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Santa Clara Valley Transportation Authority and San Mateo County Transit District

Fuel Cell Transit Buses: Evaluation Results

Kevin Chandler
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Technical Report
NREL/TP-560-40615
November 2006

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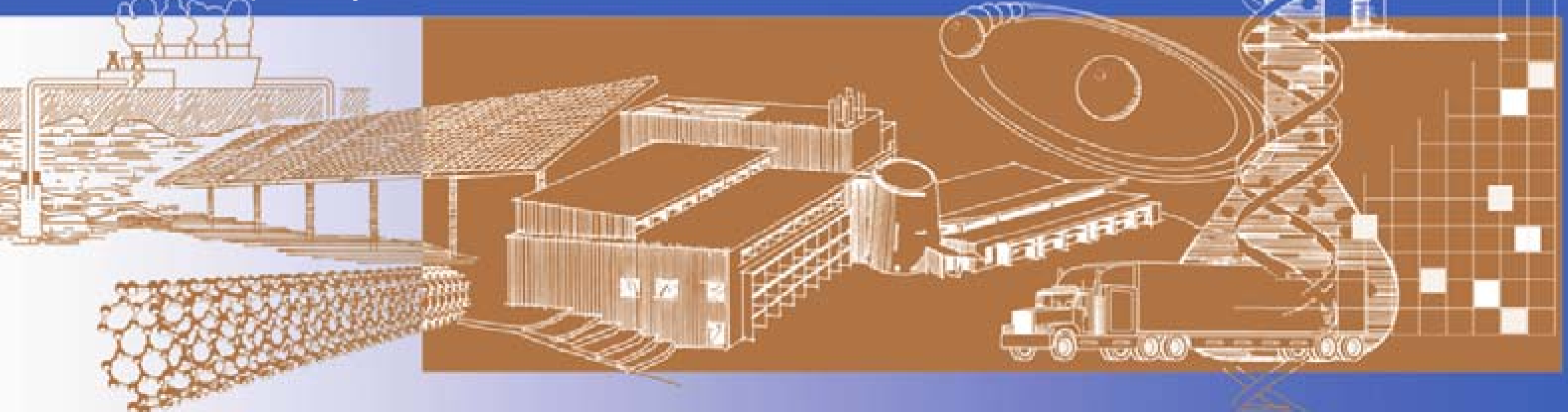

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Executive Summary

This report provides evaluation results for 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 experiences, and evaluation results from the operation of the buses and supporting hydrogen infrastructure from March 2005 through July 2006 (17 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 as well as 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.

These low-floor fuel cell buses at VTA were built by Gillig with Ballard fuel cell propulsion systems and are considered prototype technology. 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 improving the vehicles, infrastructure, and procedures.

Infrastructure and Facilities

VTA has three bus operation depots: 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 is leased from Air Products and Chemicals, Inc. (Air Products) with a three-year contract and an option for two additional years. The installation of the equipment was completed in May 2004; however, actual dispensing of hydrogen at the station did not start until November 2004. VTA also provided the concrete pad/foundation for the station and performed additional work for the utility connections and other activities for the station at an additional cost. During initial use of the hydrogen fueling infrastructure, there were some significant challenges 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 as well as typical startup issues for a new fueling technology.

Figure ES-1. Compressed hydrogen dispensing station, fuel cell bus, bus wash, and maintenance facility

A separate maintenance facility was designed and built for the fuel cell bus demonstration. The 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 issues 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 the hydrogen fuel on board the buses. The total cost for these three facilities—designed to meet the operating requirements for the VTA hydrogen fuel cell buses—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, fueling time has been reduced to an average of 10-14 minutes. The hydrogen dispensing station has had 31,836 kg of liquid hydrogen delivered to it, and the station has delivered 14,024 kg of compressed hydrogen to the fuel cell buses. This station has delivered approximately 460 fuelings at an average of 16 minutes/fill, 30.9 kg/fill, and 1.93 kg/min.

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 caused the loss of approximately 50% of the hydrogen fuel during this demonstration. Air Products reports that if the station throughput had been greater, the hydrogen losses would have been significantly reduced.

Hydrogen fuel cost an average of $9.06 per kg throughout the evaluation period (March 2005 through July 2006). This high cost is an indicator of the low volume use of hydrogen as a fuel. With the boil off of hydrogen taken into account, this cost would be double. Diesel fuel averaged $2.07 per gallon during the same evaluation period.

Early Experience

Familiarization training for hydrogen safety and general characteristics was a high priority for the fleet. Held at VTA, this training 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 from Ballard on the fuel cell propulsion system and 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. An emergency response card was prepared to provide emergency responders with a quick reference regarding the locations of fuel tanks, shut-down devices, high voltage lines, and other devices that would assist them in an emergency. 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 trained personnel including two VTA fuel cell bus mechanics, Ballard's onsite mechanic, and Air Products' staff.

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 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. The fuel cell buses are slightly newer than the diesel buses. The fuel cell buses are also 24 inches taller than the diesel buses, which caused some concerns about clearance. 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 the 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 71 fixed bus routes, 11 of which are express service. Additionally, VTA operates one bus rapid transit line and 14 shuttle service 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 fuel cell bus mechanic is available.

Bus Use and Availability—Bus use and availability are indicators of reliability. The lack of bus usage may indicate downtime for maintenance, repair, or purposeful reduction of planned work for the buses. Figure ES-2 shows mileage and fuel cell system operating hour accumulation from the start of hydrogen fueling in November 2004 through July 2006. As 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 for extra service as well as by maintenance issues and the availability of specially trained drivers and mechanics.

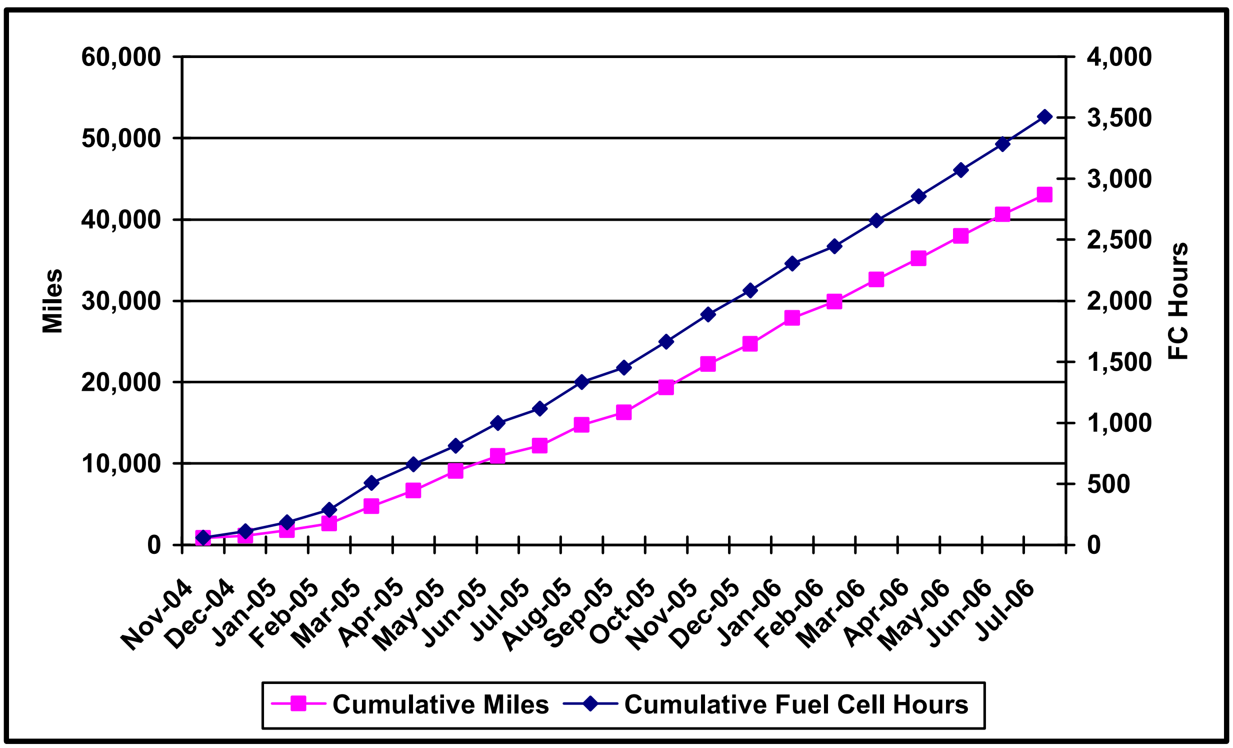

Figure ES-2. Cumulative mileage and fuel cell hours for three fuel cell buses

During the 17-month evaluation period, the three buses accumulated 40,429 miles and 3,219 hours on the fuel cell systems. Average monthly mileage per fuel cell bus was 809 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 4,335 miles (over five times higher than the FCBs).

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 unavailable for service due to maintenance issues. During the evaluation period, the diesel buses had an availability rate of 85%. VTA's goal is 80% for diesel buses. During the evaluation period, the fuel cell buses had an average availability rate of 58% for each weekday. VTA's fuel cell bus schedule was designed for two of the three fuel cell buses to be in service on weekdays, except holidays. Based on VTA's planned usage of the fuel cell buses, the availability goal was 67%.

Fuel Economy—During the evaluation period, the fuel cell buses averaged 3.12 miles per kg of hydrogen, which translates into 3.52 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 3.98 mpg. With the diesel buses as the baseline, the fuel cell buses had a fuel economy 12% 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.

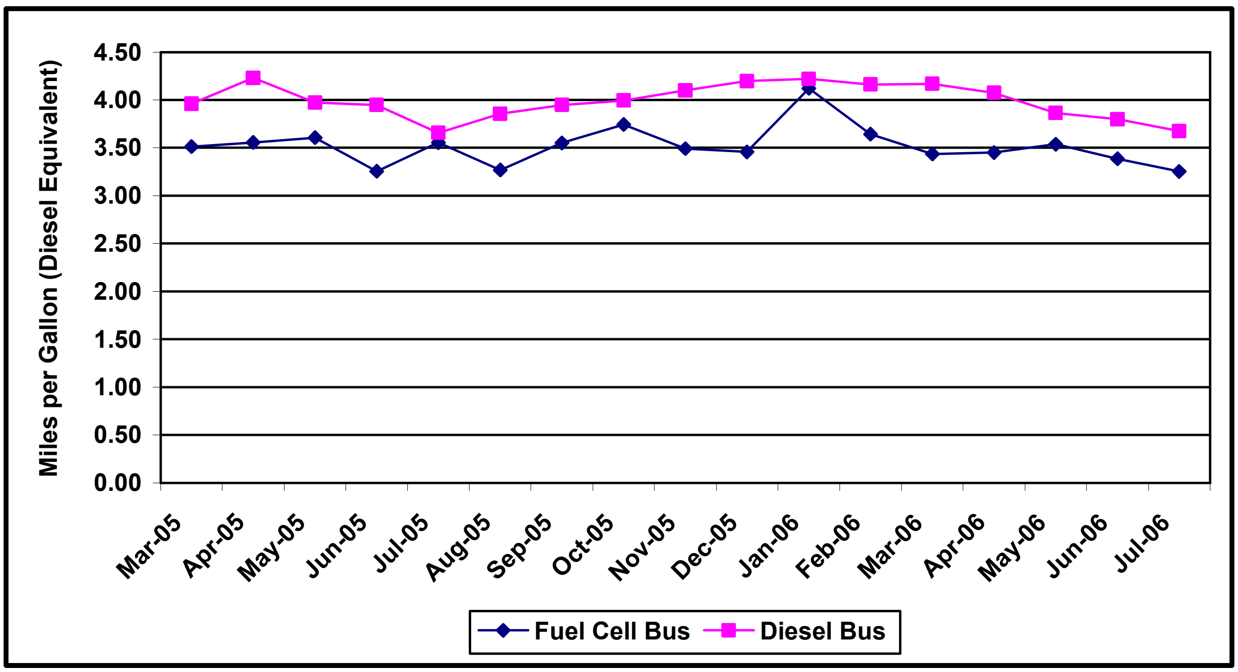

Figure ES-3. Average fuel economy (mpg) by month

Maintenance Costs—The maintenance costs in this report pertain to only the evaluation period (March 2005 through July 2006) for the two study groups of buses. All work orders for the study buses were collected and analyzed for this evaluation. For this analysis, the labor rate for maintenance was set at a constant $50 per hour; this is not reflective of an average rate at VTA.

Total maintenance costs were $3.55 per mile for the fuel cell buses and $0.54 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 caused a need for significant mechanic labor for troubleshooting.

Warranty costs were collected but not accounted for in the cost-per-mile calculations. The fuel cell buses had nearly $540,000 in warranty parts replaced during the evaluation period (March 2005 through July 2006).

