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Santa Clara Valley Transportation Authority and San Mateo County Transit District

Fuel Cell Transit Buses: Preliminary Evaluation Results

K. Chandler
Battelle

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Technical Report
NREL/TP-540-39365
March 2006

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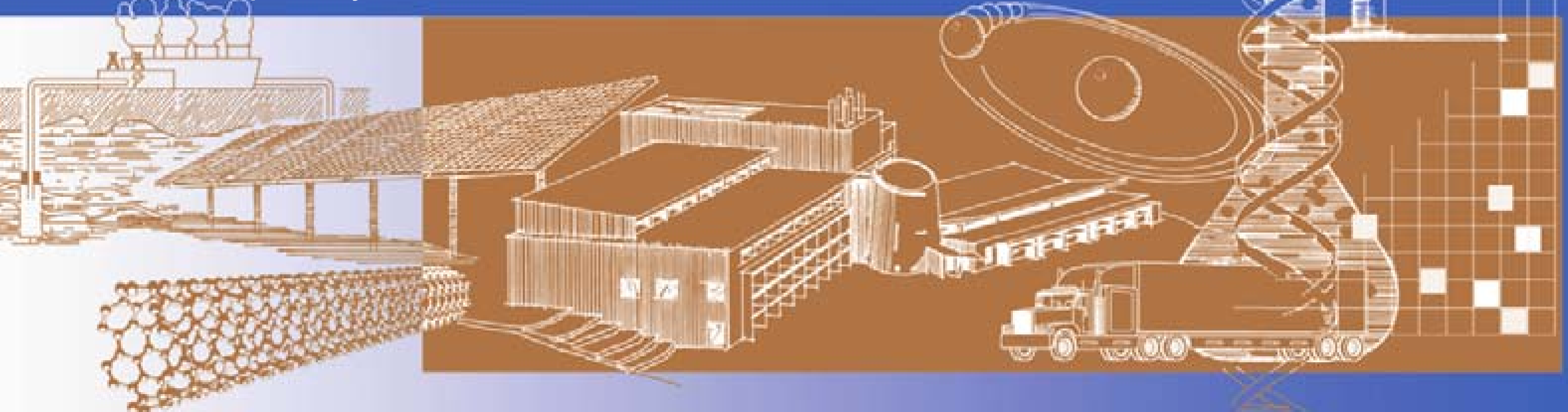

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Executive Summary

This report provides preliminary results from an evaluation of prototype fuel cell transit buses operating at Santa Clara Valley Transportation Authority (VTA) in San Jose, California. San Mateo County Transit District (SamTrans) in San Carlos, California, is a partner with VTA in this fuel cell bus demonstration. VTA has been operating three fuel cell transit buses in extra revenue service since February 28, 2005. This report provides descriptions of the equipment used (buses and infrastructure), early experience and lessons learned, and preliminary evaluation results from the operation of the buses and supporting hydrogen fuel station from March 2005 through October 2005 (eight months).

This evaluation of prototype fuel cell transit buses at VTA is a part of the U.S. Department of Energy's (DOE) Hydrogen, Fuel Cells & Infrastructure Technologies Program, which integrates activities in hydrogen production, storage, and delivery with transportation and stationary fuel cell applications.

VTA and SamTrans began planning their zero-emission bus (ZEB) demonstration in 2000. VTA is the lead agency in the operation of these buses; SamTrans shares in the demonstration's planning and operation and the capital and operating costs. The goals of this demonstration project are to:

- Determine the status of fuel cell technology in transit applications.
- Identify issues and challenges to overcome.
- Provide community outreach and educate the public on fuel cell and hydrogen technology.

The fuel cell buses at VTA are considered prototype technology, and the analysis in this report reflects the prototype status of these vehicles. **There is no intent to consider the implementation of these fuel cell buses as commercial (or full revenue transit service)**. The evaluation focuses on documenting progress and opportunities for improvement of the vehicles, infrastructure, and procedures.

Infrastructure and Facilities

VTA has three bus operation depots: the Cerone, Chaboya, and North. The Cerone operating division was selected as the home of the ZEB program primarily because of space availability. The infrastructure and facilities added for fuel cell bus operations at Cerone included a compressed hydrogen dispensing station, a stand-alone two-bay maintenance facility, and an upgraded bus wash to accommodate the taller fuel cell buses (Figure ES-1).

The hydrogen dispensing station, designed and constructed by Air Products and Chemicals, Inc. (Air Products), was completed in May 2004 (approximately $640,000 for VTA, plus liquid hydrogen shipments to the station); however, actual dispensing of hydrogen at the station did not start until November 2004. During initial use of the hydrogen fueling infrastructure, there were some significant challenges and problems that had to be overcome. The process of building, permitting, and commissioning the station took longer than expected due in part to a general lack of experience and precedence with this application of hydrogen in the San Jose area and due to some technical problems with the station.

A few setbacks have occurred at VTA's hydrogen dispensing station. These include an incident with a thermocouple failure, followed by several false alarms, which caused the local fire officials to temporarily stop the operation of the hydrogen fueling facility until corrections were made and issues were resolved. This prevented the fuel cell buses from being fueled with hydrogen for several months. Operation of the fuel cell buses and hydrogen fueling station has been under way in earnest since the end of February 2005 (the start of revenue service). VTA and local emergency responders have gained significant experience and are progressing with the demonstration.

It is important to recognize that this is a demonstration project and that some of the technology used in the hydrogen dispensing station is in early deployment and use. With any demonstration project, problems should be expected, especially during the first months of operation. Significant progress and improvements have been made to the hydrogen dispensing station during the program, including,

- Safe operation of the hydrogen dispensing station during the demonstration program with no injuries or recordable incidents.
- More than 300 successful fuel cell bus and light-duty vehicle fills.
- Systematic identification and correction of problems to ensure the hydrogen dispensing station was kept online to service the fuel cell bus fleet.
- Incorporation of modifications into the station to address lessons learned during the station operation.

A separate maintenance facility was designed and built for the fuel cell bus demonstration. This two-bay building houses the equipment and some of the spare parts needed to maintain and repair fuel cell buses. This facility was designed for hydrogen requirements and, like the fueling station, the maintenance building is equipped with the necessary devices to enable safe operation and maintenance on hydrogen vehicles. This facility opened for operation in November 2005. Delays in completion of the building were caused by problems similar to those of the hydrogen dispensing station. These included issues of building codes and familiarity with hydrogen. The new bus wash was also designed and constructed to allow for the added height of the fuel cell buses and hydrogen fuel on board the buses. The total cost for these three facilities to meet the requirements of operating the hydrogen fuel cell buses at VTA was $4.4 million.

The method for dispensing compressed hydrogen from the station into the buses has progressed. Until April 2005, it took approximately 18-24 minutes to fuel a fuel cell bus. Since April 2005, when Air Products put the new cryogenic compressor online, fueling time has been reduced to an average of 10-14 minutes.

Hydrogen fuel cost an average of $8.56 per kg throughout the evaluation period (March 2005 through October 2005). This high cost is an indicator of the low volume use of hydrogen as a fuel. Diesel fuel averaged $2.02 per gallon during the same evaluation period.

Figure ES-1. Compressed Hydrogen Dispensing Station, Fuel Cell Bus, Bus Wash, and Maintenance Facility

The hydrogen dispensing station was built to the original specifications to support a minimum of six fuel cell buses. This is double the current fleet size. If the station utilization is not high enough to overcome the liquid hydrogen storage tank boil-off rate, the tank will vent this hydrogen. The size of the station and delays in full operation of the dispensing station caused the loss of approximately 50% of the hydrogen fuel.

Early Experience

Familiarization training for hydrogen safety and general characteristics was a high priority for the fleet and was held at VTA. It included all staff at Cerone, as well as local emergency responders (fire and police). The two VTA mechanics assigned to the fuel cell buses also received training at Ballard for the fuel cell propulsion system, as well as customized training from Air Products on the operation of the hydrogen dispensing station. The bus drivers were trained on the fuel cell vehicle systems and other items on the pre-trip inspection sheet. VTA continues to provide familiarization training for emergency responders. A quick-reference card was produced for emergency responders. It showed locations of specific equipment and places on the bus that are dangerous to be cut into. VTA also accommodates requests for tours and brings the buses to events as time and resources allow.

VTA controls which drivers are assigned to operate the fuel cell buses rather than train all drivers at Cerone. The number of trained drivers started at two and is now beyond 20. Comments from the VTA drivers and staff have been positive. To ensure safety, use of the hydrogen dispensing station is restricted to the following trained personnel: two VTA mechanics, Ballard's onsite mechanic, and Air Products' staff.

A major issue during this demonstration project has been the sharing of results and experiences with hydrogen and fuel cell technologies. This remains a challenge because of intellectual property sensitivities. Fuel cell propulsion applications are still in the early stages, and manufacturers are extremely protective of their proprietary information. In California, transit agencies are currently mandated to begin purchasing fuel cell buses as early as 2008. Transit agencies affected by these regulations need to understand all aspects of the fuel and technology to plan purchases and infrastructure. Fleets that are participating in the early demonstrations are often required to sign confidentiality agreements, making it difficult to share needed information with other interested fleets.

The most serious problems encountered were related to a general lack of accurate and complete information regarding any specific aspect of the program. There appeared to be more marketing than engineering information available. This inhibits the ability to enable reasonable decisions for design, construction, and operation of a fuel cell bus demonstration. In many cases, information on fuel cell buses and infrastructure indicate that this equipment is available as commercial, off-the-shelf products. This just isn't true (yet). Care will need to be taken to ensure that marketing does not get too far ahead of the commercialization of the fuel cell propulsion and supporting infrastructure equipment.

Preliminary Evaluation Results

VTA purchased three Gillig Corporation buses featuring fuel cell propulsion systems by Ballard Power Systems at a cost of $10.6 million ($3.5 million each)—a price that includes a two-year warranty, parts, training, and support from Gillig and Ballard.

The preliminary evaluation results include both fuel cell (three buses) and diesel baseline (five buses) study groups of buses. Both bus groups are Gillig low-floor buses; however, the fuel cell buses are slightly newer than the diesel buses. The fuel cell buses are 24 inches taller than the diesel buses. This caused some concerns about clearance. But issues such as low-hanging tree limbs were taken into account. Additionally, the fuel cell buses are 6,800 lb heavier than the diesel buses. This restricted the maximum number of passengers to include all seats and five standees in the fuel cell buses (compared to all seats and 43 standees in diesel buses). The fuel cell buses do not have a hybridized system and therefore do not have regenerative braking or additional energy storage.

VTA Routes—VTA operates 54 fixed, 19 express, and 19 special/shuttle type bus routes. The weekly average bus speed at Cerone is 14.5 mph. All standard buses at Cerone are randomly dispatched on routes.

For demonstrating this advanced technology, the fleet chose to use the three fuel cell buses as "extra" service on existing routes, meaning they are placed on routes between two regularly scheduled buses. The intent is to prevent passengers from being stranded for a long time in the event of a failure. Two fuel cell buses are operated during peak weekday hours with one available as a spare. VTA limits the use of the buses to times when a trained ZEB mechanic is available.

Bus Use and Availability—Bus use is intended as an indicator of reliability and availability for bus service. The lack of bus usage may indicate downtime for maintenance or purposeful reduction of planned work for the buses. Figure ES-2 shows mileage and fuel cell module operating hour accumulation from the start of hydrogen fueling in November 2004 through October 2005. As to be expected, usage accumulated faster after the buses went into revenue service at the end of February 2005. Usage of the fuel cell buses has been limited by running the buses only on weekdays, planned work for the buses as extra service, maintenance issues, and availability of drivers and mechanics for the fuel cell bus operation.

During the eight-month evaluation period, the three buses accumulated 16,708 miles and 1,376 hours on the six fuel cell modules (two per bus). Average monthly mileage per fuel cell bus was 726 miles. The diesel study buses were operated in normal VTA service from Cerone and included weekend operation. The average monthly mileage per diesel bus during the evaluation period was 4,284 miles.

Availability of a diesel bus was measured by the number of days it might be scheduled for service and the number of days it was not available for service due to any maintenance issues. During the evaluation period, the diesel buses had an availability rate of 84%. VTA's goal is 80% for diesel buses.

During the evaluation period, the fuel cell buses had an availability rate of 52% for each weekday, with a goal of 67% of the time. (For this preliminary report, no differentiation was made between standard bus maintenance issues and those attributed specifically to the fuel cell and system.) VTA's schedule was designed for two of the three fuel cell buses to be in service on weekdays, except holidays. This would generally indicate that the fuel cell buses met the goal 78% of the time.

