Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: First Results Report

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

Technical Report
NREL/TP-5600-52015
August 2011

Contract No. DE-AC36-08GO28308

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. H270.8150

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Acronyms and Abbreviations

AQMD	Air Quality Management District
CARB	California Air Resources Board
CNG	compressed natural gas
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
FCB	fuel cell bus
ft	feet
FTA	Federal Transit Administration
hp	horsepower
HVAC	heating, ventilation, and air conditioning
in.	inches
kg	kilograms
kW	kilowatts
lb	pounds
MBRC	miles between roadcalls
mpDGE	miles per diesel gallon equivalent
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
psi	pounds per square inch
RC	roadcall

Executive Summary

In response to the California Air Resources Board (CARB) rule for transit agencies in the state, five San Francisco Bay Area transit agencies have joined together to demonstrate the largest fleet of fuel cell buses in the United States. The Zero Emission Bay Area (ZEBA) Demonstration group includes five participating transit agencies: AC Transit (lead transit agency), Santa Clara Valley Transportation Authority (VTA), Golden Gate Transit (GGT), San Mateo County Transit District (SamTrans), and San Francisco Municipal Railway (Muni). The ZEBA partners are collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. This report documents the early implementation experience for the demonstration.

The ZEBA Demonstration includes 12 next-generation fuel cell hybrid buses and two new hydrogen fueling stations. The buses are 40-foot, low floor buses built by Van Hool with a hybrid electric propulsion system that includes a UTC Power fuel cell power system and an advanced lithium-based energy storage system by Ener1. The new buses feature significant improvements over two previous generations of fuel cell buses that were demonstrated in California, Connecticut, and Belgium. Improvements include a redesigned Van Hool chassis that is lighter in weight, shorter in height, and has a lower center of gravity for improved weight distribution.

Primary power is provided by UTC Power's newest-design fuel cell power system. This fuel cell power system was improved based on lessons learned from previous operation at the various transit agencies, including the accelerated testing at AC Transit funded under the Federal Transit Administration's National Fuel Cell Bus Program. Significant progress was made in increasing reliability of the fuel cell power system, based on bus usage and roadcall rates in service at AC Transit. Average monthly bus usage more than doubled, and miles between roadcalls (MBRC) for the fuel cell power system nearly doubled from 5,017 MBRC to 9,951 MBRC. Three separate fuel cell power systems have surpassed 5,000 hours of operation without major repair or cell replacement – and one of those systems has accumulated more than 9,000 hours.[1] According to UTC Power, these powerplants continue to provide full rated power. The fact that three fuel cell power systems have achieved high operational hours is a strong indicator of progress in the lifespan and durability of the fuel cell power systems.

The first of two Linde hydrogen fueling stations is under construction at AC Transit's Emeryville Division and is expected to be fully operational by the end of August. Temporary fueling during the interim period has been provided by Air Products and Chemicals, Inc. The second hydrogen station, planned for the Seminary Division in Oakland, is in the design phase and is expected to be complete in mid-2012. Once both stations are operational, the bus fleet will be split between the two locations.

By the end of June, nine of the twelve buses had been delivered and seven of those were in service. The buses have accumulated more than 80,000 miles and a total of 7,653 hours on the

[1] On August 10, 2011, UTC Power announced that this fuel cell power system had achieved 10,000 hours of operation without major repair or cell replacement, http://www.utcpower.com/pressroom/pressreleases/utc-power-fuel-cell-system-sets-world-record-achieving-10000-hr-durability.

fuel cell systems. The results presented in this report are preliminary information from the first five fuel cell buses that have been placed into service at AC Transit from September 2010 through May 2011. These early results are presented as progress toward the full evaluation planned once all of the buses go into service and hydrogen fueling is fully available for the entire fuel cell bus fleet. The evaluation start date for each bus was chosen for convenience of the data analysis and results presentations. At a later date and in future reports, there will be a "clean point" chosen for the full NREL evaluation of the operation of these fuel cell buses and the hydrogen fueling infrastructure. That date will most likely occur after the Emeryville station is in full operation.

AC Transit will continue to operate the buses in service from the Seminary Division until the hydrogen station at Emeryville is completed, and then the buses will be moved to that location. Of the final three new buses, two are scheduled to arrive by the middle of August 2011 and the last by early September. These buses will enter passenger service after a 30-day commissioning period at AC Transit.

GGT is planning to begin operating two of the fuel cell buses after the Emeryville fueling station is fully operational – most likely by the end of August or early September. Because VTA and SamTrans are located in the southern Bay Area, those agencies will wait until the new Seminary Division station is completed before they plan to operate any of the fuel cell buses.