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 ($2.37 per mile) had significantly higher propulsion-related maintenance costs than the diesel buses ($0.20 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 898 miles between roadcalls (MBRC) for all roadcalls and 918 MBRC for propulsion-related roadcalls. The diesel buses had 8,189 MBRC for all roadcalls and 10,838 MBRC for propulsion-related roadcalls.

What's Next for This Demonstration?

This report covers VTA operation of the fuel cell buses through July 2006. This is the end of the two-year demonstration and the warranty/support period for the fuel cell buses, as defined by Ballard. VTA has continued to run the fuel cell buses beyond July 2006 and is paying for support by Ballard and parts on a month-to-month basis. VTA currently intends to attempt another full year of service; however, additional funding and level of support from Ballard and Air Products have not yet been finalized.

There are ongoing discussions between VTA and Ballard to potentially upgrade the existing fuel cell buses to a hybrid propulsion system and Ballard's newer model fuel cell modules. Issues yet to be resolved in these discussions include funding requirements and sources as well as expectations and design of operations for these new hybrid fuel cell buses.

VTA's current lease of the hydrogen fuel dispensing station runs through May 2007 with two one-year options available from Air Products. Continuation beyond this would require renegotiation of the lease rates with Air Products. Air Products indicates that it intends to support that station and continue its testing and development activities.

Ballard intends to continue to be a supplier of fuel cell power plants to vehicle manufacturers. It also has a new model fuel cell module for transportation applications. Ballard's plans are to have a potentially commercial fuel cell module product for the 2010-2015 timeframe.

Overview

This report provides 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 results from the operation of the buses and supporting hydrogen fuel station through July 31, 2006 (evaluation period of 17 months).

This evaluation is part of DOE's 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 assess technology readiness. 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 data report examines 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 July 2006—17 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.

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)	Shuttle bus in operation, data collection started
	Delivery van: Hydrogenics and Enova, fuel cell hybrid (one van)	Van just going into service
VTA (San Jose, California) and SamTrans (San Carlos, California)	Gillig/Ballard fuel cell transit bus (three buses)	Evaluation complete, data 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, all three buses in operation since March 2006, full service started in April 2006
SunLine Transit Agency (Thousand Palms, California)	New Flyer ISE Corp. hydrogen internal combustion engine transit bus (one bus-HHICE)	HHICE bus in service, data collection started
	Van Hool/UTC fuel cell hybrid transit bus integrated by ISE Corp. (one bus-FCB)	FCB evaluation in process, bus in operation since January 2006

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 collection 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 have been collected in parallel to the three fuel cell buses for the evaluation period starting in March 2005. The diesel baseline data were 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 and fill
- Hydrogen fuel consumption by vehicle and fill
- 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 has 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 an 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 the 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 all recent fuel cell transit bus demonstrations in the United States, Canada, and Europe. More details on Ballard fuel cell transit bus demonstrations are provided later in this report.

Zero Emissions Buses in California

In February 2000, the California Air Resources Board (CARB) established a new fleet rule to significantly reduce emissions of existing and new transit buses in California. A department of the California Environmental Protection Agency, CARB oversees all air pollution control efforts in the state. The rule set more stringent emissions standards for new urban bus engines and promoted advancement of the cleanest technologies—specifically, zero emission buses (ZEBs).

The ruling required transit agencies to choose a compliance path—alternative fuel or diesel—for meeting emission standards. The selection determined the fuel type for new bus acquisitions through model year 2015. 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).

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

Table 2. Fuel Cell Transit Bus Demonstrations – Overview

Project Dates	Status	Project	Description
1998	Complete	FTA/Georgetown	40-ft FCB operating on methanol using 100 kW PAFC from UTC Fuel Cells
1994-1995	Complete	FTA/Georgetown	Three 30-foot FCBs operating on methanol using 100 kW phosphoric acid fuel cell (PAFC) stacks from Fuji
1998-2000	Complete	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	Complete	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	Development	FTA/Georgetown	40-foot FCB operating on methanol using 100 kW PEM fuel cell stack from Ballard
2002-2003	Complete	ISE/UTC ThunderPower	ThunderPower 30-foot FCB operating on compressed hydrogen using 60 kW PEM fuel cell stack from UTC Fuel Cells at SunLine and AC Transit
2003-2005	Complete	CUTE, ECTOS, STEP	Demonstration project in Europe, Iceland, and Australia including 33 FCBs using Ballard PEM fuel cell stacks and compressed hydrogen in 40-foot buses
2003-2006	In-service	Hino/Toyota FCB - JHFC	Demonstration project in Japan including eight hybrid FCBs with Toyota PEM fuel cell stacks
2004-2006	In-service	VTA	Demonstration project in San Jose, California: three FCBs using Ballard fuel cell stacks and compressed hydrogen in 40-foot buses
2004-2006	In-service	UNDP-GEF China	Demonstration project in China: three FCBs using Ballard PEM fuel cell stacks and compressed hydrogen in 40-foot buses
2004-	In-service	SunLine	Demonstration project in Thousand Palms, California: one FCB using UTC fuel cell stack and compressed hydrogen in a 40-foot bus at SunLine Transit Agency
2004-	In-service	Hickam AFB	Demonstration project in Honolulu, Hawaii: one battery dominant, plug-in hybrid, FCB with Hydrogenics PEM fuel cell and Enova hybrid system
2005-2007	In-service	AC Transit	Demonstration project in Oakland, California: three FCBs using UTC fuel cell stacks and compressed hydrogen in 40-foot buses
2006-2007	In-service	HyFLEET CUTE	One-year extension of the demonstration of the Citaro/Ballard FCBs in Europe, Iceland, China, and Australia and new demonstration of 14 hydrogen fueled internal combustion engine buses (MAN) in Berlin, Germany
2006-	In-service	NRCan/Hydrogenics	Demonstration of one hybrid FCB using Hydrogenics PEM fuel cells (Canada)
2007-2010	Planning	FTA NFCBP	Demonstration of FCBs in the US to advance the commercialization of the technology. Competitive solicitation to award $49M over four years to a selection of projects.
2007-	Planning	UNDP-GEF Brazil	Demonstration of five hybrid FCBs in Sao Paolo, Brazil
2008-	Planning	BC Transit	Operation of 20 hybrid FCBs in British Columbia, Canada for the 2010 Olympics

Fleets choosing the diesel path were required to reduce the fleet average emissions through methods such as purchasing the cleanest diesel engines and retrofitting existing diesel engines with emissions control devices (i.e., diesel particulate filters). All transit agencies with 200 or more buses were subject to demonstrate and eventually procure ZEBs as 15% of all new bus purchases. Fleets choosing the diesel path were scheduled to meet these requirements on a more accelerated timeline than fleets on the alternative fuel path. 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 chose the alternative-fuel path are not required to purchase ZEBs at the 15% 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.

In June 2004, the regulations for the ZEB demonstration were modified, adjusting the required dates for the demonstration sites and clarifying how multiple transit agencies could execute the demonstrations 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 legislation.

Since the FCB demonstrations began, CARB has gathered data and experiences from California fleets (including VTA) demonstrating FCBs. Based on the early results, the board is considering further modification of the rules concerning ZEBs[3]. Although progress has been made in developing and demonstrating ZEBs, this progress has not been as rapid as initially projected. For example, the current purchase price of fuel cell buses is more than five times that of diesel buses. Purchasing 15% ZEBs under the current requirements would severely impact transit agency operations and the ability to provide public transportation.

CARB is proposing modifications to the rule including an advanced demonstration program for ZEBs and a delay of the 15% purchase requirement. The advanced demonstration would be required by fleets on the diesel path beginning in 2009. Fleets could use FCBs from the current demonstration programs to meet the requirements of this advanced demonstration, but only if they are upgraded with advanced fuel cell systems representing the latest state of the art. The requirement for purchasing ZEBs would begin in January 2011 for diesel path fleets and January 2012 for alternative fuel path fleets. For more information on the ruling, go to www.arb.ca.gov/msprog/bus/zeb/zeb.htm.

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 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 exceeded $295 million in fiscal year 2005. It is directed by a 12-member board of directors. VTA operates 427 buses (345 buses in peak demand) and 100 light rail vehicles. In fiscal year 2005, annual ridership exceeded 37

[3] California Environmental Protection Agency Air Resources Board, Staff Report: Initial Statement of Reasons, Proposed Amendments to the Zero Emission Bus Regulations, September 1, 2006.

million in a service area covering approximately 326 square miles (see Figure 2). In December 2000, the organization adopted a Clean Fuels Strategy that 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 in 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 as well as 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

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 ($5.1 million) for the purchase of the buses used in the demonstration, FTA provided guidance in the evaluation strategy.
- **DOE** provided funding directly to VTA 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 and provides technical support for maintaining the buses.
- **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. Gillig also provides technical support for these buses.
- **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 at VTA and supplies the liquid hydrogen fuel used in this project. Air Products also owns the VTA station and is responsible for its maintenance.
- **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 lease contract to Air Products to install and maintain a hydrogen fueling facility at VTA's Cerone Operations Division. Construction began in September 2003, and the station was completed by May 2004. VTA constructed a pad with the appropriate utilities including power and communication. Other demonstration-related construction projects included a new bus wash facility to accommodate the hydrogen fuel cell buses, which are 24 inches taller than the diesel 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 on February 28, 2005.

Ballard Fuel Cell Development and Testing

Ballard Power Systems, Inc. (www.ballard.com) is headquartered in Burnaby (near 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 (Table 4). 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 focuses on reducing cost, increasing durability, improving freeze start, and increasing power density.

Table 4. 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 60-passenger bus used 20 fuel cell stacks and 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 60-passenger bus 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; 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 demonstration to date. Under funding from the European Union (EU), DaimlerChrysler and Ballard embarked on an 11-city fuel cell bus implementation and demonstration program, which included 33 Mercedes-Benz Citaro buses. The goals of the project included:

- Demonstrate fuel cell buses and hydrogen infrastructure in parallel to provide regular transit service

- Investigate the potential of providing hydrogen mainly using renewable resources
- Determine if the buses and infrastructure could meet availability rates of conventional technologies
- Assess the level of acceptance of the technology in the general public and transit staff
- Demonstrate the safe use of hydrogen fuel.

The timeframe for this phase was 2002 through 2006. Each of the following 11 cities was part of the demonstration, operating three buses per site:

- 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 (ECTOS)
  - Reykjavik, Iceland
- Sustainable Transport Energy for Perth (STEP)
  - Perth, Australia.

The first of these FCBs was placed in service for the ECTOS project in Reykjavik, Iceland. The project partners presented the results of the two-year demonstration in April of 2005. (Project reports are posted online at http://newenergy.is/en/projects/finished_projects/ectos.) The results from the two-year CUTE demonstration were presented at a conference in Hamburg, Germany on May 10–11, 2006. The presentations from the conference are available online at www.cute-hamburg.de/. A report detailing the achievements of the nine fleets in the CUTE project was published in late summer 2006. This report is located in the publications section of the CUTE Web site at www.fuel-cell-bus-club.com. During the CUTE project, the buses operated for over 850,000 kilometers (over 526,000 miles) and 62,000 fuel cell system hours. The project partners learned many valuable lessons, which are outlined in the reports.

An additional three Citaro fuel cell buses with the Ballard fuel cell system were placed into service in Beijing, China in June 2006. This project was co-funded by the United Nations Development Program/Global Environment Facility (UNDP-GEF). The buses in service are identical to the buses used for the CUTE project. The demonstration in China involves two cities, Beijing and Shanghai. The Beijing demonstration is Phase 1 of the project. The goals are to accelerate the commercial application of FCBs in China and to promote a "Green Olympic Game" in Beijing in 2008. For Phase 2, a next generation FCB will be procured to operate in Shanghai.

HyFLEET:CUTE—After the original two-year CUTE project, an extension of one year of operation was approved with continued funding from the EU. Ten cities on three continents are participating in this project to demonstrate hydrogen fueled buses. The demonstration includes hydrogen fueled internal combustion engine (ICE) buses as well as the FCBs introduced in the previous CUTE project. The additional year of operation for the existing FCBs has the general objectives of getting more operating experience and possibly taking the fuel cell propulsion system to failure. The fuel cell buses from two cities not participating in the additional operation were transferred to Hamburg, giving the fleet a total of nine buses. Participating cities include:

- Fuel Cell Bus
    - Amsterdam, Netherlands
    - Barcelona, Spain
    - Beijing, China
    - Hamburg, Germany
    - London, England
    - Luxembourg, Luxembourg
    - Madrid, Spain
    - Perth, Australia
    - Reykjavik, Iceland
- Hydrogen ICEs (manufactured by MAN)
    - Berlin, Germany.

VTA Fuel Cell Bus Demonstration—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 are significantly different than the Mercedes-Benz Citaro buses used for the other Phase 5 sites.