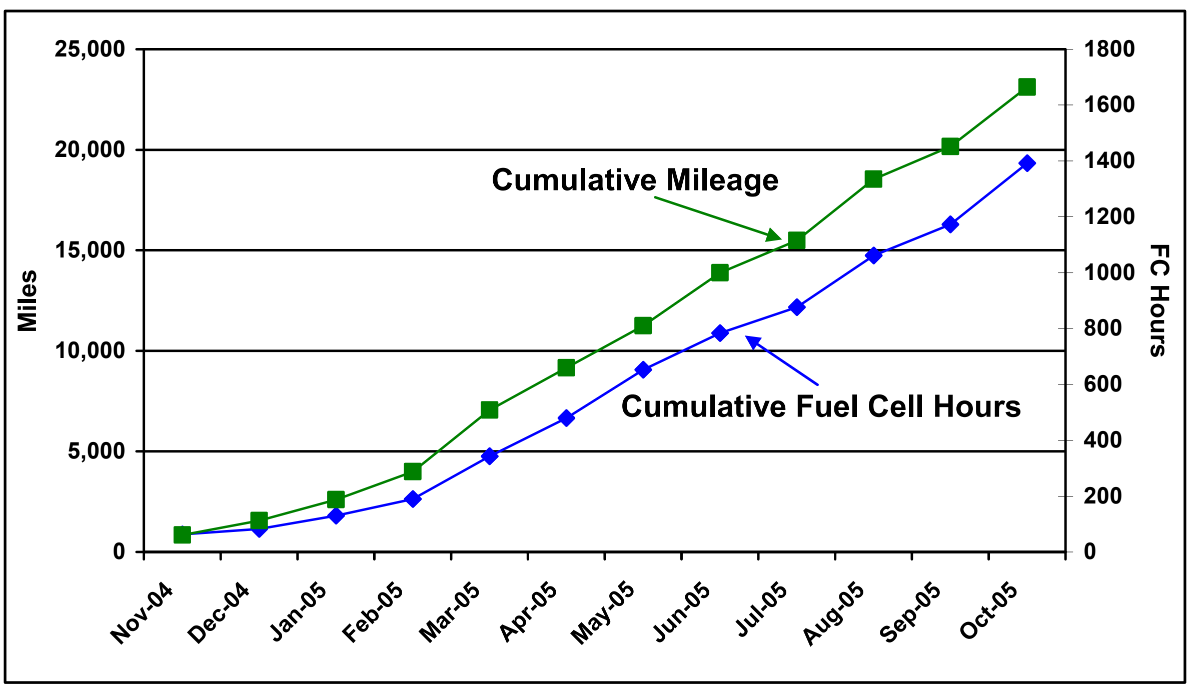

Figure ES-2. Cumulative Mileage and Fuel Cell Hours for Three Fuel Cell Buses

Fuel Economy—During the evaluation period, the fuel cell buses averaged 3.05 miles per kg of hydrogen, which translates into 3.45 miles per diesel equivalent gallons (or miles per gallon—mpg). This fuel economy includes all hydrogen fuel added to the buses even if there was some venting for maintenance or testing during the evaluation period. The diesel study group had a fuel economy of 3.95 mpg. With the diesel buses as the baseline, the fuel cell buses had a fuel economy 13% lower on an energy equivalent basis. Note that the electric propulsion design of the fuel cell buses does not include regenerative braking. Figure ES-3 shows the monthly average fuel economies of the fuel cell and diesel buses.

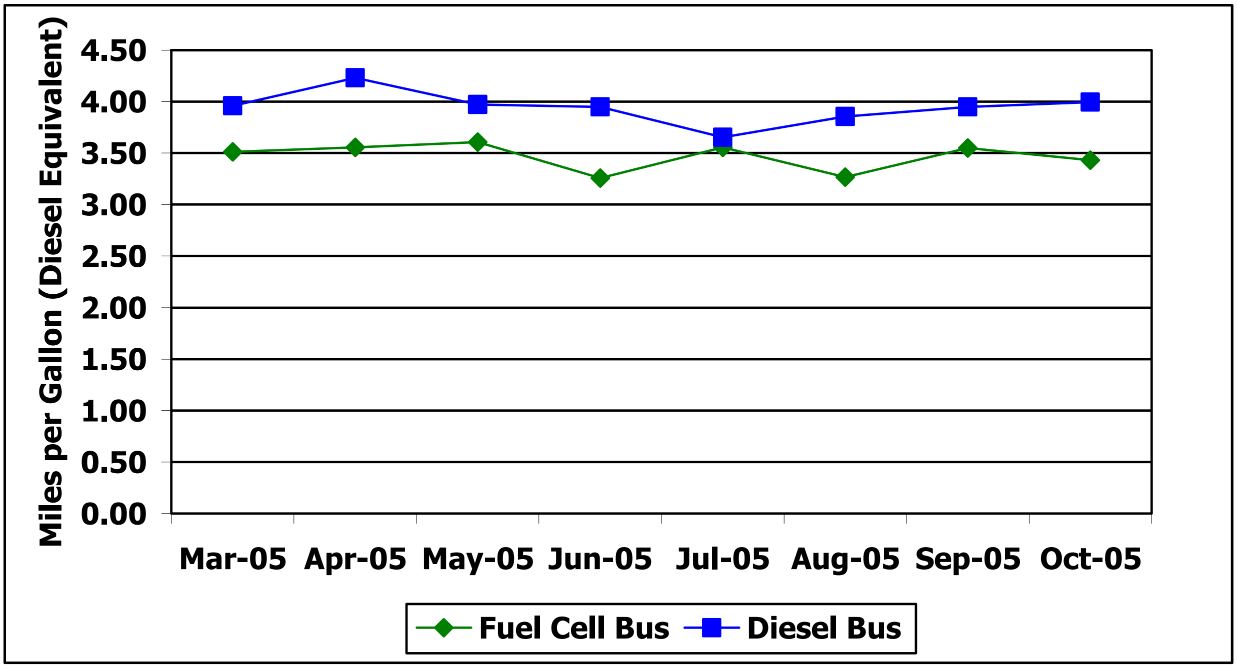

Figure ES-3. Average Fuel Economy (mpg) by Month

Maintenance Costs—The maintenance costs in this report pertain to only the evaluation period (March 2005 through October 2005) of the two study groups of buses. All work orders for the study buses were collected and analyzed for this evaluation. The labor rate for maintenance was calculated at a constant $50 per hour, and this is not reflective of an average rate at VTA.

Total maintenance costs were $4.26 per mile for the fuel cell buses and $0.59 per mile for the diesel buses. The total maintenance costs are much lower for the diesel buses compared to the fuel cell buses. This reflects the fact that the fuel cell buses are in the prototype development stage for transit bus service, which has caused a need for significant mechanic/technician labor for troubleshooting.

Warranty costs were collected but not accounted for in the cost-per-mile calculations. The fuel cell buses had nearly $70,000 in warranty parts replaced during the evaluation period; however, not all of the warranty costs have been accounted for. An action item for the final report is to collect more complete information on warranty parts replacements and labor cost.

The propulsion-related vehicle systems in the buses include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. The fuel cell buses ($3.06 per mile) had significantly higher propulsion-related maintenance costs than the diesel buses ($0.21 per mile) for all these systems, except exhaust and transmission.

Roadcalls—A roadcall (RC) is defined as a failure of an in-service bus that causes the bus to be replaced on route or a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is kept, it is not considered a RC. The analysis provided in this report includes RCs caused by "chargeable" failures. Chargeable RCs include problems with systems that can physically disable the bus from operating on route, such as interlocks (doors), engine, etc. They do not include problems with radios, destination signs, etc. The fuel cell buses had 983 miles between roadcalls (MBRC) for all roadcalls and 1,044 MBRC for propulsion-related roadcalls. The diesel buses had 9,019 MBRC for all roadcalls and 11,424 MBRC for propulsion-related roadcalls.

What's Next?

This preliminary data report includes an eight-month evaluation period (March 2005 through October 2005) of the prototype fuel cell buses in demonstration at VTA. A final report is planned for this evaluation after at least 12 months of fuel cell bus operation at VTA. This is expected to be published in mid 2006.

VTA currently plans to operate the fuel cell buses through July 2006—the end of the two-year demonstration and the warranty/support period for the fuel cell buses, as defined by Ballard. It is not clear whether this demonstration will continue beyond the end date because there are no grants or funds set aside to extend it. As described in this preliminary report, to continue operation beyond the current end point would require significant funding. VTA, Ballard, and Air Products have expressed interest in continuing this testing program if funding becomes available. Significant investment and effort have been committed to test and operate this equipment. There is still significant work to be done (and lessons to be learned) before fuel cell buses and infrastructure equipment is truly commercial.

Overview

This report provides preliminary results from an evaluation of prototype fuel cell transit buses operating at Santa Clara Valley Transportation Authority (VTA) in San Jose, California. San Mateo County Transit District (SamTrans) in San Carlos, California, is a partner with VTA in this fuel cell bus demonstration. VTA has been operating three fuel cell transit buses in extra revenue service since February 28, 2005. This report describes the equipment used (buses and infrastructure) and provides early experience details, lessons learned, and preliminary results from the operation of the buses and supporting hydrogen fuel station.

This evaluation is a part of the U.S. Department of Energy's (DOE) Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, which integrates activities in hydrogen production, storage, and delivery with transportation and stationary fuel cell applications. DOE's National Renewable Energy Laboratory (NREL) works with fleets and industry groups to test advanced technology, heavy-duty vehicles in-service and provides unbiased information resources for fleet managers considering these technologies. Information collected during vehicle performance and operation evaluations is fed back to research programs to help shape future work.

In early 2003, DOE initiated the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, which focuses on light-duty fuel cell vehicles and supporting infrastructure. The purpose of the project is to examine the impact and performance of fuel cell vehicles and supporting hydrogen infrastructure in real-world applications. The data collected and analyzed during this "learning demonstration" will be used to verify performance targets to support an industry commercialization decision by 2015. To coordinate efforts, the fuel cell bus evaluation team is working closely with the light-duty demonstration project teams. The overall goal is to collect similar data for heavy-duty fuel cell vehicles that will enable a more complete picture of fuel cell performance over a wide range of vehicle applications.

In addition to the light-duty demonstration project, DOE and NREL are also working with the Federal Transit Administration (FTA), an agency of the U.S. Department of Transportation, and heavy vehicle operators (mostly transit agencies) to demonstrate heavy fuel cell and hydrogen vehicles to collect operations experience data. This data collection and evaluation follows the DOE/NREL standardized evaluation protocol[1]. A customized version of the General Evaluation Plan was created for fuel cell bus evaluations and is described in the draft Fuel Cell Transit Bus Evaluation Protocol, June 2005. Current heavy fuel cell vehicle evaluation sites are shown in Table 1. More information is available at www.eere.energy.gov/hydrogenandfuelcells/tech_validation/ca_transit_agencies.html.

This preliminary data report examines early evaluation results from the three prototype fuel cell buses and five diesel baseline buses operating from the same VTA bus depot. The evaluation period presented in this report is March 2005 through October 2005—eight months of operation.

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[1] General Evaluation Plan, Fleet Test & Evaluation Projects, July 2002, NREL/BR-540-32392, www.nrel.gov/vehiclesandfuels/fleettest/pdfs/32392.pdf.

The next report for this evaluation will be completed after at least 12 months of operation data have been analyzed for the fuel cell and diesel baseline buses.

Table 1. DOE/NREL Heavy Vehicle Fuel Cell/Hydrogen Evaluations

Fleet	Vehicle/Technology	Evaluation Status
SunLine Transit Agency (Thousand Palms, California)	ISE Corp. ThunderPower hybrid fuel cell transit bus (one bus)	Complete and reported
U.S. Air Force/Hickam Air Force Base (Honolulu, Hawaii)	Shuttle bus: Hydrogenics and Enova, battery-dominant fuel cell hybrid (one bus); delivery van: Hydrogenics and Enova, fuel cell hybrid (one van)	Shuttle bus in operation, data collection started; van just going into service
VTA (San Jose, California) and SamTrans (San Carlos, California)	Gillig/Ballard fuel cell transit bus (three buses)	Evaluation in process, interim report presented here
Alameda-Contra Costa Transit District (AC Transit) and Golden Gate Bridge, Highway, and Transportation District (Oakland, California)	Van Hool/UTC fuel cell hybrid transit bus integrated by ISE Corp. (three buses)	Evaluation in process, buses just going into service
SunLine Transit Agency (Thousand Palms, California)	New Flyer ISE Corp. hydrogen internal combustion engine transit bus (one bus), Van Hool/UTC fuel cell hybrid transit bus integrated by ISE Corp. (one bus)	Bus in service, data collection started; evaluation in process, bus just going into service

Project Design and Data Collection

As mentioned earlier, DOE/NREL evaluation projects focus on using a standardized process for data collection and analysis, communicating results clearly, and providing an accurate and complete evaluation. The objectives of the data collections are to validate fuel cell and hydrogen technologies in bus applications to:

- Determine the status of fuel cell systems for buses and corresponding hydrogen infrastructure
- Provide feedback for DOE HFCIT Program research and development
- Provide "lessons learned" on implementing next generation fuel cell systems into bus operations

This evaluation includes prototype fuel cell powered transit buses (40-foot) operating at VTA in San Jose, California (bus shown in Figure 1). Five diesel buses were selected from VTA's newest order of Gillig diesel buses operating at the same depot (Cerone). Data is being collected in parallel to the three fuel cell buses for the evaluation period starting in March 2005. The diesel baseline data is being collected and analyzed along side the prototype fuel cell transit buses to assess the progress of the fuel cell propulsion development for heavy vehicles and specifically in this application at VTA.

Figure 1. Fuel Cell Transit Bus at VTA

Data for this evaluation were taken from VTA's data system. Data parameters included:

- Diesel fuel and engine oil consumption by vehicle
- Hydrogen fuel consumption by vehicle
- Mileage data from every vehicle in the study
- Preventive maintenance action work orders, parts lists, labor records, and related documents
- Records of unscheduled maintenance, including roadcalls and warranty actions by vendors (when available in the data system)

Additional information have been collected on the maintenance/operation experience, issues at the hydrogen fueling station and in VTA facilities, and lessons learned at the start-up and during operation of the prototype buses.

What are Fuel Cells and Why Use them in Transit Buses?

A fuel cell is an electrochemical device that uses hydrogen and oxygen to produce electricity. It is comprised of two electrodes (cathode and anode) and separated by an electrolyte. Proton exchange membrane (PEM) fuel cells are currently most commonly used for vehicle applications because they offer high power density and can operate at low temperatures. There are also other promising fuel cell technologies.

In the operation of a fuel cell, hydrogen is fed to the anode, where a catalyst-coated membrane separates the hydrogen electron from the proton. The proton passes through the membrane to the cathode side and combines with oxygen to form water. Because the electron cannot pass through the membrane, it is forced through the electrical circuit to create electricity. It then flows to the cathode where it is reunited with a proton in forming a water molecule.

A single fuel cell generates a low voltage and must be combined in a series to power applications, such as transit buses. These fuel cell stacks can consist of hundreds of individual fuel cells.