NREL will continue to evaluate the buses in service at AC Transit and at the other agencies once they put the buses in service. VTA and GGT also operate diesel hybrid-electric buses, and NREL is planning to collect data on the hybrid buses to compare fuel efficiency to the fuel cell buses in similar service. The next report is expected in early 2012.

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Introduction

This report documents early implementation experience of the Zero Emission Bay Area (ZEBA) Demonstration, which will ultimately include 12 next-generation fuel cell buses and two new hydrogen fueling stations located in the San Francisco Bay area. This effort is the largest fuel cell bus demonstration in the United States and includes five participating transit agencies:

- Alameda-Contra Costa Transit District (AC Transit) – lead transit agency for ZEBA
- Santa Clara Valley Transportation Authority (VTA)
- Golden Gate Transit (GGT)
- San Mateo County Transit District (SamTrans)
- San Francisco Municipal Railway (Muni)

The ZEBA partners are collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. NREL has been evaluating alternative fuel and advanced propulsion transit buses for DOE and the U.S. Department of Transportation's Federal Transit Administration (FTA) since the early 1990s. These evaluations focus on determining the status of hydrogen and fuel cell systems and the corresponding infrastructure in transit applications to help DOE and FTA assess the progress toward technology readiness. NREL uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations. This protocol was documented in a joint evaluation plan for transit bus evaluations.[2]

Fuel Cell Buses in California

In 2000, the California Air Resources Board (CARB) established a new transit bus fleet rule that set more stringent emission standards for new urban bus engines and promoted advances in the cleanest technologies—specifically, zero-emission buses (ZEBs). This fleet rule required transit agencies to choose a compliance path—alternative fuel or diesel—for meeting emission standards. The alternative fuel path could include low-emission alternative fuels such as compressed or liquefied natural gas, propane, electricity, hydrogen, or another advanced technology (such as gasoline hybrid-electric). Agencies choosing the diesel path were required to reduce fleet average emissions through methods such as purchasing the cleanest diesel engines and retrofitting existing diesel engines with emission control devices (i.e., diesel particulate filters).

All transit agencies with 200 or more buses were required to eventually procure ZEBs as 15% of all new bus purchases. Agencies choosing the diesel path were scheduled to meet these requirements on a more accelerated timeline than those on the alternative fuel path were. Diesel path fleets were also required to demonstrate the use of ZEB technology in revenue service starting in 2004–2006. ZEB technologies that qualify for this regulation include electric propulsion (battery or trolley buses) and fuel cell propulsion.

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

In 2002–2004, SunLine Transit Agency and AC Transit operated a prototype 35-foot fuel cell bus from ISE and UTC Power (also known as the ThunderPower bus). This demonstration provided an opportunity for California transit operators to advance their knowledge of fuel cell and electric propulsion in a transit bus. Experience from the operation at SunLine (Palm Springs area) is provided in an NREL evaluation report.[3]

In the next significant fuel cell bus demonstration, VTA and SamTrans teamed up to operate three Gillig 40-foot buses with Ballard fuel cells at VTA. The buses were operated from 2004 through 2009.[4] AC Transit and GGT also teamed up to demonstrate three Van Hool 40-foot buses with UTC Power fuel cells at AC Transit, starting in 2006 and operated into 2010, as discussed later in this report. Muni has been an interested party in the demonstrations of fuel cell buses but already meets the CARB fleet rule with their electric trolley bus fleet.

The CARB fleet rules have been modified twice since the original ruling went into effect, mainly to change the effective dates of fuel cell bus demonstrations and future bus procurements. After reviewing data from the early demonstrations at VTA and AC Transit, the Board determined that, despite the efforts of transit agencies and manufacturers, the technology had not progressed as quickly as originally expected. The modifications to the rule also included an advanced demonstration program of ZEBs and a delay of the 15% purchase requirement to January 1, 2011 (diesel path), and January 1, 2012 (alternative fuel path).

The ZEBA demonstration was originally scheduled to begin by January 2009, and CARB staff was scheduled to report the early demonstration results to the board by July 2009. However, because the procurement, design, and development of the fuel cell buses took longer than anticipated, no results were available in July. Instead, staff provided the board with an informational report on the status of implementing the Zero-Emission Bus Regulation and recommended the following actions:

- Delay the 15% purchase requirement to give staff time to gather at least one year of data on the next-generation fuel cell buses
- Continue the Advanced ZEB Demonstration of 12 buses in the Bay Area
- Develop performance criteria that the technology must meet before the purchase requirement is triggered.