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 137 buses operating seven days a week plus the three ZEBs. 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 hydrogen fueled 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 for the installation and lease of the fueling facility. Under the capital lease agreement for the facility (Figure 3), Air Products retains ownership of the equipment at the facility and is required to maintain the facility. VTA constructed the concrete pad with all the necessary utilities, including power, grounding, communications etc., in accordance with Air Products requirements.

Figure 3. Compressed hydrogen dispensing station at VTA's Cerone Operations Division

Construction of the station began in September 2003, and the station was completed in May 2004; however, actual hydrogen dispensing at the station did not start until November 2004. For the installation and lease of the fueling station as well as applicable training, VTA paid Air Products approximately $480,000 up front and has monthly payments for three years (about $4,400 per month). This amounts to a grand total of approximately $640,000 for the station.

This does not include the cost of the hydrogen fuel delivered. The fueling facility was designed to operate six hydrogen fuel cell buses. Cost factors reduced the number of buses to three.

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 six-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 preset pressure, the compressor is activated and continues fueling the buses to the maximum fill level. The cascade tanks are also refilled during this process.

The hydrogen dispenser (Figure 4) is equipped for a communications fill. The communications allow for monitoring tank pressure and temperature, and the cable also provides a connection to electrical 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 5 shows the fueling hose and the communications connections on the bus during a fill.

Figure 4. Hydrogen dispenser

Figure 5. Hydrogen fueling connection (left) and communications connection (right) on the FCB

The station design includes two compressors to avoid downtime for the fleet. This allows the station to continue operation when one of the compressors undergoes scheduled maintenance or experiences a failure. As a newer and experimental Air Products design, one of the compressors can provide a fast fill in about eight minutes (designated as prototype compressor in the following discussion). The other compressor is a reliable, proven design that provides a full bus fill in less than 20 minutes (designated as the primary compressor).

To ensure high reliability and safety, the station includes numerous devices to alert VTA and Air Products of potential problems. These devices include flame, earthquake, pressure, and temperature sensors; alarms; and emergency stop (E-stop) buttons (Figure 6) that are monitored on site by VTA and remotely by Air Products. When activated, these devices will shut down the system and close the liquid tank valves.

Figure 6. Flame sensors (left and top) and emergency shut-off (right) at the hydrogen dispensing facility

VTA uses its two assigned fuel cell bus mechanics to dispense hydrogen into the buses. To ensure safety, only trained personnel are authorized to dispense hydrogen from the station. The Ballard assigned mechanic and Air Products staff can also work with the hydrogen dispensing equipment. VTA's facility maintenance staff is also familiar with the facility and can respond to trouble notification, as required.

Early Experience with Hydrogen Dispensing—Operating and maintaining the requisite hydrogen fueling infrastructure for the fuel cell bus demonstration was 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 primary compressor failed, causing a liquid hydrogen leak that subsequently ignited. This thermocouple monitors the discharge temperature and controls the compressor. The system was going through checkout and commissioning at the time of the leak, and the E-stop was activated within seconds. In addition, system safety controls automatically activated the liquid tank's emergency shutoff valves. 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 design defect in the thermocouple. All thermocouples of that type and manufacturing batch were replaced, including units installed at two other facilities. Although no major damage resulted from the fire, the station was 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, also caused delays to VTA's station operation. Procedures in place required the fire department to be directly contacted in the case of a fire alarm without independent alarm verification by personnel. This revealed issues that could be avoided at future stations by modifying the standard procedure. The majority of the alarms were traced to one of the following causes:

- **Power Loss**: In the case of a power loss, safety systems at the VTA facilities are placed on a back up power supply. Originally, when power was restored, the system would remain on the back up power supply, including the safety systems, until they were manually reset to the standard grid power supply. As this was unknown by VTA and Air Products personnel on site, a temporary power loss occurred, but the system wasn't manually reset. This condition caused the back up power supply to be drained and the fail-safe safety system to alarm. On two occasions, false alarms were determined to be caused by temporary power losses at the fueling station. This has been changed so that when power is restored, the safety system is automatically returned to grid power and the back up power supply is recharged.

- **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 as far as 400 feet away, most likely caused the false alarms. This experience resulted in the development and installation of improved flame detectors as well as the implementation of new procedures.
- **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 was installed. This new detector greatly improved reliability and reduced the number of false alarms.

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. It involved 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. The local E-stop, or remote shut down using the electrical breaker, was not activated by personnel on site; however, this would not have stopped the leak. Additionally, a faulty fire alarm pull box did not signal the fire department.

The second incident, which occurred in February 2005, involved a small leak and vapor cloud at the fueling facility. The leak occurred at the prototype 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 primary cryogenic compressor. Repairs were made to fix the leak and the prototype cryogenic compressor was returned to service.

The third incident occurred during a bus fueling at the station in May 2005. The prototype 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 prototype compressor kept running even though the cascade tanks were not filling and venting continued. When the prototype compressor shut down, the primary system came online as back up. VTA personnel then noticed a leak and vapor cloud at the primary compressor. VTA personnel shut down the entire system using the E-stop button. An Air Products technician corrected the primary compressor leak to get the system back online. The prototype compressor needed more extensive repairs, necessitating the continued use of the primary compressor.

Although these issues were addressed and resolved, use and operation of the hydrogen station caused 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.

By the time the buses were placed in service, many of the early issues and problems had been resolved. Hardware modifications, software updates, and changes to procedures for operating and maintaining the station helped resolve many of the issues. Since February 2005, there have been several other minor incidents involving leaks or excessive venting; however, many of those incidents were isolated to the newer design (prototype) compressor. Because the primary compressor was not affected, the fueling station was still operational. In all, there were seven events classified as leaks in the system from station commissioning through July 2006. Only four of these incidents occurred after the buses went into service. The system experienced only four shutdowns during this time, resulting in a combined total of four days when the station was not available for fueling the three fuel cell buses. Of the total 11 false alarms at the station, only five occurred after the buses went into service.

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. While the prototype compressor has had multiple issues resulting in failures and major downtime, the primary compressor has proven to be extremely reliable. The prototype (newer design) compressor is in testing by Air Products. The early experience with this prototype compressor has provided them with valuable data to enable further optimization and design modifications.

Hydrogen Fuel Dispensing Analysis—The first liquid hydrogen fuel shipment occurred in May 2004. This fuel was used to test the fuel station systems. Actual bus fueling did not start until November 2004. Through July 2006, the fueling station had 31,836 kg of hydrogen delivered; 14,024 kg of hydrogen were dispensed into buses. Originally designed for the operation of six fuel cell buses, with only 3 buses, station use has been less than anticipated with the original design. This has potentially affected hydrogen loss due to boil-off. With the buses operating since late February 2005, vent and boil-off losses have been at 50%. Air Products reports that if the station throughput had been greater, the hydrogen losses would have been significantly reduced.

Figure 7 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 April 2005, the fueling times improved considerably, with fill times averaging between 12 and 18 minutes. During the 17-month evaluation period, the hydrogen dispensing station provided 460 fuelings with an overall average fill at 16 minutes, 30.9 kg/fill, and 1.93 kg/min. According to Air Products, further optimization of the station could result in reductions in fueling time. Figure 8 shows a histogram of fueling rates for the buses since the station began operation in November 2004.

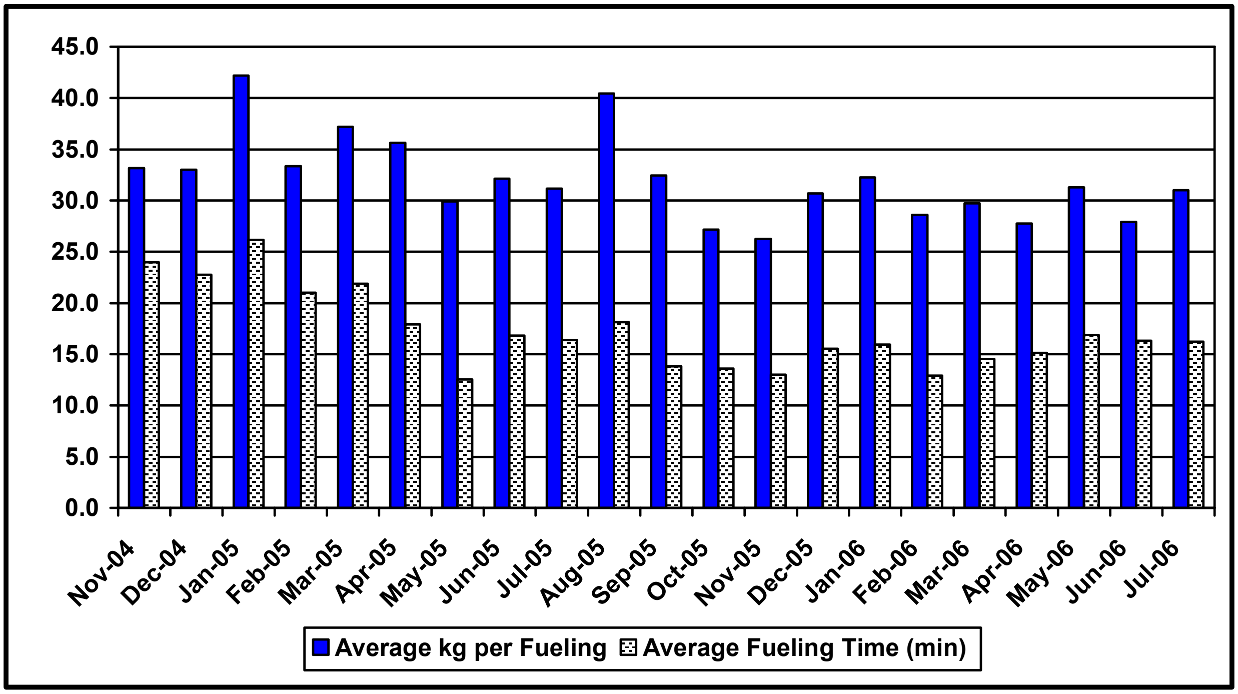

Figure 7. Average hydrogen fueling amounts and average fueling time

Figure 9 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, but came back down again in March 2006. The average hydrogen cost delivered to the station during the evaluation period was $9.06 per kg. This equates to an approximate cost of $10.24 per diesel equivalent gallon. Based on the loss of hydrogen due to venting and boil-off, the cost of hydrogen fuel might be considered to be double ($18.19 per kg).

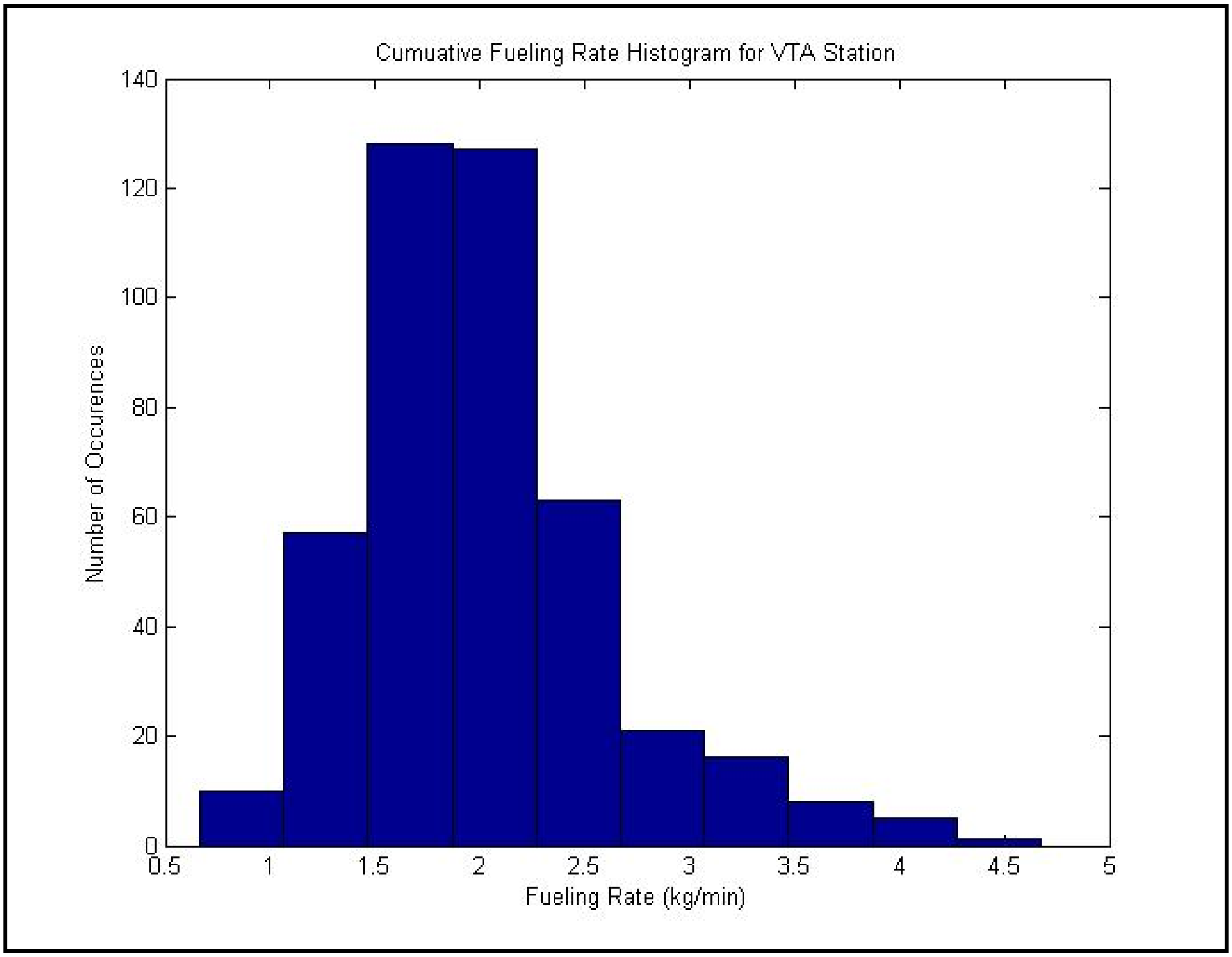

Figure 8. Fueling rate histogram for VTA hydrogen station

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 10. 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 (as it did in the rest of the country). The average diesel fuel cost per gallon for the evaluation period was $2.07.