Fuel cell propulsion provides an opportunity to reduce emissions from vehicles (and other equipment) to zero except for water vapor and some waste hydrogen. Transit bus demonstrations have typically been introduction points for new heavy-duty vehicle propulsion technologies (i.e., natural gas and hybrid electric). This is because:

- Transit buses are centrally fueled and maintained.
- Transit buses are typically operated on fixed routes in urban stop-and-go duty cycles.
- Transit bus size and weight can easily accommodate new technologies.
- Capital purchases of transit buses and supporting infrastructure are federally supported (80% federal share and other funding programs).
- Transit buses have high visibility and impact because they operate in densely populated areas[2].

During the last 10 years, there have been several fuel cell transit bus demonstrations in the United States and Canada. These demonstrations have identified areas of development to prepare fuel cell propulsion systems for heavy-duty vehicle service. Examples include:

- Reducing the size of the fuel cell stack.
- Increasing the power density of the fuel cell stack.
- Reducing overall weight of the fuel cell and electric propulsion system.
- Developing hydrogen infrastructure for vehicle use.
- Optimizing electric motors and control systems for heavy-duty vehicles.
- Demonstrating that electric propulsion systems are safe for transit vehicles and perform well in environmental extremes (high and low temperatures and humidity).

Table 2 provides a summary of fuel cell transit bus demonstrations in the United States, Canada, and Europe.

Zero Emissions Buses in California

In February 2000, the California Air Resources Board (CARB) announced regulations to significantly reduce emissions of existing and new transit buses in California through 2015. CARB is a department of the California Environmental Protection Agency and oversees all air pollution control efforts in the state. This legislative change for emissions reductions in transit buses created a schedule for transit agencies to choose an alternative fuel or diesel path. The program provided an incentive for transit agencies to adopt low-emissions alternative fuels sooner rather than later. On the other hand, a transit agency could choose the diesel path, which required an emission reduction schedule more accelerated than that of alternative fuels.

The alternative fuel path could include low-emission alternative fuels such as compressed or liquefied natural gas, propane, methanol, electricity, fuel cells, or other advanced technology (such as gasoline hybrid-electric). The alternative fuel path allows transit agencies to extend the transition period for the operation of zero-emissions technologies.

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[2] Information excerpted from an FTA presentation by Shang Hsiung at the American Public Transportation Association Bus and Paratransit Conference committee meetings in Milwaukee, Wisconsin, May 2003.

Table 2. Fuel Cell Transit Bus Demonstrations – 12 Year History

Timeframe	Description
1994-1995	FTA/Georgetown: three 30-foot fuel cell buses operating on methanol using 100 kW phosphoric acid fuel cell (PAFC) stacks from Fuji
1998	FTA/Georgetown: 40-ft fuel cell bus operating on methanol using 100 kW PAFC from UTC Fuel Cells
1998-2000	Ballard Phase III test program with six 40-foot fuel cell transit buses using 205 kW PEM fuel cell stacks from Ballard that ran on compressed hydrogen; operated three at Chicago Transit Authority and three at Coast Mountain Bus (Vancouver)
2000-2001	Ballard Phase IV test bus operating on compressed hydrogen using 200 kW PEM fuel cell stack from Ballard, which was tested at SunLine; the bus currently resides at SunLine
2001	FTA/Georgetown: 40-foot fuel cell bus operating on methanol using 100 kW PEM fuel cell stack from Ballard.
2002-2003	ThunderPower 30-foot fuel cell bus operating on compressed hydrogen using 60 kW PEM fuel cell stack from UTC Fuel Cells at SunLine and AC Transit
2003-2005	Demonstration project in Europe, Iceland, and Australia including 33 fuel cell buses using Ballard PEM fuel cell stacks and compressed hydrogen in 40-foot buses. (CUTE, ECTOS, & STEP)
2004-2006	Demonstration project in the United States: three fuel cell buses using Ballard fuel cell stacks and compressed hydrogen in 40-foot buses at VTA, three fuel cell buses using UTC fuel cell stacks and compressed hydrogen in 40-foot buses at AC Transit, one fuel cell bus using UTC fuel cell stack and compressed hydrogen in a 40-foot bus at SunLine Transit Agency
2004-2006	Demonstration project in China: three fuel cell buses using Ballard PEM fuel cell stacks and compressed hydrogen in 40-foot buses.

From model year 2008 through 2015, 15% of new bus purchases by diesel-path transit agencies (with fleets larger than 200 buses) must be ZEBs. The transit agencies that choose the alternative-fuel path are not required to purchase ZEBs at the 15% of new bus rate until 2010 (through 2015).

Transit bus fleets on the diesel path with more than 200 buses were required to demonstrate the use of zero emission bus (ZEB) technology in revenue service starting in July 2003. ZEB technology includes electric propulsion (battery or trolley buses) or fuel cell propulsion.

Since 2000, these regulations have changed. The most recent change was released in October 2005 in regards to the Zero-Emissions Bus Demonstration Project, which adjusted the required dates for the demonstration sites and clarified how multiple transit agencies could execute the demonstration projects in joint transit agency projects (as long as the joint partners are within the same air basin). The legislation required demonstrations to commence by February 28, 2006, and demonstration partners to submit demonstration result reports by July 31, 2007.

VTA and SamTrans represent one of these joint transit agency partnerships to demonstrate fuel cell buses. This demonstration started revenue service on February 28, 2005—one year ahead of the required date in the new legislation.

Host Site Profile

VTA (www.vta.org) was created in 1972 to oversee the region's transportation system with the primary responsibility of operating and maintaining the Santa Clara County's bus and light rail system. In 1995, VTA was also charged with managing the county program to reduce congestion and improve air quality. VTA's annual budget exceeds $295 million (in fiscal year 2005) and is directed by a 12-member board of directors. VTA operates 427 buses (345 buses in peak demand) and 100 light rail vehicles. Annual ridership exceeds 37 million (in fiscal year

2005) in a service area that covers approximately 326 square miles (see Figure 2). The organization adopted a Clean Fuels Strategy in December of 2000, which included a zero emission bus program. In 2002, VTA entered into a contract with Gillig Corporation and Ballard Power Systems to procure three low floor zero-emission fuel cell buses.

SamTrans (www.samtrans.com) provides transportation services to San Mateo County, which is directly south of San Francisco. Fixed-route service at SamTrans started in 1976, and the district provides daily paratransit service. SamTrans' fleet of 321 buses, vans, and sedans covers approximately 446 square miles and serves a population of more than 707,000 (Figure 2). Annual ridership was nearly 17 million (fiscal year 2002). SamTrans also manages Caltrain operations (76 trains each weekday) for a three-county joint powers authority including San Francisco, San Mateo, and Santa Clara counties.

Figure 2. VTA and SamTrans Operating area in California

VTA/SamTrans ZEB Program

VTA and SamTrans started planning their zero-emission bus demonstration in 2000 after each agency chose to embark on the CARB diesel path. VTA is the lead agency in the operation of these buses, and SamTrans shared in the demonstration planning and operation and in the capital and operating costs. Table 3 provides descriptions of the equipment and facilities involved in this demonstration. The goals of this demonstration program are to:

- Determine the status of fuel cell technology in transit applications.
- Identify issues and challenges to overcome.

- Provide community outreach and educate the public on fuel cell and hydrogen technologies.

Table 3. General Equipment for the Fuel Cell Bus Demonstration Equipment

General Equipment	Description	Project Partner
Buses	Bus manufacturer	Gillig Corporation
	Fuel cell manufacturer	Ballard Power Systems
	System integrator	Ballard in conjunction with Gillig
Fueling Facility	Compressed hydrogen station and liquid fuel delivery	Air Products and Chemicals, Inc.
Maintenance Facility	Two maintenance bays have been built to properly maintain the buses; they include hydrogen detection and other safety systems	VTA

The budget for this demonstration was $18.5 million for a two-year demonstration project and includes:

- Buses and operations: $14.1 million includes bus purchase (warranty, parts, training, and support), maintenance time, and marketing.
- Facilities: $4.4 million includes fueling, maintenance, and bus wash facilities; fuel and other miscellaneous facilities-related expenses.

This ZEB program is supported by a variety of government and industry partners. The partners and their respective roles are described below.

- **VTA** leads the ZEB program, providing funding and the demonstration site. VTA used $6 million from a 2000 Measure A Local Sales Tax funding for this project.
- **SamTrans** is working in partnership with VTA to demonstrate fuel cell buses, providing funding and demonstration support. SamTrans provided $6 million in funding for this demonstration project.
- **FTA** leads the development of fuel-efficient mass transportation systems across the United States through financial, technical, and planning assistance. In addition to providing funding for the purchase of the buses used in the demonstration ($5.1 million), FTA provided guidance in the evaluation strategy.
- **DOE** provided funding directly for this project and to NREL for data collection, analysis, and reporting.
- **California Energy Commission (CEC)** is the primary energy policy and planning agency for California. One CEC role is to help advance energy-related science and technology through research, development, and demonstration. The CEC's Transportation Technology Office is involved with assessing the market potential of new transportation technologies, including fuel cell transit buses. CEC provides funding for the development and demonstration of these buses, as well as leadership for the bus team of the California Fuel Cell Partnership (CaFCP). CEC provided $300,000 for this demonstration project
- **Bay Area Air Quality Management District (BAAQMD)** is one of California's regional agencies dealing with air quality in the state. The district's jurisdiction includes

all or a portion of nine counties around the San Francisco Bay. BAAQMD supports the demonstration of clean propulsion technologies by providing funding, specifically $1 million for this project.

- **Ballard Power Systems** designs, develops, and manufactures PEM fuel cells for transportation and stationary applications. Ballard designed and integrated the fuel cell system for this demonstration.
- **Gillig Corporation** produces heavy-duty buses. The company built the chassis for the buses in this demonstration and worked closely with Ballard on the integration of the fuel cell systems.
- **Air Products** supports a variety of customers by providing a wide range of products, including atmospheric gases, specialty gases, and chemicals. Air Products designed and constructed the fueling infrastructure and supplies the hydrogen fuel used in this project at VTA. Air Products also owns the VTA station and is responsible for its maintenance.
- The **CaFCP** is a collaborative effort between auto manufacturers, energy companies, fuel cell technology manufacturers, and government agencies. The partnership brings together a diverse group of interested parties to accomplish common goals that include demonstrating fuel cell vehicles and supporting fueling infrastructure in real-world service. VTA is an associate member of CaFCP.
- **CARB** has a mission to "promote and protect public health, welfare, and ecological resources through the effective and efficient reduction of air pollutants, while recognizing and considering the effects on the economy of the state." CARB established its commitment to fuel cell transportation technology by passing several rulings, including the Public Transit Fleet Rule for California fleets.

The VTA/SamTrans ZEB program was originally planned to include six or seven fuel cell buses at approximately $1.5 million each. However, the higher actual price of the fuel cell buses limited the demonstration to three vehicles. The first bus chassis was constructed by Gillig in April 2003 and shipped to Ballard for the installation of the fuel cell systems. This bus was run through a variety of tests prior to delivery to VTA in May 2004. The remaining two buses were entirely constructed at the Gillig facility in Hayward, California, and delivered to VTA in August 2004.

In September 2002, VTA awarded a contract to Air Products to design and build the hydrogen fueling facility at VTA's Cerone Operations Division. Construction began in September 2003, and the station was completed by May 2004.

Other construction projects included a new bus wash facility to accommodate the taller fuel cell buses and a special two-bay maintenance facility that could accommodate hydrogen use inside the building.

The revenue service kick-off event for the VTA/SamTrans fuel cell bus demonstration was held at VTA's Great Mall/Main Transit Center in Milpitas, California, on February 24, 2005 —a few days prior to beginning revenue service.

Infrastructure and Facilities

VTA has three depots for bus operations—Cerone, Chaboya, and North. The Cerone operating division was selected as the home of the fuel cell bus program primarily because of space availability. The Cerone operations include 220 buses operating seven days a week. The infrastructure and facilities added at Cerone for fuel cell bus operations included a compressed hydrogen fueling station, a stand-alone two-bay maintenance facility, and an upgraded bus wash to accommodate the taller buses.

Compressed Hydrogen Dispensing Station

VTA issued a request for proposal for the hydrogen dispensing station in January 2002 and awarded a contract to Air Products in September 2002 to design and build the fueling facility. Construction began in September 2003, and the station was completed in May 2004; however, actual dispensing of hydrogen at the station did not start until November 2004. VTA has a capital lease for the facility (shown in Figure 3), which is owned and maintained by Air Products. VTA provided the concrete pad for the station at the Cerone depot. VTA paid approximately $480,000 up front and has monthly payments for three years (about $4,400 per month) with a grand total of approximately $640,000 for the station plus the cost of liquid hydrogen.

The station features a 9,000 gallon cryogenic tank that stores liquid hydrogen. Prior to use, the liquid hydrogen is compressed to 6,000 psi and vaporized for secondary storage in a pressurized three-tank cascade. Air Products' liquid compression system enables fast filling of the buses. The fueling island dispenses pressurized gaseous hydrogen into the fuel cell buses from the cascade, which acts as a buffer. The cascade holds enough hydrogen to begin the fueling process. When the hydrogen in the cascade tanks drops below a certain level, the compressor is activated, the tanks are refilled, and the bus fueling process is completed.

Figure 3. Compressed Hydrogen Dispensing Station at VTA's Cerone Operations Division

The hydrogen dispenser (Figure 4) is equipped for a communications fill. The communications allow for monitoring of tank pressure and temperature, and the cable also provides a connection to ground. When using the communications cable, a full hydrogen bus fill can be performed in approximately 10 minutes. A non-communication fill can take upwards of 20 minutes.

Figure 4. Hydrogen Dispenser

The station design includes two compressors to avoid downtime for the fleet. This allows the station to continue operation when the primary compressor undergoes scheduled maintenance or experiences a failure. As a newer Air Products design, the primary compressor can provide a fast fill in about eight minutes. The secondary compressor is a reliable, proven design that provides a bus fill in less than 20 minutes.