The Board agreed with these recommendations and directed CARB staff to report back no later than July 2012 with any proposed modifications. For more information on the ruling, see www.arb.ca.gov/msprog/bus/zeb/zeb.htm.

[3] Fuel Cell Transit Buses, ThunderPower Bus Evaluation at SunLine Transit Agency, November 2003, DOE/GO-102003-1786, http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/sunline_report.pdf.
[4] NREL evaluation results reported in Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Evaluation Results, 2006, NREL/TP-560-40615, http://www.nrel.gov/hydrogen/pdfs/40615.pdf.

HyRoad Fuel Cell Bus Demonstration

AC Transit is a public agency that provides transit service in the East Bay of the San Francisco Bay Area. In response to the CARB fleet rule, AC Transit initiated their HyRoad Program to demonstrate one specific type of zero-emission bus technology – fuel cell buses. Figure 1 provides a timeline of AC Transit fuel cell bus demonstration activities.

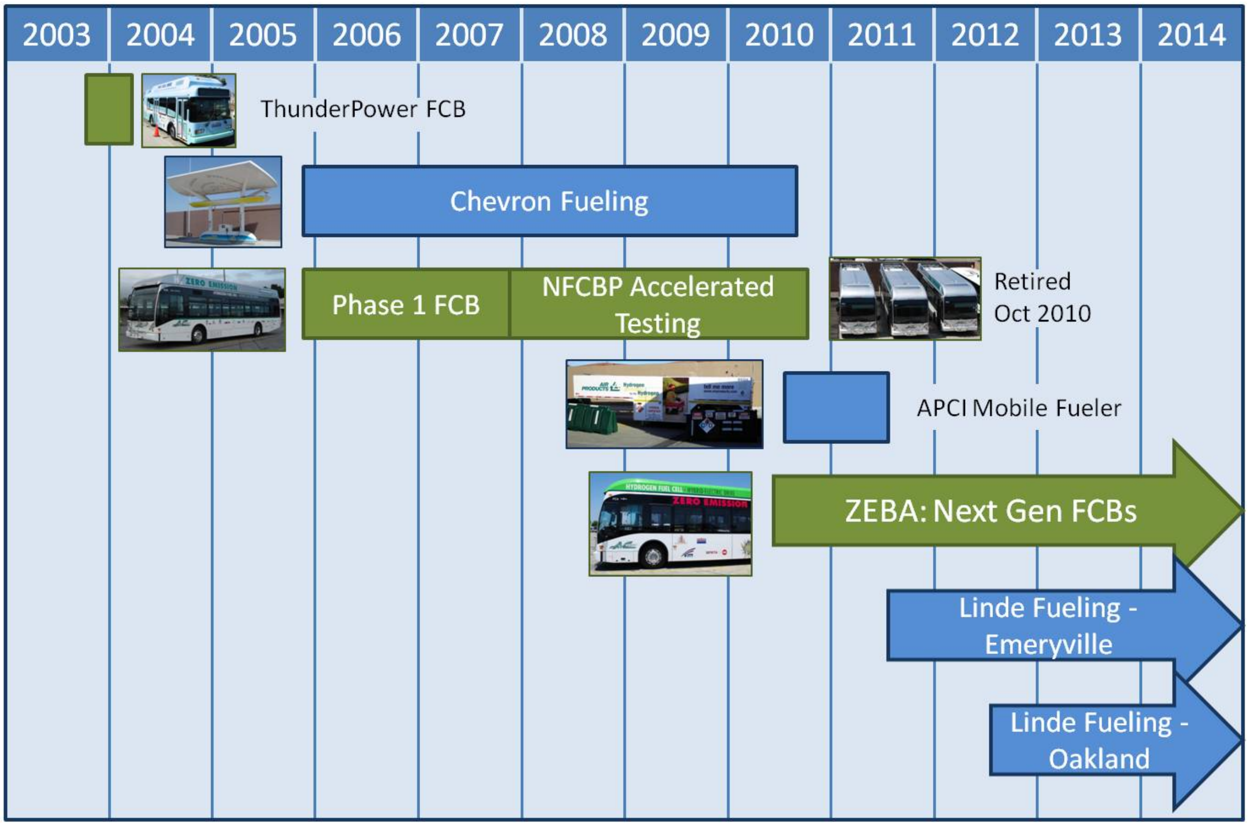

Figure 1. Timeline of AC Transit's FCB demonstrations

AC Transit created its HyRoad Program with a goal of demonstrating the viability of an emissions-free transit system. The agency began in 2000 by placing a request for proposals to develop and build fuel cell buses for the demonstration. This proved to be a challenge at that time, because very few bus manufacturers were willing to take the risk of fielding a prototype technology. Eventually, the agency entered into an agreement with UTC Power and ISE Corporation to develop a new fuel cell bus design. The bus was developed on a Van Hool chassis that was similar to the fleet of diesel Van Hool buses AC Transit was already in the process of receiving. The manufacturer team originally planned to use the standard diesel chassis but decided to redesign the chassis to better accommodate the fuel cell system and hybrid components.

The first fuel cell bus was delivered to AC Transit in October 2005, and the other two buses arrived in December 2005. The agency leveraged its investment into fuel cell technology by participating in the DOE Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project. Teaming with Chevron Technology Ventures and Hyundai under the project, the agency added hydrogen fueling at its Seminary Division and demonstrated a fleet of light-duty fuel cell vehicles along with the three buses. The on-site hydrogen fueling station from Chevron was commissioned on March 13, 2006, and the three fuel cell buses went into service on March 20, 2006.

Van Hool and UTC Power also delivered three additional buses of the same design as the three AC Transit fuel cell buses. These three buses were delivered and operated at SunLine, at Connecticut Transit (CTTRANSIT), and in Belgium (one bus at each site). Both the SunLine and CTTRANSIT buses are still in operation. The fuel cell bus in Belgium was taken out of service after its testing was completed.