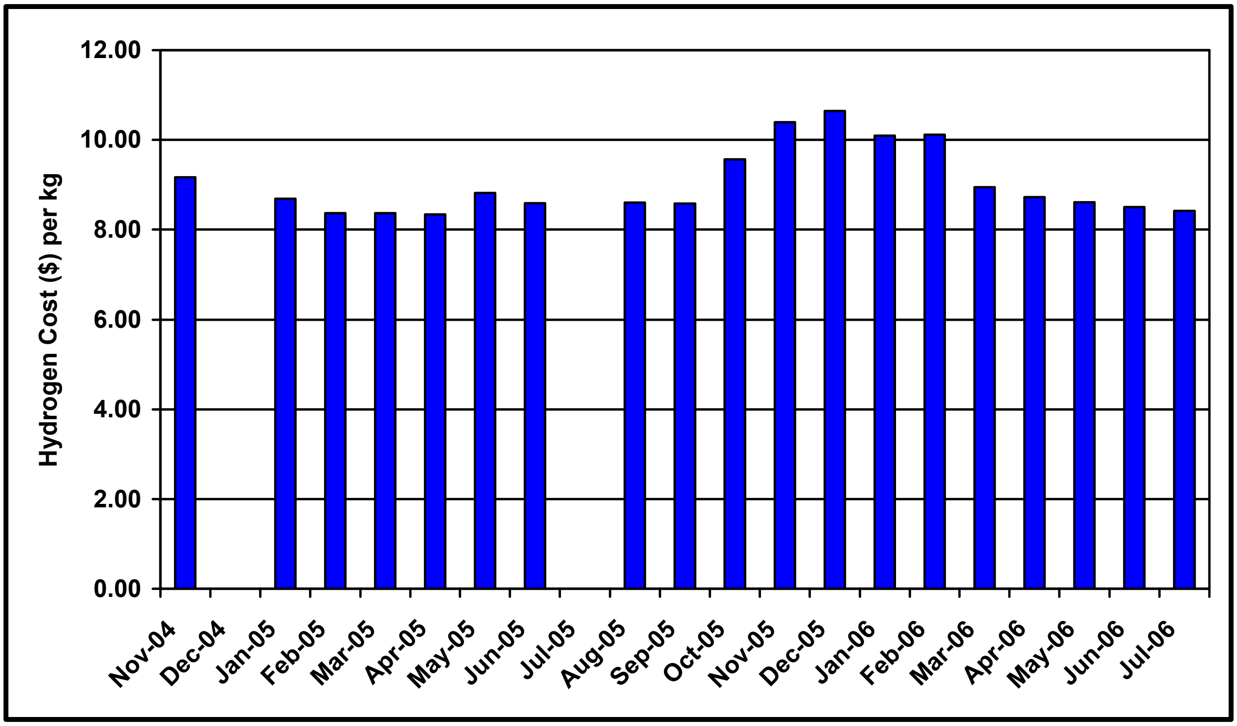

Figure 9. Average fuel cost ($/kg) for liquid hydrogen delivered to VTA station

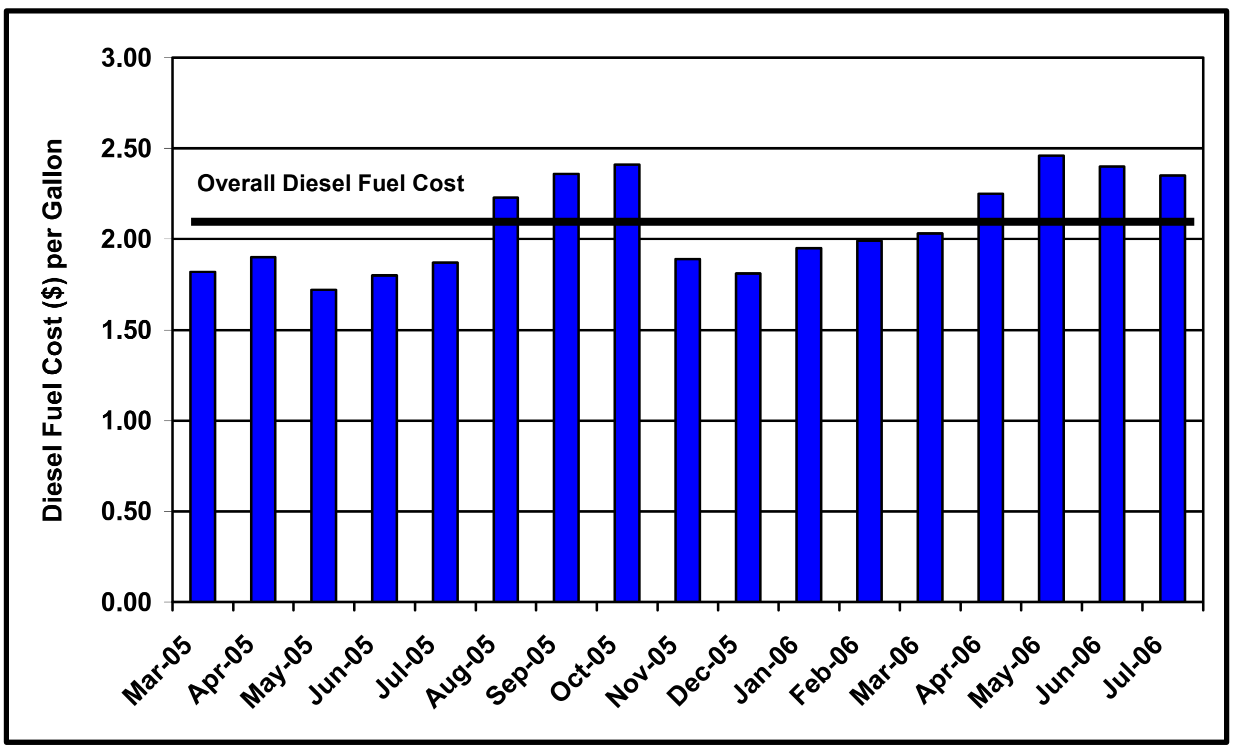

Figure 10. Average diesel fuel cost ($/gallon) at VTA (March 2005 through July 2006)

Hydrogen Bus Maintenance Facility

A separate maintenance facility was 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, without the requirement for de-fueling or purging, in accordance with building codes and the fire marshal's requirements. This two-bay facility, shown in Figure 11, 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 of hydrogen vehicles. The building is equipped with Class I Div. II electrical fixtures, a hot water heating system, hydrogen and flame sensors, and an anti-static coating on the doors. When sensors detect significant amounts of 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. At 50% LFL (2% hydrogen in air), electrical systems (except safety systems) are shut down and evacuation is required. It should be noted that the only source of hydrogen in this facility is the fuel cell bus. Therefore, if no bus is in the building, an activation of a hydrogen alarm would be a false alarm.

The new bus wash (Figure 12), 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 roof design also allows for proper ventilation and any hydrogen release to escape safely.

Figure 11. Maintenance facility used for the fuel cell buses at VTA

Control panels for the wash operation within the bus wash facility were required to have an active nitrogen purge within the panel to keep any hydrogen away from the electronics within the sealed control panel. One of the control panels was moved outside of the bus wash facility to remove the need for the nitrogen purge. The total cost for adding these three facilities to meet the requirements of operating the hydrogen fuel cell buses was $4.4 million.

Figure 12. Bus wash

Experience with Maintenance and Bus Wash Facilities – VTA encountered several challenges in adding these new buildings to the site. The maintenance building was one year behind schedule and it took much longer to get the building approved for use by safety officials. The majority of the building construction was completed in June 2005; however, the fleet did not get approval for use until November of that year. Early issues with the fueling station caused officials to be extra cautious regarding safety in the maintenance facility. VTA also had difficulties getting the required hydrogen sensors delivered and installed in the building. Once the system was installed, there were additional difficulties with communications between the sensors and control panel, causing further delays.

There have been several incidents (through July 2006) in the maintenance facility since it was approved for use. In one incident, the 15% LFL alarm was triggered during a preventive maintenance (PM) inspection of a fuel cell bus. The 7,500 mile PM for the FCB requires a test of the purge system on each fuel cell. During the test, the bus is operated while the purge valve is open. To expedite the process, the maintenance staff purged both fuel cell stacks simultaneously. This continuous purging of both stacks proved to be in excess of what the hydrogen diffuser on the bus could handle, allowing the hydrogen level to rise above the 15% threshold for the sensors. (In this case, the bus was parked such that the diffuser was almost directly under a hydrogen sensor.) An alarm was activated, which triggered the doors to open and facility ventilation to increase. Maintenance staff turned the bus off and checked the monitors for hydrogen level, which dropped from 13% LFL to zero in seconds. The safety systems in the maintenance facility worked as designed. The staff alerted the authorities that no emergency response was necessary and continued the PM. For future tests of the purge system, each fuel cell was tested separately. There have been several other incidents where the 15% LFL alarm was triggered. It was found that these were false alarms and were caused by faulty sensors. The sensors have been replaced.

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 Burnaby (near 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). This price includes system integration engineering, a two-year warranty, parts, training, and support from Gillig and Ballard.

Table 5 shows a summary of vehicle system descriptions for the fuel cell and diesel baseline study groups of buses. Figure 13 shows both types 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 at VTA about clearance. 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 transit bus transmission with an integral retarder. Neither the diesel nor the fuel cell buses have hybridized systems, and therefore do not have regenerative braking or additional energy storage. Table 6 provides more information on the fuel cell propulsion system.

Table 5. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	Operation from Cerone Depot	
	Fuel Cell Buses	Diesel Buses
Number of Buses	3	5
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

Figure 13. Fuel cell bus (left) and diesel bus (right)

Table 6. Additional Fuel Cell Propulsion System Descriptions

Propulsion Systems	Fuel Cell Buses
Manufacturer/Integrator	Gillig/Ballard
Drive System	Fuel cell power plant, 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 conducted some performance testing of the fuel cell buses. Testing was completed on fuel cell bus 4002 in May 2005. The maximum speed was demonstrated as 70 mph. Fuel efficiency testing was completed on a test route to maximize operation near 55 mph. This testing included 105 miles of operation and a fuel efficiency of 5.3 miles per kg of hydrogen, which indicated a maximum range of 275 miles.

Acceleration testing (based on the APTA Standard Bus Procurement Guidelines requirement) was completed on all three fuel cell buses in March 2006. This testing was done at gross vehicle weight for the buses. Table 7 shows the expected times to reach 20, 30, and 40 mph along with the actual average times to reach those speeds. These average times for fuel cell bus acceleration were better than the requirement for all three speed milestones.

Table 7. Fuel Cell Bus Acceleration Testing Results (March 2006)

Speed (mph)	Target Time (sec)	Tested Average Time (sec)
20	11.0	9.1
30	20.0	16.5
40	31.0	28.0

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 had a mechanic on site at VTA since the buses were delivered through the end of warranty support in July 2006. The VTA FCB mechanics maintain and support all aspects of the FCB operation including:

- Vehicle, fuel cell module, and fuel system inspections
- Hydrogen fueling
- Bus cleaning
- All vehicle maintenance (also supported by the Ballard technician)
- Parts management
- Coordination and troubleshooting with Ballard technical support (in Canada)
- Coordinating with visitors and fire department personnel.

VTA's procedure for operating the fuel cell buses includes a pre-trip inspection by a VTA FCB mechanic while the fuel cell systems are "warming up." 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 and 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.

