287.50	12,962.50
Total cost (for system)	3,262.50	2,225.00	27,287.50	12,962.50
Total cost (for system) per bus	3,262.50	2,225.00	5,457.50	2,592.50
Total cost (for system) per mile	**0.1565**	**0.1993**	**0.0853**	**0.0801**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	1,485.48	1,462.32	10,362.84	3,750.28
Labor hours	84.0	75.8	543.3	257.0
Average labor cost	4,200.00	3,787.50	27,162.50	12,850.00
Total cost (for system)	5,685.48	5,249.82	37,525.34	16,600.28
Total cost (for system) per bus	5,685.48	5,249.82	7,505.07	3,320.06
Total cost (for system) per mile	**0.2727**	**0.4702**	**0.1173**	**0.1026**
HVAC System Repairs (ATA VMRS 01)				
Parts cost	22.73	22.73	2,518.22	2,220.81
Labor hours	26.0	14.5	50.8	23.3
Average labor cost	1,300.00	725.00	2,537.50	1,162.50
Total cost (for system)	1,322.73	747.73	5,055.72	3,383.31
Total cost (for system) per bus	1,322.73	747.73	1,011.14	676.66
Total cost (for system) per mile	**0.0634**	**0.0670**	**0.0158**	**0.0209**

Maintenance Costs by Vehicle System (continued)

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Lighting System Repairs (ATA VMRS 34)				
Parts cost	150.32	33.26	892.40	722.04
Labor hours	4.0	3.3	37.5	23.3
Average labor cost	200.00	162.50	1,875.00	1,162.50
Total cost (for system)	350.32	195.76	2,767.40	1,884.54
Total cost (for system) per bus	350.32	195.76	553.48	376.91
Total cost (for system) per mile	**0.0168**	**0.0175**	**0.0086**	**0.0116**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	226.06	226.06	2,728.81	716.16
Labor hours	2.3	1.5	31.8	8.5
Average labor cost	112.50	75.00	1,587.50	425.00
Total cost (for system)	338.56	301.06	4,316.31	1,141.16
Total cost (for system) per bus	338.56	301.06	863.26	228.23
Total cost (for system) per mile	**0.0162**	**0.0270**	**0.0135**	**0.0071**
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	251.11	0.00
Labor hours	0.0	0.0	22.0	6.5
Average labor cost	0.00	0.00	1,100.00	325.00
Total cost (for system)	0.00	0.00	1,351.11	325.00
Total cost (for system) per bus	0.00	0.00	270.22	65.00
Total cost (for system) per mile	**0.0000**	**0.0000**	**0.0042**	**0.0020**
Tire Repairs (ATA VMRS 17)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	1.8	1.5	62.0	28.8
Average labor cost	87.50	75.00	3,100.00	1,437.50
Total cost (for system)	87.50	75.00	3,100.00	1,437.50
Total cost (for system) per bus	87.50	75.00	620.00	287.50
Total cost (for system) per mile	**0.0042**	**0.0067**	**0.0097**	**0.0089**

Notes

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

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

2. The propulsion-related systems were chosen to include only those systems of the vehicles that could be affected directly by the selection of a fuel/advanced technology.

3. ATA VMRS coding is based on parts that were replaced. If there was no part replaced in a given repair, then the code was chosen by the system being worked on.

4. In general, inspections (with no part replacements) were included only in the overall totals (not by system). Category 101 was created to track labor costs for PM inspections.

5. ATA VMRS 02-Cab and Sheet Metal represents seats, doors, etc.; ATA VMRS 50-Accessories represents things like fire extinguishers, test kits, etc.; ATA VMRS 71-Body represents mostly windows and windshields.

6. Average labor cost is assumed to be $50 per hour.

7. Warranty costs are not included.

Appendix F: Fleet Summary Statistics – SI Units

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

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Number of vehicles	1	1	5	5
Period used for fuel and oil op analysis	5/10–6/11	12/10–6/11	5/10–6/11	12/10–6/11
Total number of months in period	14	7	14	7
Fuel and oil analysis base fleet kilometers	33,383	17,966	514,984	260,438
Period used for maintenance op analysis	5/10–6/11	12/10–6/11	5/10–6/11	12/10–6/11
Total number of months in period	14	7	14	7
Maintenance analysis base fleet kilometers	33,556	17,966	514,984	260,438
Average monthly kilometers per vehicle	2,396	2,567	7,357	7,441
Availability	62%	64%	89%	88%
Fleet fuel usage in CNG liter equiv/H_2 kg	3,472	1,807	409,726	201,566
Roadcalls	4	2	24	24
RCs KMBRC	8,389	8,983	21,458	10,852
Propulsion roadcalls	4	2	13	13
Propulsion KMBRC	8,389	8,983	39,614	20,034
Fleet kg hydrogen/100 km	10.40	10.06	79.56	77.40
(1.13 kg H_2/gal diesel fuel)				
Rep. fleet fuel consumption (L/100 km)	34.84	33.69	71.21	69.27
Hydrogen cost per kg	8.00	8.00		
GGE cost/liter			0.24	0.26
Fuel cost per kilometer	**0.83**	**0.805**	**0.189**	**0.20**
Total scheduled repair cost per kilometer	0.01	0.12	0.08	0.08
Total unscheduled repair cost per kilometer	0.42	0.60	0.17	0.19
Total maintenance cost per kilometer	**0.52**	**0.72**	**0.25**	**0.27**
Total operating cost per kilometer	**1.35**	**1.52**	**0.44**	**0.47**

Maintenance Costs

	Fuel Cell Bus All Data	Fuel Cell Bus New Data	CNG Buses All Data	CNG Buses New Data
Fleet mileage	33,556	17,966	514,984	260,438
Total parts cost	1,949.22	1,796.00	44,240.48	25,858.95
Total labor hours	310.5	222.5	1739.3	908.5
Average labor cost (@ $50.00 per hour)	15,525.00	11,125.00	86,965.00	45,425.00
Total maintenance cost	17,474.22	12,921.00	131,205.48	71,283.95
Total maintenance cost per bus	17,474.22	12,921.00	26,241.10	14,256.79
Total maintenance cost per kilometer	**0.52**	**0.72**	**0.25**	**0.27**