National Fuel Cell Bus Program – Accelerated Testing

In late 2006, the FTA announced project awards under its National Fuel Cell Bus Program (NFCBP). This program provided $49 million in competitive 50-50 government-industry cost share grants to facilitate the development of commercially viable fuel cell bus technologies. Under one of the three consortia leads – CALSTART – AC Transit and its project partners were awarded a grant for conducting accelerated testing of its existing three fuel cell buses. This accelerated testing project included preparation and support for maximizing operation of the three fuel cell buses. The fuel cell buses were operated in revenue service 16 to 19 hours per day, up to seven days per week, allowing the manufacturers to further validate the propulsion system, identify the weakest areas, analyze the root causes of failure, and make modifications and upgrades to increase durability and reliability.

Significant progress was made toward increasing reliability of the fuel cell power system, based on bus usage and roadcall rates in service at AC Transit. Average monthly bus usage increased from 1,056 miles/month up to 2,168 miles/month in the accelerated period (more than doubling the usage per bus). Miles between roadcalls (MBRC) for the fuel cell power system nearly doubled from 5,017 MBRC up to 9,951 MBRC. Additional results were reported as part of the NFCBP.[5]

The three fuel cell buses started revenue operation on March 20, 2006, and were each retired in 2010 as follows:

- FC1 – 5/24/2010, 76,614 miles
- FC2 – 8/30/2010, 96,603 miles
- FC3 – 10/23/2010, 89,998 miles

Operation at AC Transit including all revenue service totaled 263,215 miles and 26,295 hours of fuel cell power system operation (operation at an average of 10 mph) over a nearly five-year period. The fuel cell power systems were removed and UTC Power has taken ownership of the three retired fuel cell buses. Each of the fuel cell power systems was transferred to a new/next-generation fuel cell bus to support final testing and start of service as described later in this report.

[5] National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2, June 2010, FTA-CO-26-7004-2010.1A, http://www.nrel.gov/hydrogen/pdfs/48106-1.pdf.

ZEBA Fuel Cell Bus Demonstration

Updates to the CARB transit rule in 2006 added a requirement for an advanced zero-emission bus demonstration for the larger California agencies. The five larger transit agencies in the San Francisco Bay Area formed the ZEBA demonstration group to respond to the rule, and their operating areas are shown in Figure 2. The five agencies are:

- **AC Transit –** Headquartered in Oakland, AC Transit's service area covers 364 square miles and includes 13 cities and several adjacent communities in Alameda and Contra Costa counties. The agency operates 471 transit buses in peak service (580 active buses in the fleet) on more than 105 fixed routes and also provides school bus service.
- **Santa Clara Valley Transportation Authority (VTA)** – Headquartered in San Jose, VTA is a multi-modal transportation planning organization that provides bus, paratransit, and light rail service in Santa Clara County, as well as congestion mitigation, highway improvement projects, and countywide transportation planning. VTA's service area covers approximately 326 square miles.
- **Golden Gate Transit (GGT)** – One of three divisions operated by the Golden Gate Bridge, Highway, and Transportation District, GGT's service area covers 256 square miles in Marin and Sonoma counties across the Bay northward from San Francisco. GGT operates 204 buses in various types of bus service, including intercounty, commuter express, and local.
- **San Mateo County Transit District (SamTrans)** – SamTrans provides transportation services to San Mateo County, which is directly south of San Francisco. The agency provides fixed-route and paratransit services within its approximately 446 square mile area and also manages Caltrain operations.
- **San Francisco Municipal Transportation Agency (SFMTA) –** The San Francisco Municipal Transportation Agency (SFMTA) manages and operates the surface transportation network in San Francisco. The San Francisco Municipal Railway (Muni), the largest division within the SFMTA, handles transit operations and maintenance for the city's bus, light rail, trolley, historic streetcars, and cable car fleets, as well as facility maintenance.

The ZEBA demonstration group is supported through funding and planning by the Metropolitan Transportation Commission (MTC), the Bay Area Air Quality Management District (BAAQMD), CARB, the California Energy Commission (CEC), and the FTA (including the NFCBP). Besides AC Transit, all transit agencies in the ZEBA demonstration group are providing funding, participating in training activities, and plan to periodically operate buses as part of the demonstration.

Some of the new goals for the ZEBA demonstration include the following:

- Prove full transit operations with the fuel cell buses and new hydrogen fueling infrastructure
- Improve overall vehicle performance, and generate strong driver acceptance of the technology

- Significantly improve the reliability (bus usage and roadcall rate) to at least that of baseline diesel or diesel-hybrid propulsion technology
- Improve the greenhouse gas emissions related to hydrogen production and fueling for this demonstration
- Include all of the ZEBA partner transit agencies in operating the fuel cell buses.

Another four new fuel cell buses have been purchased from AC Transit's order by UTC Power for operation in Connecticut and other selected areas under the FTA's NFCBP. Together, this fleet of 16 fuel cell buses is the premier fuel cell bus program in the United States.