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.) and inverter. 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.

At the end of the work day for a FCB, the VTA FCB mechanics take the bus and fill it up with hydrogen at the dispensing station and then re-park the buses in their specified parking spots near the hydrogen maintenance facility (Figure 14).

Figure 14. Fuel cell buses parked at the maintenance facility

Early Experience with VTA's Fuel Cell Buses

Because fuel cell bus technology is new to the transit 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 (November 2004 through February 2005). This test mode operation was conducted 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 VTA staff and conducting 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 roof-mounted on the fuel cell buses add 24 inches to the height of a standard bus. The added height meant the buses did not fit through VTA's existing bus wash. A 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 (and isolate the fuel tanks) if a collision occurs. VTA inspected 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 typical 40-foot buses, the fleet has to limit the number of standing passengers to meet weight requirements. This could be an issue when operating on 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 were not always easy to obtain. Waiting for these replacement parts can potentially increase downtime for the fuel cell buses. Ballard carefully monitored 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 worked together to successfully minimize this potential downtime due to parts availability during the evaluation period.

- **Hydrogen release:** VTA restricted operation of the buses on several routes that traveled under a shopping mall and included a stop under the mall. The concern was the release of hydrogen (caused by a PRD) while at that location.

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 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 for 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 from Ballard on the fuel cell propulsion system and 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 card was produced for emergency responders showing the locations of specific equipment and places where it would be dangerous to cut into the bus.

VTA accommodates requests for tours and brings the buses to events as time and resources allow. Such events, tours, and presentations 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 at a Santa Clara County Fuel Cell Working Group 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 1-2, 2005**: VTA participated in United Nations World Environment Day in San Francisco by displaying the ZEB and providing related information. International VIPs, 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 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 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, California. The ZEB was on display and program materials were provided to 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. VTA staff gave a presentation on the ZEB program and provided related materials.
- **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." Bagly visited VTA's Cerone facility to learn about ZEBs.
- **February 27, 2006**: VTA hosted fire fighter training for the San Jose Fire Department. The training provided a refresher to a number of fire fighters and familiarization to others recently assigned to local departments. Ballard and Air Products personnel were also on hand to answer questions.
- **March 8, 2006**: VTA hosted a tour and presentation for BC Transit. The transit agency is gathering information on FCBs as they prepare to procure and operate up to 20 FCBs in the Vancouver/Whistler area in time for the 2010 Winter Olympics.
- **March 13, 2006**: VTA hosted a visit by "Drive Around the World" as they prepared for a trip to the South Pole using a fuel cell Hummer. The team took pictures of the ZEB and fuel cell systems and discussed the design plans for the fuel cell vehicle.
- **March 23, 2006**: A GMC fuel cell vehicle and a Marine Corps fuel cell truck were fueled at the VTA station.
- **April 22, 2006**: VTA provided a ZEB for display during President Bush's visit to the California Fuel Cell Partnership.
- **April 18, 2006**: VTA staff participated in Earth Day celebration at San Jose State University.
- **May 24, 2006**: VTA staff participated in the official opening of Highway 85 and 1.01 interchange. A ZEB was used for shuttle service and display.
- **June 6, 2006**: VTA hosted a tour and presentation for Air Products Management.

- **June 8, 2006**: VTA staff provided a ZEB progress report and tour to the Technical Advisory Committee to the VTA board.
- **July 13, 2006**: VTA hosted a tour for representatives from the Mineta Institute for Transportation.
- **August 9, 2006**: VTA hosted a tour for Transmetics.
- **August 29, 2006**: VTA hosted a tour and bus review for the Federal Motor Carrier Safety Administration.
- **October 10, 2006**: VTA hosted a tour for participants at the APTA Annual Meeting in San Jose.
- **October 10, 2006**: VTA hosted a tour for EU delegates, former Secretary Norman Mineta, Mayor Gonzales, EU Ambassador Angelos Pangratis, and other dignitaries.

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 extra revenue service from the Cerone Operating Division. This report provides analysis and discussion focused on a data period including March 2005 through July 2006. Some results and discussion presented in this report 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 focuses on documenting progress and opportunities for improvement of the vehicles, infrastructure, and procedures.

Route Descriptions

VTA operates 71 fixed bus routes, 11 of which are express service. VTA also operates one bus rapid transit line and 14 shuttle service 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 8. All standard buses at Cerone are randomly dispatched on routes.

Table 8. Summary of Total Weekly Bus Usage from Cerone

Day of Week	Total Miles	Hours	Avg. Speed
Weekday	22,061	1,527	14.4
Saturday	11,294	776	14.6
Sunday	9,600	667	14.4
Weekly Total	**131,200**	**9,078**	**14.5**

For demonstrating this advanced technology, the fleet chose to use the three fuel cell buses for "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 time in the event of a fuel cell bus failure. The three 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 also 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. These blocks have changed over time to enable the fuel cell buses to operate on several VTA routes and experience different types of operation. 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 assignments is shown in Table 9. The fuel cell buses have generally been used at an average speed (approximately 12.6 mph during the evaluation period) that is slightly less than the fleet average for the diesel buses at Cerone.

Table 9. Route Block Assignments for the Fuel Cell Buses

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

Bus Use and Availability

Bus use and availability are indicators of reliability. 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 15 shows mileage and fuel cell system operating hour accumulation from the start of hydrogen fueling in November 2004 through July 2006. 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 to weekdays and extra service within an 8-hour shift. Other limiting factors included maintenance issues and the availability of trained drivers and mechanics for the fuel cell buses.

Table 10 summarizes average monthly mileage accumulation by bus and study group for the evaluation period. The three fuel cell buses accumulated 40,429 miles in the 17-month evaluation period and 3,219 hours on the fuel cell systems. This equates to an average operating speed for the fuel cell buses of 12.6 mph, which is slightly slower than the overall (diesel bus) average speed for Cerone buses (14.5 mph). Average monthly mileage per fuel cell bus was 809 miles during the evaluation period.

The diesel study buses were operated in normal VTA service from Cerone, including weekend operation. The average monthly mileage per bus during the evaluation period was 4,335 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 similar to that experienced during the evaluation period.

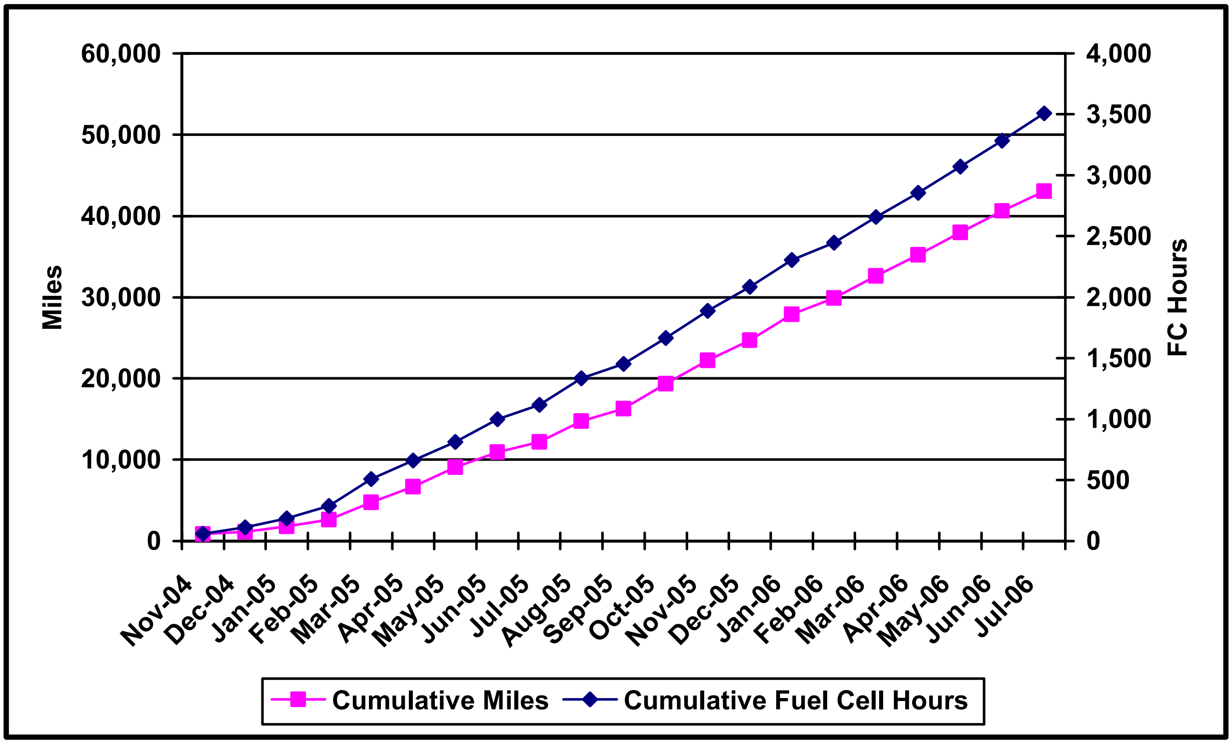

Figure 15. Cumulative mileage and fuel cell hours for three fuel cell buses

Table 10. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage	Fuel Cell System Hours
4001	7,930	21,469	13,539	17	796	1,109
4002	959	14,514	13,560	16	848	1,075
4003	954	14,284	13,330	17	784	1,035
Fuel Cell			**40,429**	**50**	**809**	**3,219**
2229	134,738	203,719	72,275	17	4,251	N/A
2230	115,857	191,778	75,921	17	4,466	N/A
2231	130,452	205,917	77,688	17	4,570	N/A
2232	122,086	195,148	73,062	17	4,298	N/A
2233	134,142	203,690	69,548	17	4,091	N/A
Diesel			**368,494**	**85**	**4,335**	**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 unavailable for service due to any maintenance issues (weekends were included in the calculation). During the evaluation period, the diesel buses had an availability rate of 85%. VTA's goal is 80% for diesel buses.

During the evaluation period, the fuel cell buses had an availability rate of 58% for each weekday, with a goal of 67%. 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 87% of the time. Figure 16 shows monthly average availability for the fuel cell buses. Figure 17 shows a breakdown of the general causes of the fuel cell buses being unavailable for service. As shown in Figure 16, the fuel cell buses met (or nearly met) the VTA availability target of 67% during seven of the 16 evaluation months. Each of the fuel cell buses had a similar availability rate, which averaged between 57% and 59% during the evaluation period. This is an indication of VTA's intent to use all three fuel cell buses in a similar manner and as much as possible.