To ensure high reliability and safety, the station includes numerous shut down and alarming devices to alert the fleet and Air Products of any potential problems. These devices include flame sensors, alarms, and emergency stop (E-stop) buttons (Figure 5) that are monitored onsite by VTA and remotely by Air Products. When activated, the E-stop buttons shut down the system and close the liquid tank valves.

VTA uses its two assigned fuel cell bus mechanics to dispense hydrogen into the buses. To ensure safety, no other VTA employees are authorized to dispense hydrogen from the station. The Ballard assigned mechanic and Air Products staff can also work with the hydrogen dispensing equipment.

Figure 5. Flame Sensors (left and top) and Emergency Shut-off (right) at the Hydrogen Dispensing Facility

Early Experience with Hydrogen Dispensing—Operating and maintaining the requisite hydrogen fueling infrastructure for the fuel cell bus demonstration had been an early challenge. VTA experienced several problems and delays in the process of building and commissioning the fueling station. Because hydrogen infrastructure is in the early stage of development, precedent for building stations has not yet been set—except in a few locations. Each station installation is unique, with various approaches to producing and dispensing hydrogen. When planning its station, VTA staff cited the need for a uniform approach to codes and standards, as well as standardized interfaces and fueling connectors. Some of the early issues encountered by VTA are summarized below.

During the commissioning of the station in May 2004, the discharge thermocouple on the compressor failed, causing a liquid hydrogen leak and fire. This thermocouple monitors the discharge temperature and is used to control the compressor. The system was going through checkout and commissioning at the time of the leak, and the E-stop was activated within seconds. Damage was minimal and limited to the immediate area where the leak and fire occurred. There were no injuries. Air Products determined that the failure was the result of a manufacturing defect in the thermocouple. All thermocouples of that type and manufacturing batch were replaced, including units installed at two other facilities. Although there was no major damage resulting from the fire, the station had to be shut down for investigation, repair, and inspections by local fire officials. This ultimately delayed the start of full operation of the dispensing station until November 2004.

Multiple false alarms, which triggered calls to the local fire department, have also caused delays to VTA's station operation. The majority of the alarms could be traced to one of the following causes.

- **Power Loss**: In the case of a power loss, safety systems at the VTA facilities will trigger an alarm. On two occasions, false alarms were determined to be caused by temporary power losses at the fueling station.
- **Detector Sensitivity**: Safety systems are in place to detect conditions that may pose a danger or signal an incident. Sensors and detectors are extremely sensitive and were triggered by events such as maintenance work in the area. Investigation of events at VTA showed that maintenance work, including grinding or welding in the area, could have caused the false alarms. This experience resulted in the development and installation of improved flame detectors as well as the implementation of new procedures if such activities take place.
- **Detector Failure**: The detectors were replaced due to a manufacturing defect.

Because most of the false alarms occurred during or shortly after maintenance work was performed, VTA now requires advanced notification of work on or near the hydrogen facilities. During this time, the systems are placed in test mode. Valuable experience was gained on the flame detectors during the initial operation of the station. As a result of the numerous problems experienced with the ultra-violet flame detector, a new and improved infra-red flame detector which greatly improved the reliability and reduced the number of false alarms, was installed.

Several incidents occurred at the VTA station that resulted in excessive venting or hydrogen leaks. On at least three separate occasions, vapor clouds were detected by VTA personnel at the hydrogen fueling facility.

The first incident occurred in October 2004. This was a small leak and vapor cloud at the front of the liquid hydrogen storage tank. The leak occurred at the stem packing of a cryogenic valve. VTA personnel signaled for an evacuation and pulled the fire alarm to notify the fire department. An Air Products technician diagnosed the problem and stopped the leak by tightening the packing vent valve. Although the repair was simple and quick, the incident involved the San Jose fire and police departments and resulted in a temporary evacuation of the facility. Several training issues were discovered during the incident that needed correction. The local E-stop, or remote shut down using the electrical breaker, was never activated by personnel onsite, which would have stopped the leak. Additionally, a faulty fire alarm pull box did not signal the fire department.

The second incident was a small leak and vapor cloud at the fueling facility. The leak occurred at the primary cryogenic compressor. VTA personnel activated the E-stop at the dispenser to shut down the system and notified Air Products. The leak was isolated and the system was placed back into service with the secondary cryogenic compressor. Repairs were made to fix the leak and the primary cryogenic compressor was returned back into service.

The third incident occurred during a bus fueling at the station. The primary cryogenic compressor continued to operate but was not providing any hydrogen flow into the system or the fuel cell bus. The system was venting excessively and continuously. The bus fueling was stopped and VTA staff notified Air Products. The primary compressor kept running even though the cascade tanks were not filling and venting continued. When the primary compressor shut down, the secondary system came online as back up. VTA personnel then noticed a small leak and vapor cloud at the secondary compressor. VTA personnel shut down the entire system using the E-stop button. An Air Products technician corrected the secondary compressor leak to get the system back online. The primary compressor needed more extensive repairs, necessitating the continued use of the back up.

Although these issues were addressed and resolved, use and operation of the hydrogen station caused delays and challenges for the fleet. Multiple problems with the various systems at the station caused delays that directly affected VTA's ability to provide service to its customers. Many of the alarms resulted in calls to the San Jose fire department, which dispatched fire trucks that were not technically needed. VTA staff members cited concerns that repeated false alarms could erode the company's relationship with the local fire department. VTA continues to work with project partners to prevent future problems from occurring and to fully train onsite personnel, fire officials, and emergency responders to handle hydrogen-related incidents. Modifications to equipment, software, and procedures seem to be working; there have been no incidents at the station since July 2004.

It is important to recognize that this is a demonstration project and that some of the technology used in the hydrogen dispensing station is in early deployment and use. As with any demonstration project, problems should be expected, especially during the first months of operation. Significant progress and improvements have been made to the hydrogen dispensing station during the program, including:

- The safe operation the hydrogen dispensing station during the demonstration program with no injuries or recordable incidents.
- More than 300 successful fuel cell bus and light-duty vehicle fills.
- The systematic identification and correction of problems to ensure the hydrogen dispensing station was kept online to service the fuel cell bus fleet.
- Incorporating modifications into the station to address lessons learned during the station operation.

Hydrogen Fuel Dispensing Analysis—The first liquid hydrogen fuel shipment occurred in May 2004; (however, fueling of the buses did not start until November 2004) for testing of the bus fuel and propulsion systems. Through early November 2005, the fueling station has 22,045 kg of hydrogen delivered. The station has insufficient fueling use, causing much of the fuel to be lost to boil-off. With the buses operating since February 2005, vent and boil-off losses have been at approximately 50%. This implies that the other 50% of the hydrogen has been lost to boil-off from the station. As the bus use increased, the use of the hydrogen has improved.

Figure 6 shows average hydrogen dispensing amounts and times per fueling. As mentioned earlier, fuelings at the beginning of the station operation took an average of about 20 minutes. Since the newer (primary) compressor came online in April 2005, the fueling times improved considerably, with fill times averaging between 10 and 14 minutes.

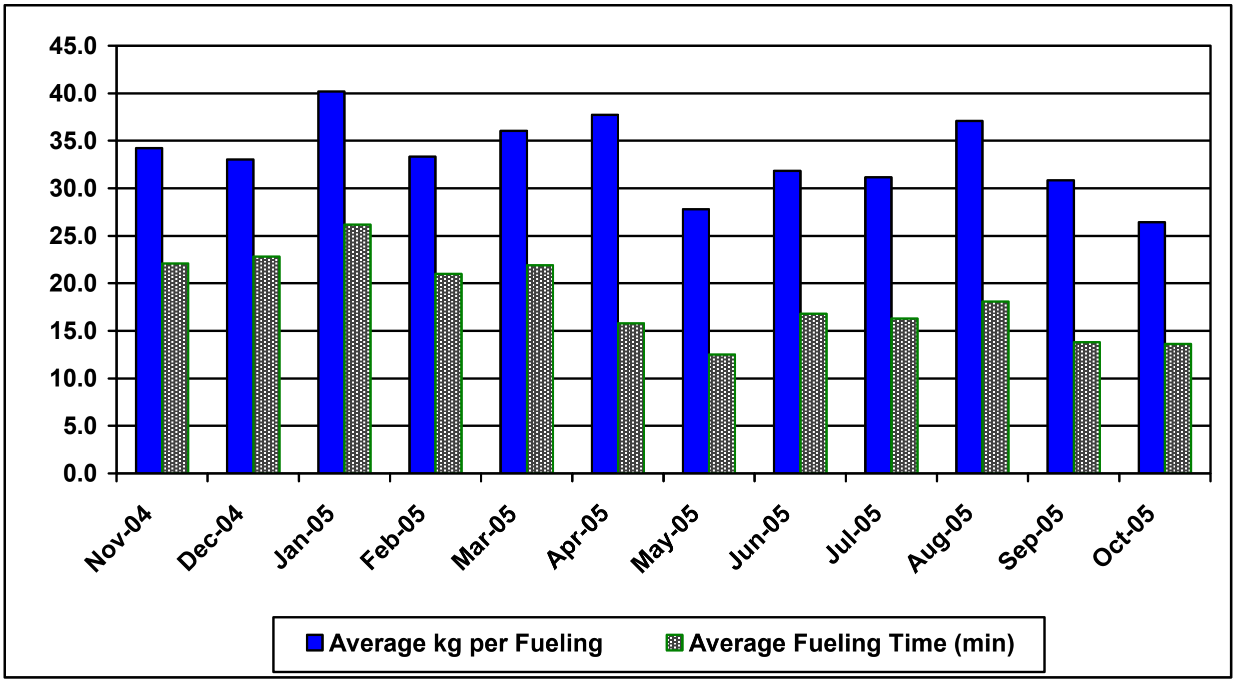

Figure 6. Average Hydrogen Fueling Amounts and Average Fueling Time

Figure 7 shows average hydrogen fuel cost over time. For most of the period shown, the hydrogen cost was between $8 and $9 per kg of hydrogen. The price increased considerably in October 2005 and November 2005 to $10.39 per kg of hydrogen. This cost would equate to approximately $11.77 per diesel equivalent gallon. Based on the loss of hydrogen due to venting and boil-off losses as described above, the cost of hydrogen fuel might be considered to be double. The average hydrogen cost per kg used for the evaluation, discussed later in this report, is $8.56 for the data period of March 2005 through October 2005.

Diesel Fuel Cost—During the evaluation period, the diesel fuel cost at VTA was tracked as a monthly average cost per gallon, as shown in Figure 8. The diesel fuel at VTA is ultra low sulfur diesel with a sulfur content of less than 15 parts per million (ppm). The diesel fuel cost started out well below $2 per gallon and increased in August 2005 (like with the rest of the country). The average diesel fuel cost per gallon for the evaluation period was $2.02.

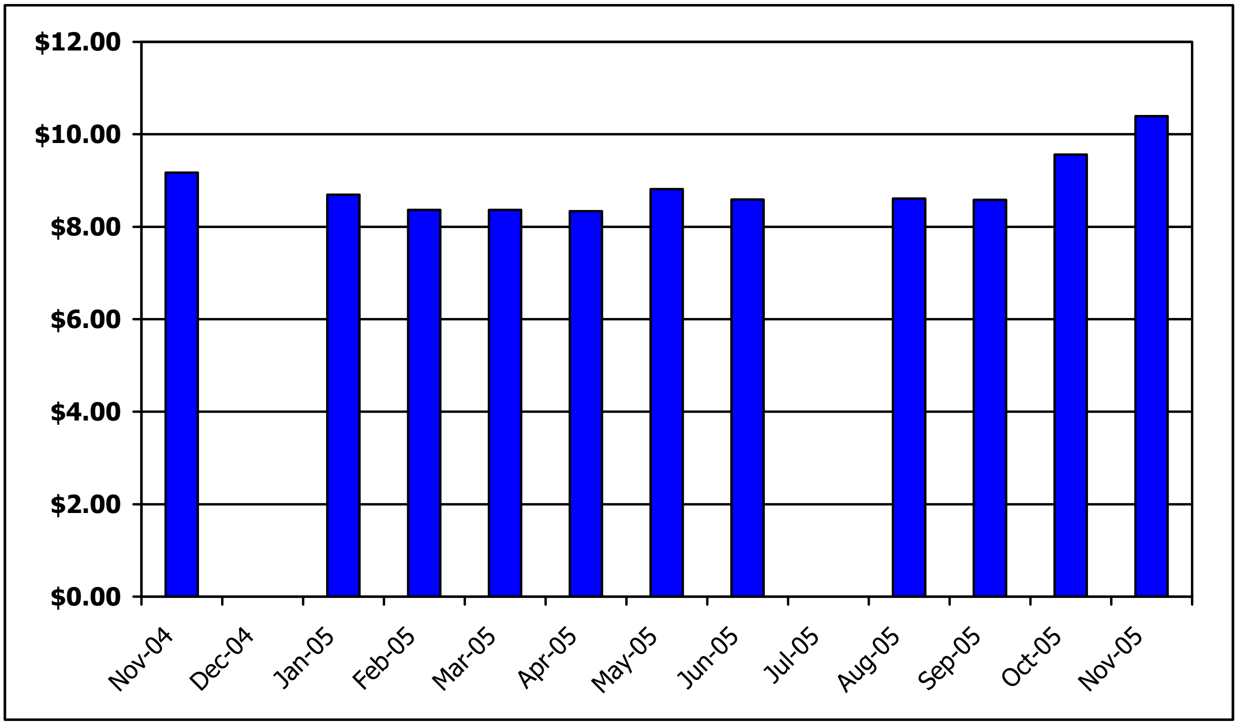

Figure 7. Average Price Paid ($/kg) for Liquid Hydrogen Delivered to VTA Station

Hydrogen Bus Maintenance Facility

A separate maintenance facility was also designed and built for the ZEB demonstration. The new facility was required in order to accommodate the hydrogen rating for the maintenance of the hydrogen fuel cell buses in accordance with the fire marshal requirements. This two-bay facility, shown in Figure 9, houses the equipment and spare parts needed to maintain and repair hydrogen fuel cell buses. Like the fueling station, the maintenance building is equipped with the necessary devices to enable safe operation and maintenance on hydrogen vehicles. These include hydrogen and flame sensors and an anti-static coating on the doors. When sensors detect hydrogen, alarms are triggered. At a lower flammability limit (LFL) of 15% (0.6% hydrogen in air), the doors open and fans are automatically activated to clear the air in the building. Evacuation is required at 50% (2% hydrogen in air) LFL.