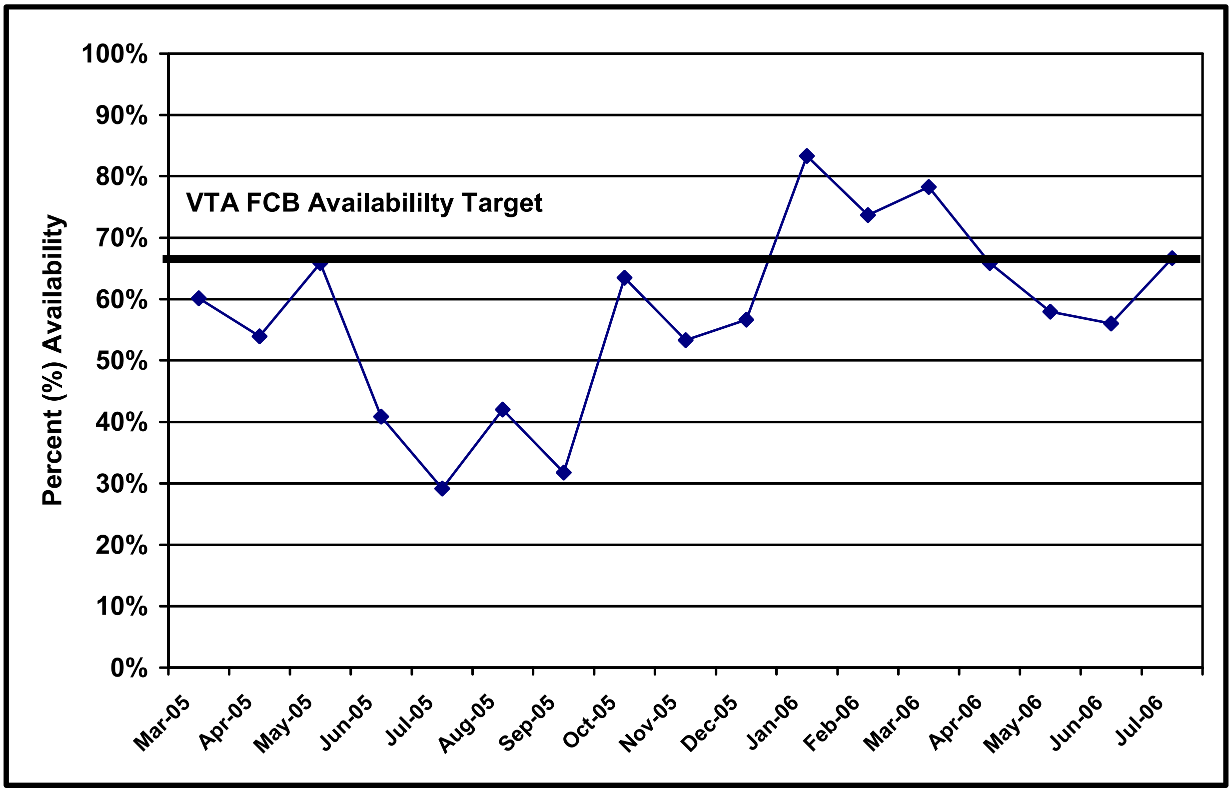

Figure 16. Fuel cell bus monthly average availability

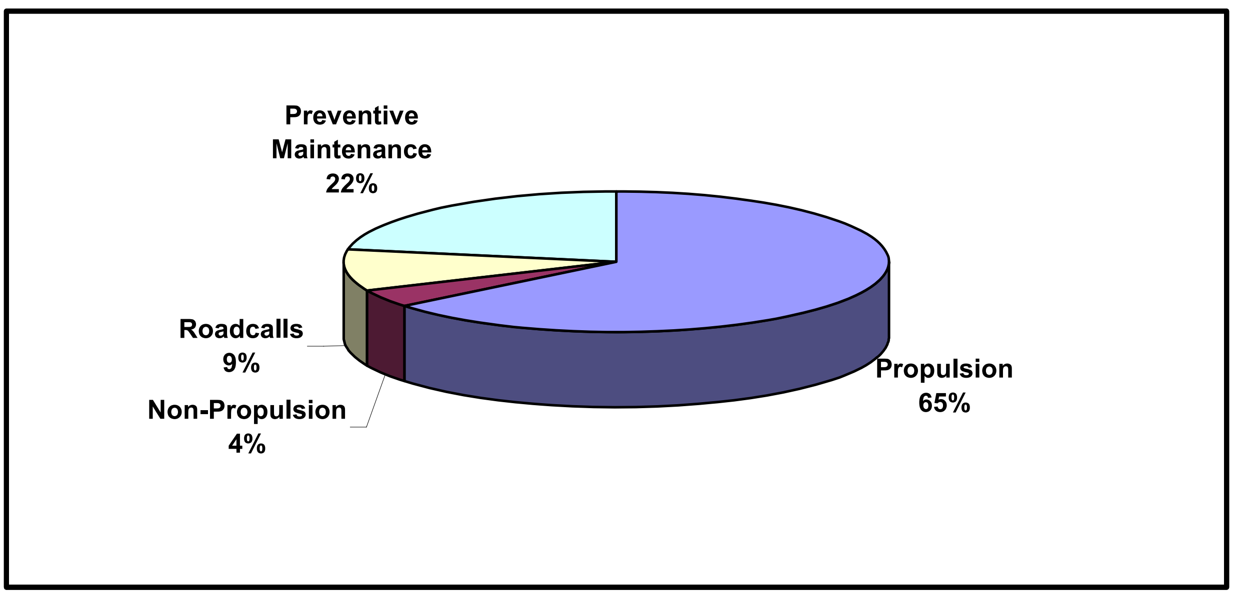

Figure 17. Breakdown of causes for fuel cell buses being unavailable for service

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 dispensing 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 are shown at the end of the Appendix.

Table 11 shows hydrogen and diesel fuel consumption and fuel economy for the two study groups during the evaluation period. The fuel cell buses averaged 3.12 miles per kg of hydrogen, which translates into 3.52 miles per diesel equivalent 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 3.98 mpg. With diesel as the baseline, the fuel cell buses had a fuel economy that was 12% lower on an energy equivalent basis (note that these fuel cell buses do not use a hybrid propulsion configuration). Figure 18 shows average monthly energy equivalent fuel economies throughout the evaluation period for the fuel cell and diesel buses.

Table 11. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (Gallon)	Miles per Gallon
4001	13,539	4,528	2.99	4,007	3.38
4002	13,339	4,232	3.15	3,745	3.56
4003	13,330	4,144	3.22	3,668	3.63
Fuel Cell	**40,208**	**12,904**	**3.12**	**11,420**	**3.52**
2229	67,717			16,762	4.04
2230	75,760			19,329	3.92
2231	74,360			18,444	4.03
2232	73,062			18,751	3.90
2233	69,548			17,217	4.04
Diesel	**360,447**			**90,503**	**3.98**

As reported earlier, the average cost of hydrogen during the evaluation period was $9.06 per kg of hydrogen and the average cost of diesel fuel was $2.07 per gallon. These average fuel costs translate into a fuel cost per mile of $2.91 for the fuel cell buses and $0.52 per mile for the diesel buses. If hydrogen fuel losses at the station are taken into account, the fuel cost per mile for the fuel cell buses would essentially double.

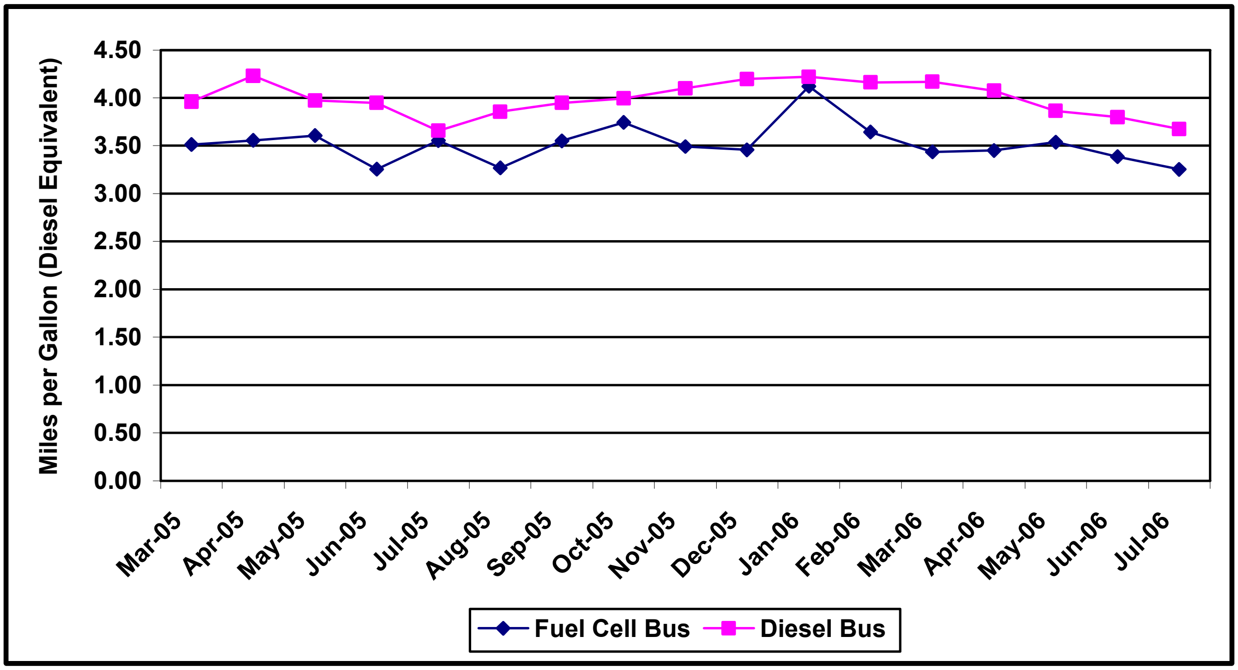

Figure 18. Average fuel economy (mpg) by month

Maintenance Analysis

The maintenance cost analysis in this section is only for the evaluation period (March 2005 through July 2006) for the two study groups of buses. Warranty costs are not included in the cost-per-mile calculations, but are shown separately. 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; 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 12 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; however, since then, bus 4002 has had usage increased up to the same level as the other two for the evaluation period. The overall average maintenance cost per mile for the fuel cell buses was $3.55.

Table 12. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Warranty Parts ($)	Parts ($)	Labor Hours	Cost per Mile ($)
4001	13,539	96,128.21	295.61	832.2	3.10
4002	13,560	190,566.36	1,179.43	986.3	3.72
4003	13,330	250,767.74	183.14	1,018.9	3.84
Total Fuel Cell	**40,429**	**537,462.31**	**1,658.18**	**2,837.4**	**3.55**
Avg. per Bus	**13,476**	**179,154.10**	**552.73**	**945.8**	**--**
2229	72,275	1,238.75	12,359.35	669.7	0.63
2230	75,921	7,156.86	9,705.95	540.3	0.48
2231	77,688	1,981.25	11,414.94	536.5	0.49
2232	73,062	3,909.44	11,919.28	541.8	0.53
2233	69,548	1,059.14	13,202.74	540.8	0.58
Total Diesel	**368,494**	**15,345.14**	**58,602.26**	**2,829.1**	**0.54**
Avg. per Bus	**73,699**	**3,069.03**	**11,720.45**	**565.8**	**--**

Warranty costs listed are those that were available for the data collection and evaluation. 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. Figure 19 shows monthly total warranty costs for parts over the evaluation period. The three peaks (October 2005, April 2006, and June 2006) in this chart are almost entirely costs for replacing fuel cell rows. This will be discussed more in the propulsion-related maintenance section below. VTA reports that some of the warranty parts costs may not be accounted for in this chart, but the vast majority are.

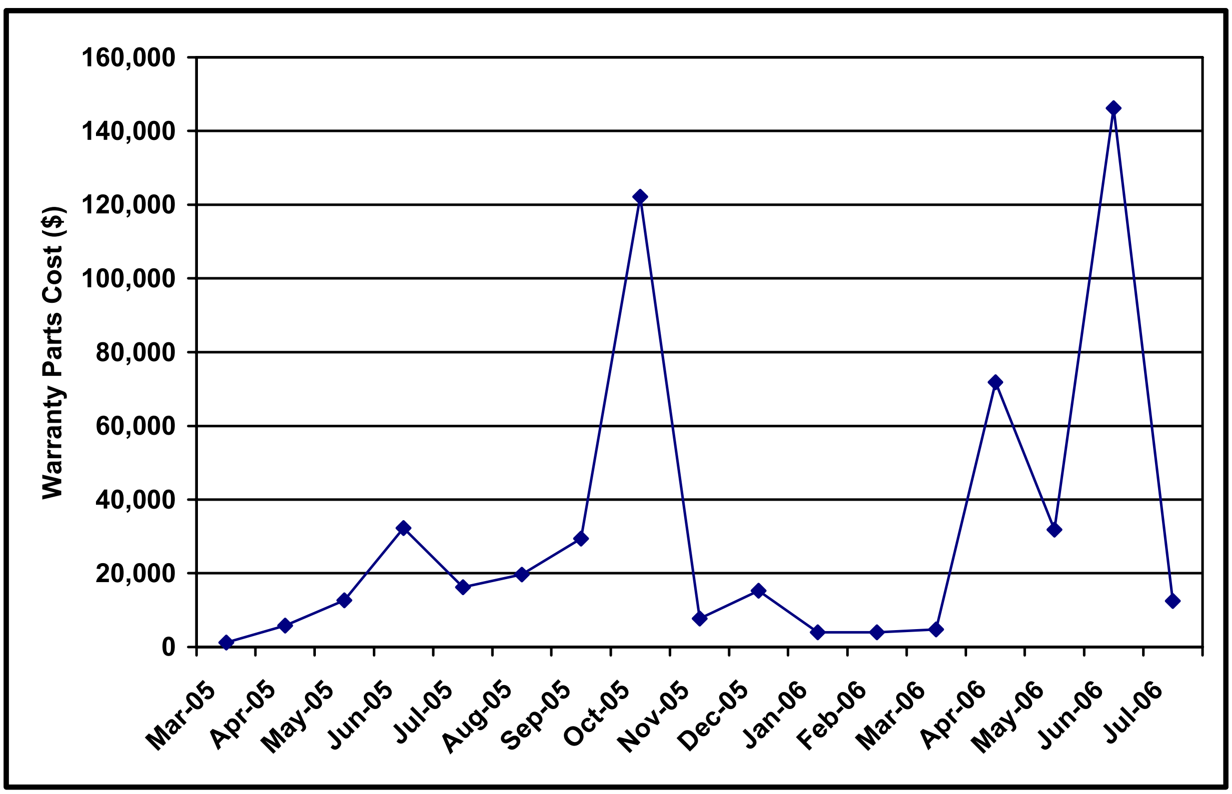

Figure 19. Monthly total warranty parts costs ($) for fuel cell buses (evaluation period)

The diesel buses had similar maintenance costs per mile for four of the five buses. The overall average maintenance cost per mile for the diesel group was $0.54. Bus 2229 had a slightly 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. The per-bus results for the fuel cell buses compared to the diesel buses are as follows:

- Usage/Mileage – 82% lower
- Warranty Parts Costs – much higher
- Parts Costs – 95% lower (many parts costs covered in warranty for fuel cell buses)
- Labor Hours – 67% higher
- Cost per Mile (without warranty costs) – 6.6 times higher.

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 13 shows maintenance costs by vehicle system and bus study group (without warranty costs included). The vehicle systems shown in the table include the following:

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

The systems with the highest percentage of maintenance costs for the fuel cell buses were propulsion-related; PMI; and cab, body, and accessories. These three systems, along with the frame, steering, and suspension system, were also the highest maintenance cost systems for the diesel buses. The additional category of frame, steering, and suspension reflects the higher use of the diesel buses compared to the fuel cell buses.

Table 13. 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	0.31	9	0.13	24
Propulsion-Related	2.38	67	0.20	37
PMI	0.61	17	0.09	16
Brakes	0.06	2	0.02	4
Frame, Steering, and Suspension	0.02	1	0.05	9
HVAC	0.10	3	0.02	4
Lighting	0.01	0	0.02	4
Air, General	0.04	1	0.01	2
Axles, Wheels, and Drive Shaft	0.01	0	0.00	0
Tires	0.01	0	0.00	0
Total	**3.55**	**100**	**0.54**	**100**

Preventive maintenance for the fuel cell and diesel buses was nearly 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 (7,500 miles and 15,000 miles) for coach and drive train components based on bus operation in addition to the 6,000 mile interval for the remainder of the bus. These preventive maintenance schedules for the fuel cell buses do not necessarily overlap. At times, the fuel cell buses may be in for preventive maintenance for one schedule one week and another the following week. The mileage-based schedules were essentially converted from the European schedules that were based on kilometers. Ballard has been working to harmonize these mileage and fuel cell system hour PM schedules. A daily pre-trip inspection of the ZEBs is also required by maintenance personnel.

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 14 shows a breakdown of the propulsion-related system repairs for the two study groups during the evaluation period (no warranty costs). The fuel cell buses had significantly higher maintenance costs for all of the systems shown in the table except for the exhaust and transmission systems.

Several maintenance issues for the fuel cell buses arose during the evaluation period. The major issues are listed below with some comments as to resolution. All parts replacements discussed here were covered under warranty; only mechanic labor for these repairs is included in the maintenance cost analysis.

- **Fuel cell row replacement** – There were a total of 15 fuel cell row replacements on the three buses during the evaluation period. For reference, there are six fuel cell rows in each of the two fuel cell modules on each bus. The cell rows required replacements due to low output voltage of a number of individual cells. These replacements were typically due to single cell issues within the row caused by blockage/contaminants. According to Ballard, the cell rows required repair, but did not indicate end of life failure.

- **Sensor for air intake pressure differentiation** – There were several failures early on because of a specification issue. This problem continues, but at a much lower rate of failure.

Table 14. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	40,429	368,494
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	243.23	26,538.65
Labor hours	1914.8	969.8
Total cost ($)	95,983.23	75,030.15
Total cost ($) per mile	**2.37**	**0.20**
Exhaust System Repairs		
Parts cost ($)	0.00	7,079.25
Labor hours	0.0	275.3
Total cost ($)	0.00	20,844.75
Total cost ($) per mile	**0.00**	**0.06**
Fuel System Repairs		
Parts cost ($)	0.00	3,469.40
Labor hours	385.6	44.6
Total cost ($)	19,280.00	5,696.90
Total cost ($) per mile	**0.48**	**0.02**
Engine System Repairs		
Parts cost ($)	151.34	6,585.60
Labor hours	691.7	268.0
Total cost ($)	34,736.34	19,983.60
Total cost ($) per mile	**0.86**	**0.05**
Electric Motor and Fuel Cell Module Repairs		
Parts cost ($)	0.00	0.00
Labor hours	267.2	0.0
Total cost ($)	13,360.00	0.00
Total cost ($) per mile	**0.33**	**0.000**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	1.50	1,691.77
Labor hours	188.1	82.4
Total cost ($)	9,406.50	5,811.77
Total cost ($) per mile	**0.23**	**0.02**
Air Intake System Repairs		
Parts cost ($)	0.00	845.14
Labor hours	153.8	4.1
Total cost ($)	7,690.00	1,050.14
Total cost ($) per mile	**0.19**	**0.00**
Cooling System Repairs		
Parts cost ($)	0.00	3,988.62
Labor hours	200.4	174.6
Total cost ($)	10,020.00	12,716.12
Total cost ($) per mile	**0.25**	**0.03**
Transmission Repairs		
Parts cost ($)	90.44	2,878.87
Labor hours	26.0	120.6
Total cost ($)	1.390.44	8,906.87
Total cost ($) per mile	**0.03**	**0.02**

- **CVM board** – This board is used to monitor each fuel cell within the modules. There is one board for each of the six fuel cell rows as well as a master board. Several early failures of this board were due to moisture getting into the board and components. This has essentially been resolved by using a different sealant coating for the boards.
- **Coolant (glycol and deionized water) level switch** – The coolant reservoir is on the roof of the bus and there is a level switch to monitor the amount of coolant. This switch was problematic during the evaluation period with several failures, but appeared to be essentially resolved after November 2005.
- **Fuel system regulator** – This is the main fuel pressure regulator to take the high pressure hydrogen from storage down to working pressure for the fuel cells. There were some issues of contaminants causing the needle and seat design to not reseat in some cases. The manufacturer provided a redesign that appeared to be working before the end of the evaluation period.
- **Pressure relief devices and solenoid valves** – These are devices that were used as part of the fuel storage system. There were several failures reported because of contaminants and quality control issues with the assembly of the components. This was resolved on the first replacement.
- **Hydrogen sensors** – There are two types of sensors on the buses—one type in the fuel cell modules and one type in the rest of the bus, most of which were located in the engine compartment. The fuel cell module hydrogen sensors were replaced by an upgraded part about half way through the program. There were some failures of the hydrogen sensors in the rest of the coach. The main issue for failures of both types of sensors was contamination over time.
- **Power inverters** – There were 12 inverter failures during the evaluation period. Most of the failures were due to high heat exposure. This was resolved by changing the amount of coolant flow and by lowering the coolant temperature. There were also some connector issues that caused a few of the failures.

Roadcall Analysis

A roadcall (RC) or revenue vehicle system failure (as named for the National Transit Database[4]) is defined as a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a RC. The analysis provided here only includes RCs that were caused by "chargeable" failures. Chargeable RCs include systems that can physically disable the bus from operating on route, such as interlocks (doors), engine, etc. They do not include RCs for things such as radios or destination signs.

Table 15 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.

[4] 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.

Table 15. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC
4001	13,539	16	846	16	846
4002	13,560	17	798	16	848
4003	13,330	12	1,111	12	1,111
Fuel Cell	**40,429**	**45**	**898**	**44**	**919**
2229	72,275	8	9,034	7	10,325
2230	75,921	8	9,490	8	9,490
2231	77,688	8	9,711	3	25,896
2232	73,062	9	8,118	9	8,118
2233	69,548	12	5,796	7	9,935
Diesel	**368,494**	**45**	**8,189**	**34**	**10,838**

Demonstration Achievements and Challenges

This section summarizes some of the achievements and challenges encountered during the two-year VTA fuel cell bus demonstration program through July 2006.

Achievements

VTA and SamTrans teamed up to successfully fund, design, and complete a full scale demonstration of fuel cell buses as part of a two-year program with 17 months of extra revenue service at VTA (March 2005 through July 2006). This program involved the purchase of three 40-foot fuel cell buses (Gillig buses with Ballard fuel cell propulsion) for $14.1 million, including a two-year warranty, parts, training, and service from Ballard and Gillig. A hydrogen dispensing station was designed, constructed, and operated on site by Air Products at VTA's Cerone bus operating division. Additionally, a new, stand-alone maintenance facility was designed, constructed, and operated as well as a new bus wash to accommodate the taller fuel cell buses and the hydrogen fuel onboard the buses. Construction and operating costs were $4.4 million for all three facilities. VTA reported excellent management and union support for this fuel cell bus demonstration program.

Hydrogen Fueling – 31,836 kg of liquid hydrogen were delivered to the hydrogen fueling station. 14,024 kg of gaseous hydrogen were dispensed into buses at up to 5,000 psi (460 hydrogen fuelings). During the 17-month evaluation period, the hydrogen dispensing station provided overall average fills at 16 minutes, 30.9 kg/fill, and 1.93 kg/min.

Fuel Cell Buses – The three fuel cell buses were operated in extra revenue service for 17 months. This operation accumulated 40,429 total miles and 3,219 total hours of operation. This indicated an average operating speed of 12.6 mph. Fuel cell buses achieved a 3.52 miles per diesel energy equivalent gallon fuel efficiency during the evaluation period.

Bus Operations – Two VTA mechanics were fully trained by Ballard to work on the fuel cell buses. Ballard also provided a technician during the warranty period (up to July 2006). The two VTA fuel cell bus mechanics completed all fuel cell bus inspections, cleanings, fuelings, and maintenance, including repairs (along with the Ballard technician). The fuel cell bus mechanics entered all work orders to assure proper tracking of work performed. They also maintained communication with Ballard personnel to assure data on the buses was maintained. The VTA fuel cell bus mechanics provided support to Ballard for troubleshooting the bus propulsion systems and to Air Products for troubleshooting the hydrogen dispensing station. The VTA fuel cell bus mechanics also kept the drivers informed of potential conditions that could occur with the fuel cell buses. All public events that the fuel cell buses were a part of required the presence of a VTA fuel cell bus mechanic. Operation of the fuel cell buses was kept to weekday service during normal working hours to ensure that a fuel cell bus mechanic could be available for any potential issues.

Challenges

The main challenges for this fuel cell bus demonstration at VTA were extremely high capital and operating costs, a need for standardized hydrogen building codes, hydrogen fuel cost, and reliability of the fuel cell buses.

Capital Costs – This fuel cell bus program required $14.1 million for the fuel cell buses and the warranty and support package. The facilities additions (hydrogen dispensing, maintenance, and bus wash) were an additional $4.4 million.

Bus Operating Costs – The current cost to operate these prototype fuel cell buses is still extremely high, making it difficult for most transit agencies to participate in demonstrations (fuel and maintenance costs for fuel cell buses is $6.46 per mile; diesel comparison buses cost $1.06 per mile). More research is needed to investigate ways to reduce the cost.

Fuel Economy – The fuel cell buses had a fuel economy 12% lower than the diesel comparison buses. The fuel cell buses had an electric drive train, but did not incorporate a hybrid propulsion system design, which would have increased the fuel economy.

Hydrogen Fuel Cost – For this demonstration project, the hydrogen fuel dispensing station was sized for the operation of six fuel cell buses; however, only three fuel cell buses were operated. This sizing difference caused a higher level of the hydrogen fuel to be vented during the evaluation period than was anticipated. Additionally, the prototype compressor was also designed to reduce hydrogen venting; however, due to its lack of operation, this benefit could not be verified. The average hydrogen fuel delivery cost (trucking liquid hydrogen from Sacramento to San Jose) is $9.06 per kg of hydrogen, but with the venting taken into account, this cost is actually $18.12 per kg when placed into the buses.

Fuel Cell Bus Reliability – Diesel buses in VTA service (and in most transit fleets) are often operated in excess of 12 hours per day, seven days per week with an average usage of 4,000 monthly miles per bus, an availability rate of 85%, and a roadcall rate of over 5,000 miles between roadcalls. The VTA diesel comparison buses achieved more than 4,000 monthly miles per bus, an availability rate of 85%, and over 8,000 miles between roadcalls during the evaluation period. During this evaluation, the fuel cell buses operated only eight hours per day, five days per week, and achieved only 800 monthly miles per bus with an availability rate of 58% (which was lower than the target availability rate of 67%). The fuel cell bus roadcall rate was only 900 miles between roadcalls. While the fuel cell buses did have significant operation, this technology does not yet come close to meeting standard transit bus operating expectations. Manufacturers need to work with transit agencies to further improve the technology to meet industry standards and expectations.

Consistent Maintenance Practices – Fuel cell buses have preventive maintenance (PM) schedules that are tracked by mileage as well as hours. Because the different PM schedules do not often overlap, proper maintenance of these buses requires more downtime than a conventional bus. This downtime could be lessened by optimizing the various PM schedules to coincide with standard PM schedules. Specific PMs for fuel cell buses also require staff to remove large components to perform checks and maintenance. This can be time consuming and result in even more downtime for the bus. Manufacturers should work closely with the transit industry to design the next generation systems and components for optimal ease and speed of maintenance.