The new bus wash (shown in Figure 10) planned as part of the Cerone improvement program, was also designed and constructed to allow for the added height of the fuel cell buses due to the hydrogen fuel storage tanks on the roof. This included higher brushes and rinse arches, as well as a fire sprinkler system. The total cost for adding these three facilities to meet the requirements of operating the hydrogen fuel cell buses was $4.4 million.

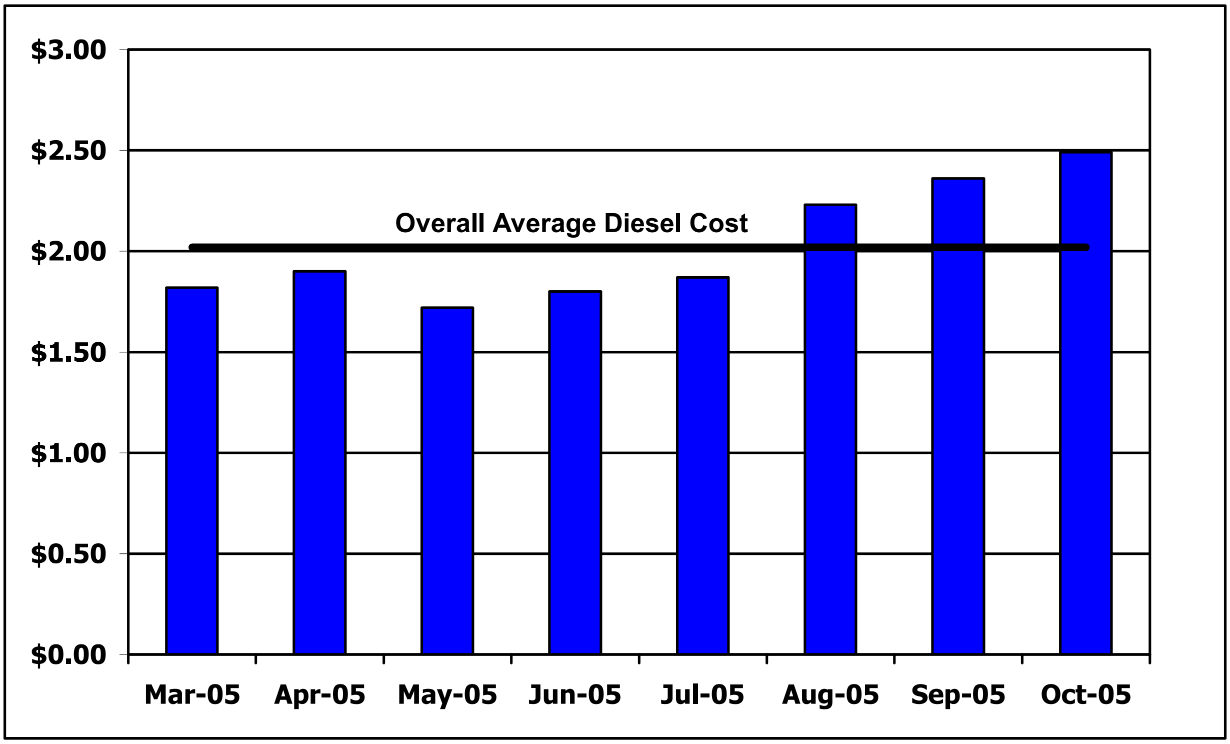

Figure 8. Average Diesel Fuel Cost ($/gallon) at VTA (March 2005 through October 2005)

Figure 9. Maintenance Facility Used for the Fuel Cell Buses at VTA

Figure 10. Bus Wash (left) and Maintenance Facility (right)

Fuel Cell and Diesel Bus Descriptions

In June 2002, VTA awarded a contract to Gillig Corporation to build three buses featuring fuel cell propulsion systems by Ballard Power Systems. The first bus chassis was constructed by Gillig in April 2003 and shipped to Ballard's Canadian headquarters in Vancouver, British Columbia, for the installation of the fuel cell system. This bus was run through a variety of tests, and the integration was finalized prior to delivery to VTA in May 2004. The remaining two buses were entirely constructed at the Gillig facility in Hayward, California, with Ballard staff support and delivered to the fleet in August 2004. The buses cost $10.6 million ($3.5 million each)—a price that includes system integration engineering, a two-year warranty, parts, training, and support from Gillig and Ballard.

Table 4 shows a summary of vehicle system descriptions for the fuel cell and diesel baseline study groups of buses. Both bus groups are Gillig low-floor buses; however, the fuel cell buses are slightly newer than the diesel buses. The fuel cell buses are 24 inches taller than the diesel buses, which caused some concerns about clearance. But issues such as low-hanging tree limbs were taken into account. Additionally, the fuel cell buses are 6,800 lb heavier than the diesel buses. This restricted the maximum number of passengers to include all seats and five standees in the fuel cell buses (compared to all seats and 43 standees in diesel buses). Both groups of buses have a standard transmission and retarder. The fuel cell buses do not have a hybridized system, and therefore, do not have regenerative braking or additional energy storage. Table 5 provides several additional details on the fuel cell propulsion system, including the electric motor and hydrogen fuel storage details.

Table 4. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	Cerone Depot	
	Fuel Cell Buses	Diesel Buses
Number of Buses	Three	Five
Bus Manufacturer and Model	Gillig low-floor	Gillig low-floor
Model Year	2004	2002
Length/Width/Height	40 feet/102 in/144 in	40 feet/102 in/120 in
GVWR/Curb Weight	40,600 lb/34,100 lb	39,600 lb/27,300 lb
Wheelbase	284 in	284 in
Passenger Capacity	37 seated or 29 seated and two wheelchairs five standing	38 seated or 31 seated and two wheelchairs 43 standing
Engine Manufacturer and Model	Two Ballard fuel cell modules P5-2	Cummins ISL (8.9 liter)
Rated Power	150 kW each (300 kW total)	280 bhp @ 2,200 rpm
Rated Torque	790 lb-ft @ 1,350 rpm (1250 Nm)	900 lb-ft @ 1,300 rpm
Accessories	Mechanical	Mechanical
Emissions Equipment	None	Diesel oxidation catalyst
Transmission/Retarder	ZF transmission/integrated retarder	Voith transmission/integrated retarder
Fuel Capacity	Approx. 55 kg hydrogen at 5,000 psi	115 gallons
Bus Purchase Cost	$3.5 million (average)	$316,000

Table 5. Additional Fuel Cell Propulsion System Descriptions

Propulsion Systems	Fuel Cell Buses
Manufacturer/Integrator	Gillig/Ballard
Drive System	Fuel cell powerplant, inverter, one electric propulsion motor, six-speed transmission
Propulsion Motor	Reuland Electric, three-phase induction motor rated at 225 kW
Energy Storage	None (not hybrid)
Fuel Storage	Eleven, roof mounted, Dynetek Dynecell carbon fiber-wrapped tanks

VTA Fuel Cell Bus Operation

VTA has two mechanics assigned to the fuel cell bus project that were trained at Ballard to work on the fuel cell modules and propulsion system. Ballard also has had a mechanic onsite at VTA since the buses were delivered. VTA's procedure for operating the fuel cell buses includes a pre-trip by a VTA mechanic while the fuel cell systems are "warming up."

The fuel cell modules use hydrogen and oxygen to produce electricity, heat, and water. The electricity produced powers the bus through an electric motor directly connected to the drive axle. The fuel cell bus system enters a start-up mode when the key is turned on. This initiates:

- The electric motor going into idle mode.
- The air compressor starting airflow to the cathode side of the fuel cell.
- The hydrogen pressure regulator starting the hydrogen flow to the anode side of the fuel cell.

The inverter is switched on when the power from the fuel cell reaches a minimum operating voltage for the motor/inverter. Once conditions are stabilized, the bus is ready to drive. The bus can be driven immediately; however, full power operation typically takes 15 to 20 minutes. While this "warm up" process is occurring, the drivers perform their pre-trip safety inspections of the bus before starting a route.

During driving, the electricity from the fuel cell feeds the motor to provide traction for the bus and power for the auxiliaries (air compressor, air conditioning, alternator, etc.). As the driver presses the accelerator pedal, air flow and hydrogen pressure are increased to provide the requested power. The system uses valves and regulators to strictly control the air and hydrogen flow.

At the end of operation, the fuel cell propulsion system goes through a shut-down procedure, which is triggered by the driver (key-off) or safety system. The valves for each hydrogen fuel cylinder/tank are closed while any hydrogen remaining in the lines is evacuated through the purge diffuser. The traction motor stops turning and the electrical systems are disconnected. The system is now in safe shut-down mode.

Early Experience with VTA's Fuel Cell Buses

Because fuel cell bus technology is new to the industry and this fleet, VTA took a conservative approach to the demonstration. Once hydrogen fuel was available, the fleet operated the buses in test mode for several months. VTA operated the buses in test mode as much as possible to identify problems and allow drivers and maintenance staff to become familiar with the differences between the fuel cell and conventional buses. During this time, VTA made the fuel cell buses available for training maintenance workers and other VTA staff and conducted familiarization classes for local fire officials and first responders. After an official kick-off event in late February 2005, the buses began extra revenue service.

VTA has experienced several issues and challenges demonstrating fuel cell buses. Some comments regarding early experience with the fuel cell buses are summarized below.

- **Sensor Defect**: Due to a materials compatibility issue, a pressure-sensing device on the fuel cell system was determined to be faulty. At that time, VTA had received only one of the three buses. At the recommendation of the bus manufacturer, VTA did not operate the bus until the issue was resolved. The sensor manufacturer developed a new pressure sensor using materials appropriate for high-pressure hydrogen applications. The sensors were replaced on the first bus at VTA and installed on the remaining buses at the Gillig manufacturing facility prior to delivery.
- **Bus Height**: The compressed hydrogen cylinders mounted on the roof of fuel cell buses adds 24 in to the height of a standard bus. The added height meant the buses did not fit through VTA's existing bus wash. The new bus wash was designed and constructed to allow for the washing of the hydrogen fuel cell buses. The added height also necessitated extra precautions when placing the buses on specific routes. The buses were designed with crash sensors on the roof that shut down the buses if a collision occurs. The fleet had to inspect routes for obstacles, such as low hanging tree branches, to avoid potential shut down of the bus while in service.
- **Bus Weight**: Because fuel cell buses are heavier than a typical 40-foot bus, the fleet has to limit the number of standing passengers to meet weight requirements. This could be an issue when operating on some of the higher-use routes where standing passengers are common.
- **Range**: The lower range of the buses also limited the routes and schedules that the buses could operate. The range of a standard diesel bus is approximately 400 miles in revenue service as compared to approximately 140 miles for the fuel cell buses.
- **Parts Availability**: VTA's contract for purchasing the buses includes a certain number and type of replacement parts for bus repair. Transit agencies typically stock a large selection of parts for each type of bus they operate. This enables quick repairs of most failures and reduces downtime. While standard bus parts are readily available from Gillig, parts for the advanced fuel cell propulsion system are not always easy to obtain. Waiting for these replacement parts can potentially increase downtime for the fuel cell buses. Ballard carefully monitors the minimum/maximum numbers of many high-cost parts for the fuel cell bus system. Many of these parts are produced by second-tier suppliers, making this a challenge. VTA and Ballard have been working together to try to minimize this potential downtime.

VTA controls which drivers are assigned to operate the fuel cell buses rather than train all drivers at Cerone. The number of trained drivers started at a two and has grown to more than 20. Based on several discussions with VTA staff, the following comments reflect impressions from VTA fuel cell bus drivers.

- "Operating the fuel cell buses has been fun; the bus has smooth acceleration (probably because it's heavier than a diesel bus)."
- "I like the fact that it's a new bus."
- "The bus is really quiet. The loudest noise is the air conditioning fan; it's a lot quieter than the diesel buses."
- "I'm a little concerned about "hurting" the bus."
- "The bus gets attention from the public while on the street."
- "The bus is a little slower from stop than a diesel bus, but it tops out at a higher speed."
- "The bus is a little top heavy. I can feel a little lean during turns."
- "The braking and retarder feel better than the diesel buses."

Training and Public Awareness

As previously mentioned, familiarization training for hydrogen safety and general characteristics was held at VTA for all staff at Cerone and local emergency responders. Training groups included:

- Bus operators.
- Bus technicians/mechanics.
- Cleaners.
- General personnel.
- Operations control center.
- Facility maintenance personnel.
- VTA emergency response personnel.
- Emergency responders outside of VTA.

The VTA mechanics assigned to the fuel cell buses received training at Ballard for the fuel cell propulsion system, as well as customized training from Air Products on the hydrogen dispensing station operation. The drivers of the fuel cell buses were also trained on vehicle systems and additional items on the pre-trip inspection sheet. VTA continues to provide familiarization training for emergency responders (fire and police). A quick reference emergency response card was produced for emergency responders showing location of specific equipment and places where it would be dangerous for the bus to be cut into.

VTA accommodates requests for tours and brings the buses to events as time and resources allow. Events attended, tours of, and presentations about the fuel cell buses at VTA include:

- **March 14, 2005**: VTA hosted a tour for the Chinese Fuel Cell Bus program.
- **March 17, 2005**: VTA participated in the Santa Clara Valley Science and Engineering Fair Association; one fuel cell bus was on display.
- **March 29, 2005**: VTA hosted a tour of the hydrogen dispensing station for the Hazardous Materials Subcommittee of the Northern California Fire Prevention Officers.
- **April 21, 2005**: VTA participated at San Jose State University's Earth Day; one fuel cell bus was on display.
- **May 6, 2005**: VTA and CaFCP made a presentation to the Santa Clara County Fuel Cell Working Group at its workshop. The group was given a ride in a fuel cell bus.
- **May 10-12, 2005**: VTA provided training for Milpitas Fire Department with CaFCP; one of the fuel cell buses was used in the training.
- **May 24, 2005**: VTA took a fuel cell bus to Sheppard Middle School as a community outreach event; 34 students and teachers took a ride on the bus.
- **June 1-June 2, 2005**: VTA participated in the United Nations World Environment Day in San Francisco by displaying the ZEB and providing related information. International VIP's, environmental experts, and media representatives rode the ZEB on pre-scheduled routes.