Hydrogen Use Infrastructure and Building Codes – Hydrogen manufacturers and other interested parties need to continue work to standardize hydrogen building codes and provide familiarization for the authorities with jurisdiction in locations where hydrogen infrastructure is planned. This lack of hydrogen familiarity was made even worse by the number of false alarms as the hydrogen dispending station was being tested. False alarms at the hydrogen station and maintenance facility caused shutdowns, resulted in delayed or lost service, and created concern by the local emergency responders regarding the operational safety of this equipment. Many of the alarms at VTA could have been prevented with good system design and by providing the on-site staff with a clear understanding of how the system and components worked. Station and fuel providers should work closely with transit agency partners to rectify the issues and reduce the potential for false alarms that impact the operation of the depot.

Extreme Pressure for Implementation – In California, there is extreme pressure to speed up the introduction of zero emission vehicles because of serious air quality challenges. This pressure needs to match the ability of new and experimental hydrogen and fuel cell propulsion systems for the transit industry. Based on the results of this demonstration, much more work (research and optimization) is needed before these technologies are ready for full-scale implementation. However, the way to accomplish this needed research and optimization is to support such research and continue to field test new and advanced zero emission propulsion technologies.

What's Next for this Demonstration?

This report covers VTA operation of the fuel cell buses through July 2006. This is the end of the two-year demonstration and the warranty/support period for the fuel cell buses, as defined by Ballard. VTA has continued to run the fuel cell buses beyond July 2006 and is paying for support by Ballard and parts on a month-to-month basis. VTA currently intends to attempt another full year of service; however, additional funding and level of support from Ballard and Air Products have not yet been finalized.

There are ongoing discussions between VTA and Ballard to potentially upgrade the existing fuel cell buses to a hybrid propulsion system and Ballard's newer model fuel cell modules. Issues yet to be resolved in these discussions include funding requirements and sources as well as expectations and design of operations for these new hybrid fuel cell buses.

VTA's current lease of the hydrogen fuel dispensing station runs through May 2007 with two one-year options available from Air Products. Continuation beyond this would require renegotiation of the lease rates with Air Products. Air Products indicates that it intends to support the station and continue its testing and development activities.

Ballard intends to continue to be a supplier of fuel cell power plants to vehicle manufacturers. It also has a new model fuel cell module for transportation applications. Ballard plans to have a potentially commercial fuel cell module product for the 2010-2015 timeframe.

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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
ECTOS	Ecological City Transport System (Reykjavik, Iceland)
E-stop	Emergency stop
FCB	Fuel cell bus
FTA	Federal Transit Administration
GVWR	Gross vehicle weight rating
HFCIT	Hydrogen, Fuel Cells & Infrastructure Technologies
HHICE	Hybrid hydrogen internal combustion engine
HVAC	Heating, ventilation, and air conditioning
in	Inches
JHFC	Japan Hydrogen and Fuel Cell Demonstration Project
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
STEP	Sustainable Transport Energy for Perth
UNDP-GEF	United Nations Development Programme – Global Environment Facility
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	3/05-7/06	3/05-7/06
Total Number of Months in Period	17	17
Fuel and Oil Analysis Base Fleet Mileage	360,447	40,208
Period Used for Maintenance Op Analysis	3/05-7/06	3/05-7/06
Total Number of Months in Period	17	17
Maintenance Analysis Base Fleet Mileage	368,494	40,429
Average Monthly Mileage per Vehicle	4,335	809
Availability	85%	58%
Fleet Fuel Usage in Diesel Gal/H2 kg	90,503	12,904
Roadcalls	45	45
RCs MBRC	8,189	898
Propulsion Roadcalls	34	44
Propulsion MBRC	10,838	918
Fleet Miles/kg Hydrogen		3.12
(1.13 kg H2/gal Diesel Fuel)		
Representative Fleet MPG (energy equiv.)	3.98	3.52
Hydrogen Cost per kg		9.06
Diesel Cost per Gallon	2.07	
Fuel Cost per Mile	**0.52**	**2.91**
Total Scheduled Repair Cost per Mile	0.12	0.70
Total Unscheduled Repair Cost per Mile	0.42	2.85
Total Maintenance Cost per Mile	**0.54**	**3.55**
Total Operating Cost per Mile	**1.06**	**6.46**

Maintenance Costs

	Diesel Buses	Fuel Cell Buses
Fleet Mileage	368,494	40,429
Total Parts Cost	58,602.26	1,658.18
Total Labor Hours	2829.1	2837.4
Average Labor Cost (@ $50.00 per hour)	141,455.00	141,870.00
Total Maintenance Cost	200,057.26	143,528.18
Total Maintenance Cost per Bus	40,011.45	47,842.73
Total Maintenance Cost per Mile	**0.54**	**3.55**

Breakdown of Maintenance Costs by Vehicle System

	Diesel Buses	Fuel Cell Buses
Fleet Mileage	368,494	40,429
Total Propulsion-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 65)		
Parts Cost	26,538.65	243.23
Labor Hours	969.8	1914.8
Average Labor Cost	48,491.50	95,740.00
Total Cost (for system)	75,030.15	95,983.23
Total Cost (for system) per Bus	15,006.03	31,994.41
Total Cost (for system) per Mile	**0.20**	**2.37**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost	7,079.25	0.00
Labor Hours	275.3	0.0
Average Labor Cost	13,765.50	0.00
Total Cost (for system)	20,844.75	0.00
Total Cost (for system) per Bus	4,168.95	0.00
Total Cost (for system) per Mile	**0.06**	**0.00**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost	3,469.40	0.00
Labor Hours	44.6	385.6
Average Labor Cost	2,227..50	19,280.00
Total Cost (for system)	5,696.90	19,280.00
Total Cost (for system) per Bus	1,139.38	6,426.67
Total Cost (for system) per Mile	**0.02**	**0.48**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost	6,585.60	151.34
Labor Hours	268.0	691.7
Average Labor Cost	13,398.00	34,585.00
Total Cost (for system)	19,983.60	34,736.34
Total Cost (for system) per Bus	3,996.72	11,578.78
Total Cost (for system) per Mile	**0.05**	**0.86**
Electric Propulsion Repairs (ATA VMRS 46)		
Parts Cost	0.00	0.00
Labor Hours	0.0	267.2
Average Labor Cost	0.00	13,360.00
Total Cost (for system)	0.00	13,360.00
Total Cost (for system) per Bus	0.00	4,453.33
Total Cost (for system) per Mile	**0.00**	**0.33**

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	1,691.77	1.50
Labor Hours	82.4	188.1
Average Labor Cost	4,120.00	9,405.00
Total Cost (for system)	5,811.77	9,406.50
Total Cost (for system) per Bus	1,162.35	3,135.50
Total Cost (for system) per Mile	**0.02**	**0.23**
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost	845.14	0.00
Labor Hours	4.1	153.8
Average Labor Cost	205.00	7,690.00
Total Cost (for system)	1,050.14	7,690.00
Total Cost (for system) per Bus	210.03	2,563.33
Total Cost (for system) per Mile	**0.00**	**0.19**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost	3,988.62	0.00
Labor Hours	174.6	200.4
Average Labor Cost	8,727.50	10,020.00
Total Cost (for system)	12,716.12	10,020.00
Total Cost (for system) per Bus	2,543.22	3,340.00
Total Cost (for system) per Mile	**0.03**	**0.25**
Hydraulic System Repairs (ATA VMRS 65)		
Parts Cost	0.00	0.00
Labor Hours	0.4	2.0
Average Labor Cost	20.00	100.00
Total Cost (for system)	20.00	100.00
Total Cost (for system) per Bus	4.00	33.33
Total Cost (for system) per Mile	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)		
Parts Cost	1,114.34	191.67
Labor Hours	96.4	27.0
Average Labor Cost	4,820.00	1,350.00
Total Cost (for system)	5,934.34	1,541.67
Total Cost (for system) per Bus	1,186.87	513.89
Total Cost (for system) per Mile	**0.02**	**0.04**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Buses	Fuel Cell Buses
Brake System Repairs (ATA VMRS 13)		
Parts Cost	668.69	0.00
Labor Hours	129.1	50.5
Average Labor Cost	6,455.00	2,525.00
Total Cost (for system)	7,123.69	2,525.00
Total Cost (for system) per Bus	1,424.74	841.67
Total Cost (for system) per Mile	**0.02**	**0.06**
Transmission Repairs (ATA VMRS 27)		
Parts Cost	2,878.87	90.44
Labor Hours	120.6	26.0
Average Labor Cost	6,028.00	1,300.00
Total Cost (for system)	8,906.87	1,390.44
Total Cost (for system) per Bus	1,781.37	463.48
Total Cost (for system) per Mile	**0.02**	**0.03**
Inspections Only – No Parts Replacements (101)		
Parts Cost	0.00	0.00
Labor Hours	639.6	493.4
Average Labor Cost	31,980.00	24,670.00
Total Cost (for system)	31,980.00	24,670.00
Total Cost (for system) per Bus	6,396.00	8,223.33
Total Cost (for system) per Mile	**0.09**	**0.61**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost	15,485.05	1,001.63
Labor Hours	625.3	232.9
Average Labor Cost	31,265.5	11,645.00
Total Cost (for system)	46,750.55	12,646.63
Total Cost (for system) per Bus	9,350.11	4,215.54
Total Cost (for system) per Mile	**0.13**	**0.31**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost	1,696.43	153.64
Labor Hours	85.8	77.8
Average Labor Cost	4,290.00	3,890.00
Total Cost (for system)	5,986.43	4,043.64
Total Cost (for system) per Bus	1,197.29	1,347.88
Total Cost (for system) per Mile	**0.02**	**0.10**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Buses	Fuel Cell Buses
Lighting System Repairs (ATA VMRS 34)		
Parts Cost	3,479.95	56.08
Labor Hours	76.1	9.2
Average Labor Cost	3,802.50	460.00
Total Cost (for system)	7,282.45	516.08
Total Cost (for system) per Bus	1,456.49	172.03
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	9,472.75	0.00
Labor Hours	174.1	18.5
Average Labor Cost	8,702.50	925.00
Total Cost (for system)	18,175.25	925.00
Total Cost (for system) per Bus	3,635.05	308.33
Total Cost (for system) per Mile	**0.05**	**0.02**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost	146.40	11.88
Labor Hours	33.0	7.5
Average Labor Cost	1,647.50	375.00
Total Cost (for system)	1,793.90	386.88
Total Cost (for system) per Bus	358.78	128.96
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**	**0.01**

Notes

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

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

2. The propulsion-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.

Appendix: Fleet Summary Statistics – SI Units

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	3/05-7/06	3/05-7/06
Total Number of Months in Period	17	17
Fuel and Oil Analysis Base Fleet Kilometers	580,067	64,707
Period Used for Maintenance Op Analysis	3/05-7/06	3/05-7/06
Total Number of Months in Period	17	17
Maintenance Analysis Base Fleet Kilometers	593,017	65,062
Average Monthly Kilometers per Vehicle	6,977	1,302
Availability	85%	58%
Fleet Fuel Usage in Diesel L/H2 kg	342,554	12,904
Roadcalls	45	45
RCs Kilometers Between Roadcalls (kMBRC)	13,178	1,446
Propulsion Roadcalls	34	44
Propulsion kMBRC	17,442	1,479
Fleet kg Hydrogen/100 km		19.94
Representative Fleet MPG (L/100 km)	59.05	66.80
Hydrogen Cost per kg		9.06
Diesel Cost per Liter	0.55	
Fuel Cost per Kilometer	**0.32**	**1.81**
Total Scheduled Repair Cost per Kilometer	0.08	0.43
Total Unscheduled Repair Cost per Kilometer	0.26	1.77
Total Maintenance Cost per Kilometer	**0.34**	**2.21**
Total Operating Cost per Kilometer	**0.66**	**4.01**

Maintenance Costs

	Diesel Buses	Fuel Cell Buses
Fleet Mileage	593,017	65,062
Total Parts Cost	58,602.26	1,658.18
Total Labor Hours	2829.1	2837.4
Average Labor Cost (@ $50.00 per hour)	141,455.00	141,870.00
Total Maintenance Cost	200,057.26	143,528.18
Total Maintenance Cost per Bus	40,011.45	47,842.73
Total Maintenance Cost per Kilometer	**0.34**	**2.21**

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14. ABSTRACT *(Maximum 200 Words)*
This report provides evaluation results for prototype fuel cell transit buses operating at Santa Clara Valley Transportation Authority (VTA) in San Jose, California, in partnership with the San Mateo County Transit District in San Carlos, California. 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, early experiences, and evaluation results from the operation of the buses and the supporting hydrogen infrastructure from March 2005 through July 2006.

15. SUBJECT TERMS
fuel cell bus; fuel cell transit bus; hydrogen infrastructure; hydrogen refueling; zero-emision bus; Santa Clara Valley Transportation Authority; San Mateo County Transit District

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