- **July 12, 2005**: VTA hosted a tour for Ron Dodsworth, Assistant General Manager of Denver RTD and several RTD board members at VTA’s Cerone Operations Division.
- July 14, 2005: VTA provided a ZEB presentation to the Risk and Insurance Management Society.
- **July 15, 2005**: Representatives from DaimlerChrysler and Matt Nauman of the *Mercury News* visited VTA’s Cerone facility to fill a DaimlerChrysler fuel cell vehicle at the hydrogen fueling station.
- **September 30, 2005**: Staff participated in the CaFCP Road Rally 2005 at San Jose State University. The ZEB was on display and program materials were provided to attendees.
- **September 30, 2005**: The Road Rally caravan vehicles were fueled at VTA’s hydrogen fueling station. The media was invited to attend.
- **September 30, 2005**: Staff also participated in the Road Rally VIP event at the Doubletree Hotel in San Jose. The ZEB was on display, and program materials were provided to event attendees.
- **October 4, 2005**: VTA hosted a tour for representatives of the Swedish Broadcasting Company who visited VTA's Cerone facility to learn about ZEBs.
- **October 26, 2005**: Staff participated in the Fuel Cell Workshop at West Valley College in Saratoga, CA. The ZEB was on display and program materials were provided to workshop attendees.
- **November 2, 2005**: Staff participated in the California Transit Association conference by hosting the ZEB Technical Tour, which included a ride on the ZEB and a visit to the hydrogen fueling station and maintenance facility. Tour attendees received materials and a presentation by VTA staff on the ZEB program.
- **November 8, 2005**: VTA hosted a tour for Emilio Hoffmann, Director of Brazil H2 Fuel Cell Energy, which is devoted to spreading information on the hydrogen and fuel cell economy in Brazil
- **November 9, 2005**: VTA hosted a tour for Nick Bagly of "Drive Around the World," who visited VTA's Cerone facility to learn about the ZEBs.

Ballard Fuel Cell Development and Testing

Ballard Power Systems, Inc., (www.ballard.com) is headquartered in Vancouver, British Columbia, Canada, and was founded in 1979 as a research company investigating high-energy lithium batteries. Ballard started work on PEM fuel cells in 1983 and began demonstration of this fuel cell technology in transit buses in 1991 (shown in Table 6). Ballard has been working to commercialize fuel cells for transportation applications as well as electrical equipment and portable power. Ballard reports that these fuel cell systems have evolved into pre-commercial prototypes and initial commercial products. Current work on fuel cells at Ballard is focused on reducing cost, increasing durability, improving freeze start, and increasing power density.

Table 6. Ballard Fuel Cell Development Phases

Phase	Timeframe	Bus/Fuel Cell Module	No. of Buses
Phase 1: Proof of Concept	1991-1992	Small bus/MK500, 100kW	One
Phase 2: Commercial Prototype	1993-1995	Bus/MK513, 200 kW	One
Phase 3: Fleet Demonstration –Alpha Sites	1996-1999	Bus/MK513, 200 kW	Three in Chicago and three in Vancouver
Phase 4: Fuel Cell Engines	1999-2002	Bus/MK705, 200 kW	One
Phase 5: Serial Production	2002-2006	Bus/P5-2, 300 kW	39 around the world

Source: Ballard presentation in Vancouver, 2005

Phase 1: Proof of Concept—Ballard developed a proof-of-concept bus with a working PEM fuel cell propulsion system using compressed hydrogen in the 1991-1992 timeframe. The vehicle was a small 20-passenger shuttle bus with a 100 kW fuel cell system. Range of the vehicle was reported as approximately 100 miles.

Phase 2: Commercial Prototype—The next fuel cell bus from Ballard was a 40-foot New Flyer low-floor bus in the 1993-1995 timeframe. This bus could hold 60 passengers, used 20 fuel cell stacks, had a range of 250 miles on compressed hydrogen, and a power plant rated at 200 kW. The challenges for this bus were weight, fuel economy, and maintainability. Successes from this demonstration were reported to be significant work in systems integration and improved component selection for the fuel cell propulsion systems.

Phase 3: Fleet Demonstration-Alpha Sites—Phase 3 was a much more ambitious demonstration: six fuel cell buses split between two transit agencies, Chicago Transit Authority and Coast Mountain Bus in Vancouver. These buses were essentially the same as the New Flyer bus in Phase 2 with some advances based on lessons learned in Phase 2. This development and demonstration effort spanned 1996-1999. Phase 3 was a full-scale demonstration that included facility adaptation to the use of

hydrogen and the inclusion of transit agency personnel in operations and maintenance for the fuel cell buses. The following objectives for this phase were reported by Ballard.

- Learn about fuel cell technology in real, everyday operation and transfer that knowledge to subsequent engine and component development phases.
- Gain an understanding of vehicle performance, failures, and operating costs.
- Better understand the infrastructure required for the operation of this technology.
- Prepare the market for the entrance of fuel cell vehicles.
- Educate the public on the safety and reliability of fuel cell vehicles.
- Prepare and train potential transit customers to work with fuel cell vehicles.

Lessons learned in this phase included the need for additional work in durability of the propulsion systems and experience working within the two colder climate areas. Successes included learning about meeting the needs of working in two locations and creating training programs for transit personnel. Some revenue service was completed with these buses. A high-level summary report for this demonstration can be found at www.cleanairnet.org/infopool/1411/articles-35634_cleaning_up.pdf.

Phase 4: Fuel Cell Engines—Ballard focused on vehicle performance in Phase 4 with one New Flyer low-floor bus, called the zero emission bus (ZEbus). The fuel cell propulsion system was made smaller (higher power density) with eight fuel cell stacks instead of the 20 in the previous two phases. This bus could hold 60 passengers, had a range of 250 miles on 48 kg of compressed hydrogen, and the power plant was rated at 200 kW. This bus was tested as a demonstration at SunLine Transit Agency in the 1999-2002 timeframe. SunLine operates in the desert in the Coachella Valley, near Palm Springs, California. This demonstration was an opportunity to test the fuel cell propulsion systems in high-temperature and low-humidity operations.

Challenges in this phase were reported as temperature, weight, and cooling, and successes were meeting the challenges and training collaboration with the Coachella Valley's College of the Desert. These training materials are available at www.eere.energy.gov/hydrogenandfuelcells/tech_validation/h2_manual.html. Lessons learned from this phase were the need for cooling system improvement and fuel cell propulsion component improvements for inverter cooling and traction drive. A final summary report for this demonstration can be found at www.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/sunline_final_report1.pdf

Phase 5: Serial Production—Phase 5 has been the most ambitious to date. DaimlerChrysler and Ballard embarked on an 11-city fuel cell bus implementation and demonstration program, which included 33 Mercedes-Benz Citaro buses. The timeframe for this phase is 2002-present and is now planned to operate through 2006. Some significant results are expected to be reported in early 2006.

Each of the following 11 cities have received and have been operating three fuel cell buses each:

- Clean Urban Transport for Europe (CUTE)
  - Amsterdam, Netherlands
  - Barcelona, Spain
  - Hamburg, Germany
  - London, England
  - Luxembourg, Luxembourg
  - Madrid, Spain
  - Porto, Portugal
  - Stockholm, Sweden
  - Stuttgart, Germany

- Ecological City Transport System
  - Reykjavik, Iceland

- Sustainable Transport Energy for Perth
  - Perth, Australia

The original two-year demonstration for these 11 cities is essentially over now; however, an extension of one year of operation has been approved. So far, seven of the original 11 cities have agreed to participate in this additional year of operation. The general objectives for this extra year are to get more operating experience and possibly take the fuel cell propulsion system to failure. This additional operation is a part of a program called HyFLEET:CUTE. The fuel cell buses from two cities not participating in the additional operation are planned to be transferred to Hamburg for operation. Hamburg will have a total of nine buses in operation for this demonstration. Additional information on these demonstration sites is provided at www.fuel-cell-bus-club.com.

On November 23, 2005, Ballard Power Systems announced that three more Citaro fuel cell buses from Mercedes-Benz were placed into service in Beijing, China. This project was co-funded by the United Nations Development Program/Global Environment Facility.

The VTA fuel cell buses also have a fuel cell propulsion system that is essentially the same as the other buses in the Phase 5 programs. However, the VTA buses use the Gillig low-floor bus model. The packaging and integration for VTA's three fuel cell buses is significantly different than the Mercedes-Benz Citaro buses used for the other Phase 5 sites.

Evaluation Results

In this evaluation, the starting point was chosen by VTA as February 28, 2005, the day that the agency's fuel cell buses first went into revenue service from the Cerone Operating Division. This report provides analysis and discussion focused on a data period including March 2005 through October 2005, an eight-month evaluation period. Some results and discussion presented in this report will include information and data results prior to March 2005. The data period used is provided in each case.

In this evaluation, the fuel cell buses at VTA are considered prototype technology, and the analysis and comparison discussions with standard diesel buses reflects this status. The intent of this analysis is to determine the status of this implementation and improvements that have been made over time at VTA. There is no intent to consider this implementation of fuel cell buses as commercial (or full revenue transit service). The evaluation is focused on documenting progress and opportunities for improvement of the vehicles, infrastructure, and procedures.

Route Descriptions

VTA operates 54 fixed, 19 express, and 19 special/shuttle type bus routes. Cerone is one of three bus operating divisions at VTA and provides 140 buses for standard weekday service. The weekly average mileage and speed for buses operating from Cerone is shown in Table 7. All standard buses at Cerone are randomly dispatched on routes.

Table 7. Summary of Total Weekly Bus Usage from Cerone

Day of Week	Total Miles	Hours	Avg. Speed
Weekday	22,061.2	1,527.22	14.4
Saturday	11,294.2	776.13	14.6
Sunday	9,600.6	666.55	14.4
Weekly Total	**131,200.8**	**9,078.78**	**14.5**

For demonstrating this advanced technology, the fleet chose to use the three fuel cell buses as "extra" service on existing routes, meaning they are placed on routes between two regularly scheduled buses. This is meant to prevent a situation where passengers are stranded for a long period in the event of a failure of the fuel cell bus. The fuel cell buses are operated during peak weekday hours with two buses in service and one as a spare. This allows for service interruptions if a bus needs maintenance or is scheduled for a public event. VTA limits the use of the buses to times when a trained ZEB mechanic is available.

The scheduling department created two blocks of work for the fuel cell buses, which have changed over time to accommodate having the fuel cell buses operate on several VTA routes and experience different operating types. VTA's strategy for testing the overall bus performance was to select shorter routes close to the Cerone base to start and gradually introduce the buses to longer routes that cover more ground. A summary of these blocks and assignments are shown in Table 8. The fuel cell buses have generally been used at an average speed slightly less than the fleet average for the diesel buses at Cerone.

Table 8. Route Block Assignments for the Fuel Cell Buses

Block	Routes	Effective Date	Pull Out Time	Pull In Time	Total Time	Total Miles	Average Speed
9781	45	2/28/2005	8:03 a.m.	2:00 p.m.	5:57	52.0	8.7
	33	5/2/2005	8:00 a.m.	2:30 p.m.	6:30	86.5	13.3
	47	7/5/2005	8:00 a.m.	2:14 p.m.	6:14	71.5	11.5
	102/22/71	9/6/2005	6:42 a.m.	2:27 p.m.	7:45	114.7	14.8
9782	47	2/28/2005	8:22 a.m.	2:00 p.m.	5:38	71.5	12.6
	46	5/2/2005	8:00 a.m.	2:23 p.m.	6:23	84.0	13.2
	32	5/31/2005	8:00 a.m.	2:21 p.m.	6:21	85.5	13.5
	53	7/5/2005	8:00 a.m.	2:22 p.m.	6:22	61.0	9.6
	62	9/6/2005	6:42 a.m.	2:23 p.m.	7:41	88.0	11.5

Bus Use and Availability

Bus use is intended as an indicator of reliability and availability for bus service. The lack of bus usage may be an indication of downtime for maintenance or purposeful reduction of planned work for the buses. This section provides a summary of bus usage and availability for the two study groups of buses.

Figure 11 shows mileage and fuel cell module operating hour accumulation from the start of hydrogen fueling in November 2004 through October 2005. As would be expected, usage began to accumulate faster after the buses went into revenue service at the end of February 2005. Use of the fuel cell buses was limited by using the buses only on weekdays, planned work for the buses as extra service, maintenance issues, and availability of drivers and mechanics for the fuel cell bus operation.

Table 9 summarizes average monthly mileage accumulation by bus and study group for the evaluation period. The three fuel cell buses accumulated 16,708 miles in the eight-month evaluation period and 1,376 hours on the fuel cell modules. Average monthly mileage per fuel cell bus was 726 miles.

The diesel study buses were operated in normal VTA service from Cerone, including weekend operation. The average monthly mileage per bus from the evaluation period was 4,284 miles. In calendar year 2004, these five buses had an average monthly mileage per bus of 4,027 miles; however, bus 2230 was out of service for significant maintenance. With bus 2230 removed from this average, the diesel buses had an average monthly mileage per bus of 4,273 miles, which is essentially the same as that experienced during the evaluation period.

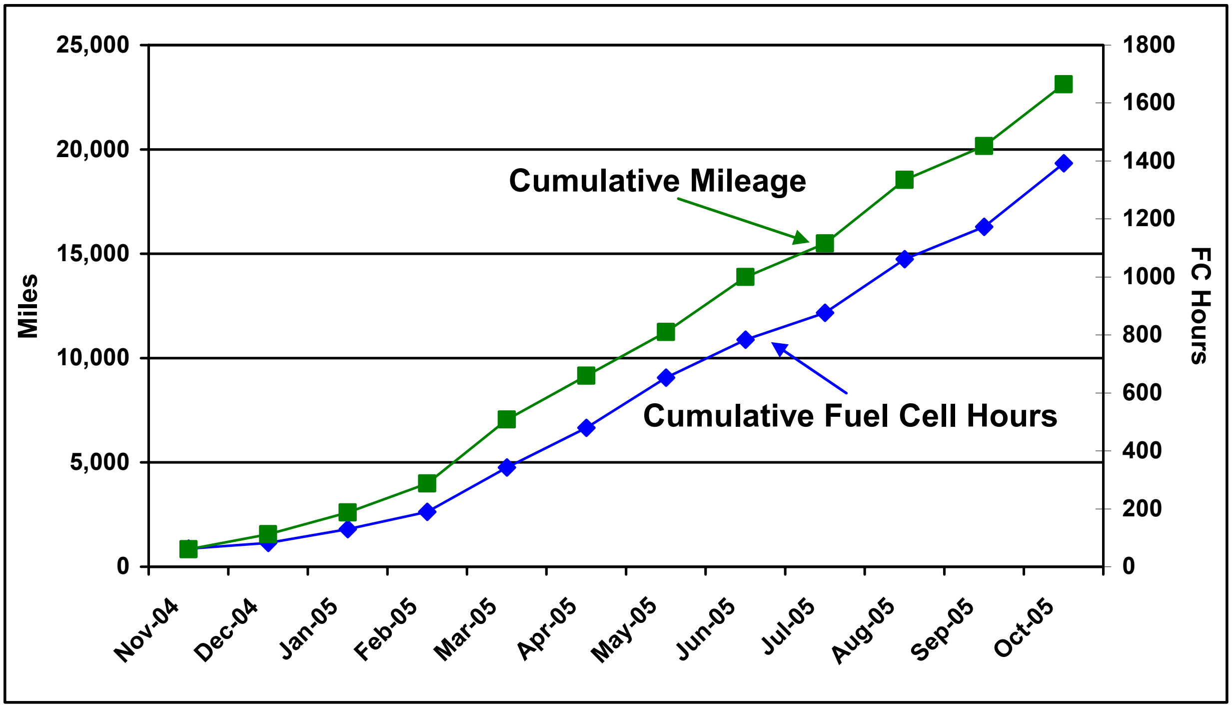

Figure 11. Cumulative Mileage and Fuel Cell Hours for Three Fuel Cell Buses

Table 9. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage	Fuel Cell Module Hours
4001	7,930	14,428	6,498	8	812	561
4002	959	5,781	4,822	7	689	402
4003	954	6,342	5,388	8	674	413
Fuel Cell			**16,708**	**23**	**726**	**1,376**
2229	134,738	161,852	30,408	8	3,801	N/A
2230	115,857	152,772	36,915	8	4,614	N/A
2231	130,452	164,663	36,434	8	4,554	N/A
2232	122,086	156,950	34,864	8	4,358	N/A
2233	134,142	166,880	32,738	8	4,092	N/A
Diesel			**171,359**	**40**	**4,284**	**N/A**

Availability of a diesel bus was measured by the number of days it might be scheduled for service and the number of days it was not available for service due to any maintenance issues. During the evaluation period, the diesel buses had an availability rate of 84%. VTA's goal is 80% for diesel buses.

During the evaluation period, the fuel cell buses had an availability rate of 52% for each weekday, with a goal of 67% of the time. (For this preliminary report, no differentiation was made between standard bus maintenance issues and those attributed specifically to the fuel cell and system.) VTA's schedule was designed for two of the three fuel cell buses to be in service on weekdays, except holidays. This would generally indicate that the fuel cell buses met the goal 78% of the time.

Fuel Economy and Cost

As previously mentioned, hydrogen fuel was trucked as a liquid from near Sacramento, California, to San Jose and added to the fuel station at Cerone. For trucking commerce, the liquid hydrogen was tracked as mass (kg) of fuel delivered to the hydrogen dispensing station. Fueling records for the fuel cell buses were tracked as mass (kg) of hydrogen dispensed for each fuel fill. To compare the hydrogen fuel dispensed and fuel economy to diesel, the hydrogen dispensed was also calculated into diesel energy equivalent gallons. The general energy conversions used in this report is shown in the Appendix.

Table 10 shows hydrogen and diesel fuel consumption and fuel economy for the two study groups during the evaluation period. The fuel cell buses averaged 3.05 miles per kg of hydrogen, which translates into 3.45 miles per diesel equivalent gallons (mpg). This fuel economy includes all hydrogen fuel added to the buses even if there was some venting for maintenance or testing during the evaluation period. The diesel study group had a fuel economy of 3.95 mpg. With diesel as the baseline, the fuel cell buses had a fuel economy that was 13% lower on an energy equivalent basis. Figure 12 shows average monthly energy equivalent fuel economies throughout the evaluation period for the fuel cell and diesel buses.

Table 10. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (Gallon)	Miles per Gallon
4001	6,498	2,188.8	2.97	1,937.0	3.35
4002	4,822	1,584.4	3.04	1,402.1	3.44
4003	5,388	1,696.1	3.18	1,501.0	3.59
Fuel Cell	**16,708**	**5,469.3**	**3.05**	**4,840.1**	**3.45**
2229	25,996			6,412.4	4.05
2230	36,915			9,741.4	3.79
2231	33,106			8,507.1	3.89
2232	34,864			8,940.0	3.90
2233	32,738			7,873.2	4.16
Diesel	**163,619**			**41,474.1**	**3.95**

As reported earlier, the average cost of hydrogen during the evaluation period was $8.56 per kg of hydrogen and the average cost of diesel fuel during the evaluation period was $2.02 per gallon. These average fuel costs translate into a fuel cost per mile of $2.80 for the fuel cell buses and $0.51 per mile for the diesel buses. If hydrogen fuel losses at the station were taken into account, the fuel cost per mile for the fuel cell buses would be essentially double.

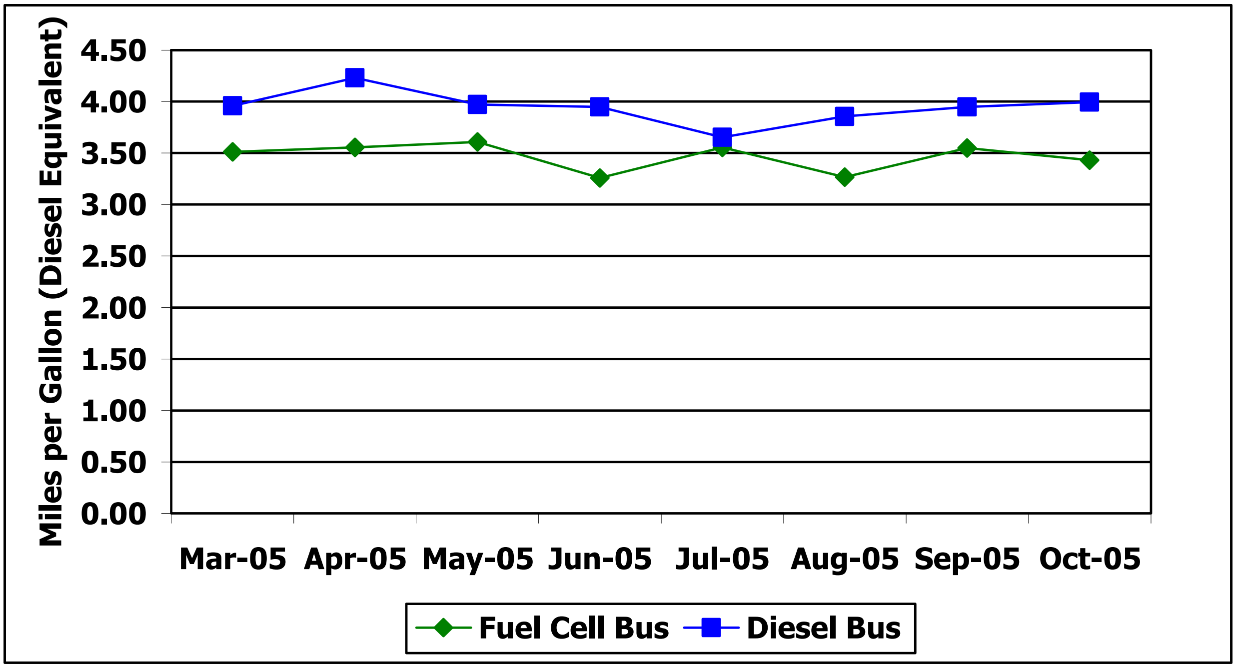

Figure 12. Average Fuel Economy (mpg) by Month

Maintenance Analysis

The maintenance cost analysis in this section is for only the evaluation period (March 2005 through October 2005) for the two study groups of buses. Warranty costs are shown but not included in the cost-per-mile calculations. All work orders for the study buses were collected and analyzed for this evaluation. The labor rate for maintenance was kept at a constant $50 per hour, and this is not reflective of an average rate at VTA. This section first covers total maintenance costs, then maintenance costs broken down by bus system.

Total Maintenance Costs—Total maintenance costs include the price of parts and hourly labor rates of $50 per hour; they do not include warranty costs. Cost per mile is calculated as follows:

Cost per mile = ((labor hours * 50) + parts cost) / mileage

Table 11 shows total maintenance costs for the fuel cell and diesel buses. Warranty costs are shown in the table but not included in the cost-per-mile calculation shown. For the fuel cell buses, bus 4001 has the lowest cost per mile and the other two have similar costs per mile. This most likely occurred because of the testing and shakedown of bus 4001 done at Ballard before the bus was delivered to VTA. The other two buses have had ongoing work to sort out integration issues. The warranty cost by bus also supports this hypothesis.

Bus 4002 had some significant repairs on the fuel cell modules and fuel system in September 2005 and October 2005. This bus had lower mileage than the other two because of these ongoing troubleshooting activities. The overall average maintenance cost per mile for the fuel cell buses was $4.26.

Table 11. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Warranty Parts ($)	Parts ($)	Labor Hours	Cost per Mile ($)
4001	6,498	5,350.25	520.52	347.8	2.76
4002	4,822	31,395.50	1,528.56	496.4	5.46
4003	5,388	32,022.64	349.91	531.4	5.00
Total Fuel Cell	**16,708**	**68,768.39**	**2,398.99**	**1,375.6**	**4.26**
Avg. per Bus	**5,569**	**22,922.80**	**799.66**	**458.5**	**--**
2229	30,408	1,238.75	7,839.45	383.0	0.89
2230	36,915	468.81	5,697.16	271.1	0.52
2231	36,434	1,981.25	5,075.11	234.7	0.46
2232	34,864	2,871.45	5,246.33	276.3	0.55
2233	32,738	440.20	6,446.44	247.5	0.58
Total Diesel	**171,359**	**7,000.46**	**30,304.49**	**1,412.6**	**0.59**
Avg. per Bus	**34,272**	**1,400.09**	**6,060.90**	**282.5**	**--**

Warranty costs listed are those that were available for the data collection and evaluation. A significant portion of the cost for parts covered under warranty is not yet accounted for. A priority for the final results report for this evaluation is to attempt to collect more of the warranty costs for the fuel cell buses. Some of the warranty costs that were not collected at this point include the preventive maintenance filter parts, which were listed as no-cost to VTA. Warranty parts costs for the fuel cell propulsion systems were expected to be expensive (compared to mature diesel technology) because of the developmental nature of the technology and relatively low volume production of these systems.

The diesel buses had similar maintenance costs per mile for four of the five buses and the overall average maintenance cost per mile for the diesel group was $0.59. Bus 2229 had a significantly higher maintenance cost, which was caused by major repairs for the transmission, air compressor, and exhaust systems.

The total maintenance costs, without warranty costs, are much lower for the diesel buses. This reflects the stage of development for the fuel cell buses and the fact that they are in the prototype development stage for transit bus service.

Maintenance Cost Broken Down by System—Table 12 shows maintenance costs by vehicle system and bus study group. The vehicle systems shown in the table include the following.

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

- **Heating, Ventilation, and Air Conditioning (HVAC)**
- **Lighting**
- **Air System, General**
- **Axles, Wheels, and Drive Shaft**
- **Tires**

The highest percent maintenance cost systems for the fuel cell buses were propulsion-related, PMI, and cab, body and accessories. The diesel buses had those three system maintenance groups as the highest cost and also frame, steering, and suspension. The additional category of frame, steering, and suspension reflects the higher use of the diesel buses compared to the fuel cell buses.

Table 12 Breakdown of Vehicle System Maintenance Cost per Mile (Evaluation Period)

System	Fuel Cell		Diesel	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Cab, Body, and Accessories	0.39	9	0.12	21
Propulsion-Related	3.06	72	0.21	36
PMI	0.65	15	0.09	15
Brakes	0.07	2	0.02	3
Frame, Steering, and Suspension	0.00	0	0.08	14
HVAC	0.05	1	0.02	3
Lighting	0.01	0	0.02	3
Air, General	0.00	0	0.03	5
Axles, Wheels, and Drive Shaft	0.01	0	0.00	0
Tires	0.02	1	0.00	0
Total	**4.26**	**100**	**0.59**	**100**

Preventive maintenance for the fuel cell and diesel buses was the same percent portion of total maintenance cost. The diesel buses have a preventive maintenance schedule of 6,000 miles. The fuel cell buses have preventive maintenance inspections scheduled for 160 hours and 320 hours based on fuel cell module operation and every 3,700 miles based on bus operation. These preventive maintenance schedules for the fuel cell buses do not necessarily overlap, and at times, the fuel cell buses may be in for preventive maintenance for one schedule one week and another the following week. Ballard has been working to harmonize these schedules.

Propulsion-Related Maintenance Costs—The propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. Table 13 shows a breakdown of the propulsion-related system repairs for the two study groups during the evaluation period. The fuel cell buses had significantly higher maintenance costs for all of the systems shown in the table except for exhaust and transmission systems.

Table 13. Propulsion-Related Maintenance Cost by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	16,708	171,359
Total Propulsion-related Systems (Roll-Up)		
Parts cost ($)	2,381.59	11,737.99
Labor hours	973.6	491.6
Total cost ($)	51,061.59	36,315.49
Total cost ($) per mile	**3.06**	**0.21**
Exhaust System Repairs		
Parts cost ($)	0.00	86.97
Labor hours	0.0	100.4
Total cost ($)	0.00	5,106.97
Total cost ($) per mile	**0.00**	**0.03**
Fuel System Repairs		
Parts cost ($)	1,042.00	3,226.63
Labor hours	184.9	33.1
Total cost ($)	10,287.00	4,879.13
Total cost ($) per mile	**0.62**	**0.03**
Engine System Repairs		
Parts cost ($)	299.93	3,924.18
Labor hours	351.0	158.7
Total cost ($)	17,849.93	11,859.18
Total cost ($) per mile	**1.07**	**0.07**
Electric Motor and Fuel Cell Module Repairs		
Parts cost ($)	0.00	0.00
Labor hours	106.4	0.0
Total cost ($)	5,320.00	0.00
Total cost ($) per mile	**0.32**	**0.000**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts Cost ($)	0.00	463.33
Labor Hours	70.9	25.5
Total Cost ($)	3,545.00	1,738.33
Total cost ($) per mile	**0.21**	**0.01**
Air Intake System Repairs		
Parts cost ($)	509.50	312.79
Labor hours	109.8	0.5
Total cost ($)	5,999.50	337.79
Total cost ($) per mile	**0.36**	**0.00**
Cooling System Repairs		
Parts cost ($)	530.16	1,895.65
Labor hours	141.1	84.4
Total cost ($)	7,585.16	6,113.15
Total cost ($) per mile	**0.45**	**0.04**
Transmission Repairs		
Parts cost ($)	0.00	1,828.44
Labor hours	9.5	89.1
Total cost ($)	475.00	6,280.94
Total cost ($) per mile	**0.023**	**0.04**

Roadcall Analysis

A roadcall (RC) or revenue vehicle system failure (as named for the National Transit Database[3]) is defined as a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a RC. The analysis provided here only includes RCs that were caused by "chargeable" failures. Chargeable RCs includes systems that can physically disable the bus from operating on route, such as interlocks (doors), engine, etc. They do not include RCs for things such as radios or destination signs.

Table 14 shows the RCs and miles between roadcalls (MBRC) for each study bus and breaks them down by all RCs and propulsion-related-only RCs. The diesel buses have much better MBRC rates for both categories. This is indicative of the low usage and prototype status of the fuel cell buses.

Table 14. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC
4001	6,498	6	1,083	6	1,083
4002	4,822	6	804	5	964
4003	5,388	5	1,078	5	1,078
Fuel Cell	**16,708**	**17**	**983**	**16**	**1,044**
2229	30,408	3	10,136	3	10,136
2230	36,915	2	18,458	2	18,458
2231	36,434	4	9,109	2	18,217
2232	34,864	4	8,716	4	8,716
2233	32,738	6	5,456	4	8,185
Diesel	**171,359**	**19**	**9,019**	**15**	**11,424**

[3] Revenue vehicle system failures are defined for the FTA's National Transit Database in the Reporting Manual, Resource Module, which can be found at www.ntdprogram.com/NTD/ReportingManual/2005/Annual/PDFFiles/2005%20Resource%20Module.pdf.

What's Next?

This preliminary data report includes an eight-month evaluation period (March 2005 through October 2005) of the prototype fuel cell buses in demonstration at VTA. A final report is planned for this evaluation following at least 12 months of fuel cell bus operation at VTA. This is expected to be published in mid-2006.

VTA currently plans to operate the fuel cell buses through July 2006—the end of the two-year demonstration and the warranty/support period for the fuel cell buses, as defined by Ballard. It is not clear whether this demonstration will continue beyond the end date because there are no grants or funds set aside to extend it. As described in this preliminary data report, to continue operation beyond the current end point would require significant funding. VTA, Ballard, and Air Products have expressed interest in continuing this testing program if funding becomes available. Significant investment and effort have been committed to test and operate this equipment. There is still significant work to be done (and lessons to be learned) before fuel cell buses and infrastructure equipment is truly commercial.

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Acronyms and Abbreviations

APTA	American Public Transportation Association
BAAQMD	Bay Area Air Quality Management District
Btu	British thermal units
CaFCP	California Fuel Cell Partnership
CARB	California Air Resources Board
CEC	California Energy Commission
CUTE	Clean Urban Transport for Europe
DOE	U.S. Department of Energy
E-stop	Emergency stop
FCB	Fuel cell buses
FTA	Federal Transit Administration
GVWR	Gross vehicle weight rating
HFCIT	Hydrogen, Fuel Cells & Infrastructure Technologies
HVAC	Heating, ventilation, and air conditioning
in	Inches
kg	Kilograms
kW	Kilowatt
lb	pound
lb-ft	Pound feet
LFL	Lower flammability limit
LHV	Lower heating value
MBRC	Miles between roadcalls
mpg	Miles per gallon
Nm	Newton meter
NREL	National Renewable Energy Laboratory
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane
PMI	Preventive maintenance inspection
ppm	Parts per million
psi	pounds per square inch
RC	Roadcalls
rpm	revolutions per minute
SamTrans	San Mateo County Transit District
UTC	United Technologies Corporation
VTA	Santa Clara Valley Transportation Authority
ZEB	Zero emissions bus
ZEbus	Ballard zero emission bus

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Appendix: Fleet Summary Statistics

Fleet Summary Statistics: Santa Clara Valley Transportation Authority (VTA) Diesel and FCB Study Groups

Fleet Operations and Economics

	Diesel Buses	Fuel Cell Buses
Number of Vehicles	5	3
Period Used for Fuel and Oil Op Analysis	3/05-10/05	3/05-10/05
Total Number of Months in Period	8	8
Fuel and Oil Analysis Base Fleet Mileage	163,619	16,708
Period Used for Maintenance Op Analysis	3/05-10/05	3/05-10/05
Total Number of Months in Period	8	8
Maintenance Analysis Base Fleet Mileage	171,359	16,708
Average Monthly Mileage per Vehicle	4,284	696
Availability	84%	1.56/2.00
Fleet Fuel Usage in Diesel Gal/H2 kg	41,474	5,469
Roadcalls	19	17
RCs MBRC	9,019	983
Propulsion Roadcalls	15	16
Propulsion MBRC	11,424	1,044
Fleet Miles/Kg Hydrogen		3.05
(1.13 kg H2/gal Diesel fuel)		
Representative Fleet MPG (energy equiv)	3.95	3.45
Hydrogen cost per kg		8.56
Diesel Cost per gallon	2.02	
Fuel Cost per Mile	**0.51**	**2.8**
Total Scheduled Repair Cost per Mile	0.122	0.715
Total Unscheduled Repair cost per Mile	0.467	3.545
Total Maintenance Cost per Mile	**0.59**	**4.26**
Total Operating Cost per Mile	**1.10**	**7.06**

Maintenance Costs

	Diesel Buses	Fuel Cell Buses
Fleet Mileage	171,359	16,708
Total Parts Cost	30,304.64	2,398.99
Total Labor Hours	1412.6	1375.6
Average Labor Cost (@ $50.00 per hour)	70,627.50	68,780.00
Total Maintenance Cost	100,932.14	71,178.99
Total Maintenance Cost per Bus	20,186.43	23,726.33
Total Maintenance Cost per Mile	**0.59**	**4.26**

Breakdown of Maintenance Costs by Vehicle System

	Diesel Buses	Fuel Cell Buses
Fleet Mileage	171,359	16,708
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45)		
Parts Cost	11,737.99	2,381.59
Labor Hours	491.6	973.6
Average Labor Cost	24,577.50	48,680.00
Total Cost (for system)	36,315.49	51,061.59
Total Cost (for system) per Bus	7,263.10	17,020.53
Total Cost (for system) per Mile	**0.21**	**3.06**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost	86.97	0.00
Labor Hours	100.4	0.0
Average Labor Cost	5,020.00	0.00
Total Cost (for system)	5,106.97	0.00
Total Cost (for system) per Bus	1,021.39	0.00
Total Cost (for system) per Mile	**0.03**	**0.00**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost	3,226.63	1,042.00
Labor Hours	33.1	184.9
Average Labor Cost	1,652.50	9,245.00
Total Cost (for system)	4,879.13	10,287.00
Total Cost (for system) per Bus	975.83	3,429.00
Total Cost (for system) per Mile	**0.03**	**0.62**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost	3,924.18	299.93
Labor Hours	158.7	351.0
Average Labor Cost	7,935.00	17,550.00
Total Cost (for system)	11,859.18	17,849.93
Total Cost (for system) per Bus	2,371.84	5,949.98
Total Cost (for system) per Mile	**0.07**	**1.07**
Electric Propulsion Repairs (ATA VMRS 46)		
Parts Cost	0.00	0.00
Labor Hours	0.0	106.4
Average Labor Cost	0.00	5,320.00
Total Cost (for system)	0.00	5,320.00
Total Cost (for system) per Bus	0.00	1,773.33
Total Cost (for system) per Mile	**0.00**	**0.32**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Buses	Fuel Cell Buses
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost	463.33	0.00
Labor Hours	25.5	70.9
Average Labor Cost	1,275.00	3,545.00
Total Cost (for system)	1,738.33	3,545.00
Total Cost (for system) per Bus	347.67	1,181.67
Total Cost (for system) per Mile	**0.01**	**0.21**
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost	312.79	509.50
Labor Hours	0.5	109.8
Average Labor Cost	25.00	5,490.00
Total Cost (for system)	337.79	5,999.50
Total Cost (for system) per Bus	67.56	1,999.83
Total Cost (for system) per Mile	**0.00**	**0.36**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost	1,895.65	530.16
Labor Hours	84.4	141.1
Average Labor Cost	4,217.50	7,055.00
Total Cost (for system)	6,113.15	7,585.16
Total Cost (for system) per Bus	1,222.63	2,528.39
Total Cost (for system) per Mile	**0.04**	**0.45**
Hydraulic System Repairs (ATA VMRS 65)		
Parts Cost	0.00	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00
Total Cost (for system) per Mile	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)		
Parts Cost	933.50	0.00
Labor Hours	74.4	0.0
Average Labor Cost	3,720.00	0.00
Total Cost (for system)	4,653.50	0.00
Total Cost (for system) per Bus	930.70	0.00
Total Cost (for system) per Mile	**0.03**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Buses	Fuel Cell Buses
Brake System Repairs (ATA VMRS 13)		
Parts Cost	346.28	0.00
Labor Hours	74.2	22.0
Average Labor Cost	3,710.00	1,100.00
Total Cost (for system)	4,056.28	1,100.00
Total Cost (for system) per Bus	811.26	366.67
Total Cost (for system) per Mile	**0.02**	**0.07**
Transmission Repairs (ATA VMRS 27)		
Parts Cost	1,828.44	0.00
Labor Hours	89.1	9.5
Average Labor Cost	4,452.50	475.00
Total Cost (for system)	6,280.94	475.00
Total Cost (for system) per Bus	1,256.19	158.33
Total Cost (for system) per Mile	**0.04**	**0.03**
Inspections Only – No Parts Replacements (101)		
Parts Cost	0.00	0.00
Labor Hours	296.3	216.6
Average Labor Cost	14,815.00	10,830.00
Total Cost (for system)	14,815.00	10,830.00
Total Cost (for system) per Bus	2,963.00	3,610.00
Total Cost (for system) per Mile	**0.09**	**0.65**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost	7,150.35	0.00
Labor Hours	255.8	130.6
Average Labor Cost	12,787.50	6,530.00
Total Cost (for system)	19,937.85	6,530.00
Total Cost (for system) per Bus	3,987.57	2,176.67
Total Cost (for system) per Mile	**0.12**	**0.39**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost	647.82	7.50
Labor Hours	40.9	17.5
Average Labor Cost	2,042.50	875.00
Total Cost (for system)	2,690.32	882.50
Total Cost (for system) per Bus	538.06	294.17
Total Cost (for system) per Mile	**0.02**	**0.05**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Buses	Fuel Cell Buses
Lighting System Repairs (ATA VMRS 34)		
Parts Cost	1,473.89	0.00
Labor Hours	37.4	4.0
Average Labor Cost	1,870.00	200.00
Total Cost (for system)	3,343.89	200.00
Total Cost (for system) per Bus	668.78	66.67
Total Cost (for system) per Mile	**0.02**	**0.01**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost	7,966.52	0.00
Labor Hours	130.9	1.0
Average Labor Cost	6,545.00	50.00
Total Cost (for system)	14,511.52	50.00
Total Cost (for system) per Bus	2,902.30	16.67
Total Cost (for system) per Mile	**0.08**	**0.00**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost	48.29	9.90
Labor Hours	11.2	4.5
Average Labor Cost	560.00	225.00
Total Cost (for system)	608.29	234.90
Total Cost (for system) per Bus	121.66	78.30
Total Cost (for system) per Mile	**0.00**	**0.01**
Tire Repairs (ATA VMRS 17)		
Parts Cost	0.00	0.00
Labor Hours	0.0	5.8
Average Labor Cost	0.00	290.00
Total Cost (for system)	0.00	290.00
Total Cost (for system) per Bus	0.00	96.67
Total Cost (for system) per Mile	**0.00**	**0.02**

Notes

1. To compare the hydrogen fuel dispensed and fuel economy to diesel, the hydrogen dispensed was also calculated 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

2. The engine/fuel-related systems were chosen to include only those systems of the vehicles 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.

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