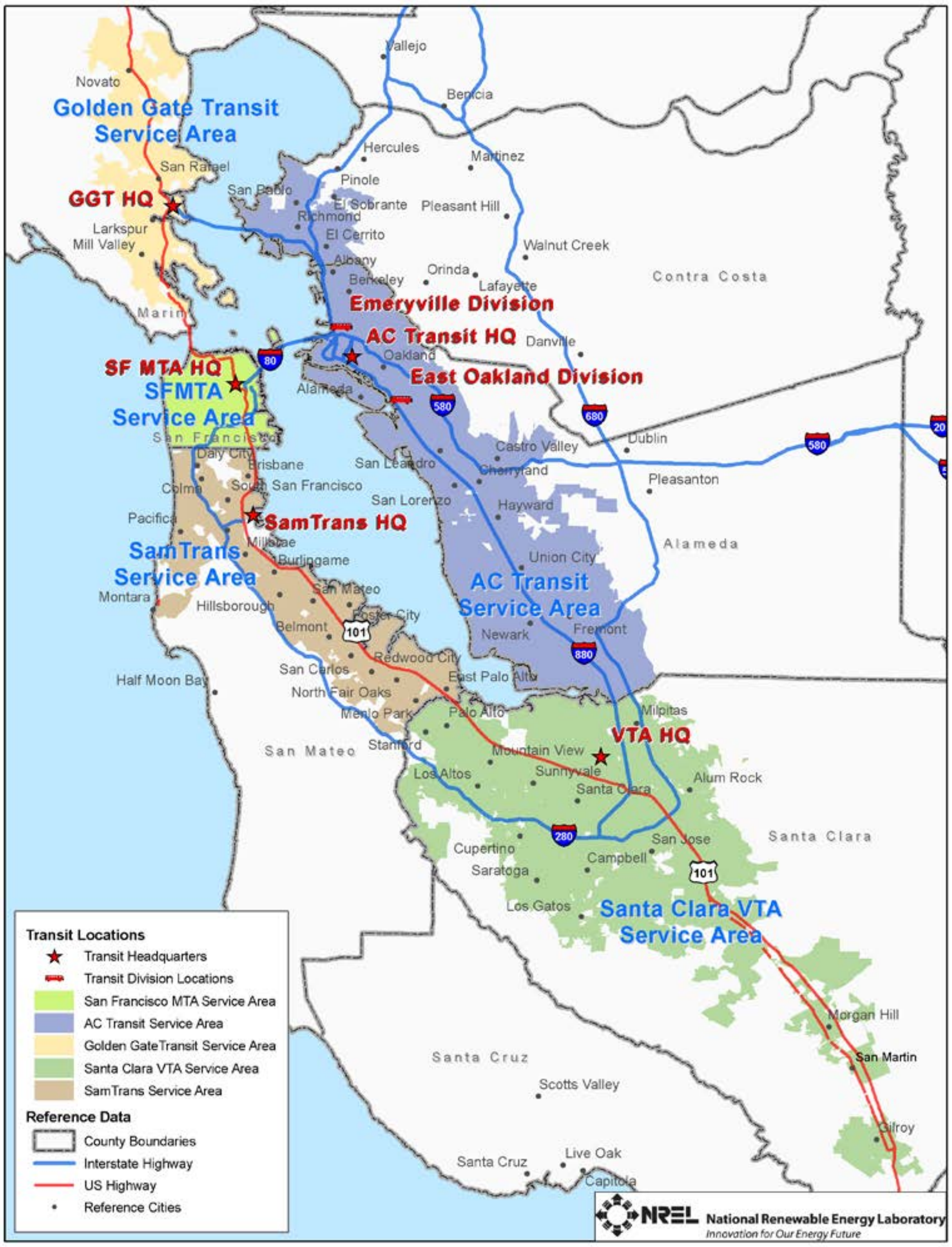

Figure 2. Map of ZEBA transit partner operating locations

Bus Technology Descriptions

Table 1 provides bus system descriptions for the fuel cell and diesel buses that were studied in this evaluation. The fuel cell buses in service at AC Transit (Figure 3) are 40-foot, low floor buses built by Van Hool with a hybrid electric propulsion system that includes a UTC Power fuel cell power system. In the evaluation of the first three fuel cell buses at AC Transit, the diesel buses studied were not equipped with air conditioning. For this study/evaluation, three diesel buses that include air conditioning were selected. The fuel cell and diesel buses are controlled to operate on similar routes, and those routes are discussed later in this report.

Table 1. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	Fuel Cell	Diesel
Number of buses	12	3
Bus manufacturer and model	Van Hool A300L FC low floor	Van Hool A300L low floor
Model year	2010	2009
Length/width/height	40 ft/102 in./136 in.	40 ft/102 in./121 in.
GVWR/curb weight	39,350 lb/31,400 lb	40,800 lb/27,800 lb
Wheelbase	228 in.	235 in.
Passenger capacity	29 seated plus 2 wheelchair positions; or 33 seats without wheelchairs	31 seated or 28 seated and 2 wheelchairs; 53 standing
Engine manufacturer and model	UTC Power PureMotion[6] 120 fuel cell power system	Cummins ISL
Rated power	Fuel cell power system: 120 kW	280 hp @ 2200 rpm
Accessories	Electrical	Mechanical
Emissions equipment	None	Diesel Oxidation Catalyst
Transmission/retarder	Seico Brake resistors Regenerative braking	Voith Integrated retarder
Fuel capacity	40 kg hydrogen	92 gal
Bus purchase cost	$2.5 million	$323,000

Table 2 provides a description of some of the electric propulsion systems for the fuel cell buses. Note that the diesel buses are not a hybrid configuration and do not have regenerative braking or energy storage for the drive system.

The new fuel cell buses have a fuel cell dominant hybrid electric propulsion system in a series configuration. Van Hool fully integrated the hybrid design using a Siemens ELFA 2 hybrid system; UTC Power's newest-design fuel cell power system that includes lessons learned from previous operation and the accelerated testing at AC Transit; and an advanced lithium-based energy storage system by Ener1. The new buses feature significant improvements over two previous generations of fuel cell buses, including a redesigned Van Hool chassis that is 5,000 lb lighter in weight and 3 in. shorter in height than that of the earlier-generation buses. The bus has a top speed of 55 mph.

[6] PureMotion is a registered trademark of UTC Power.

Figure 3. One of AC Transit's new fuel cell buses

Table 2. Additional Electric Propulsion System Descriptions

Propulsion Systems	Fuel Cell Bus
Integrator	Van Hool
Hybrid type	Series, charge sustaining
Drive system	Siemens ELFA
Propulsion motor	2-AC induction, 85 kW each
Energy storage	Battery: Ener1, lithium ion, Rated energy: 17.4 kWh Rated capacity: 29 Ah Rated power: 76 to 125 kW
Fuel storage	Eight roof mounted, Dynetek, type 3 tanks; 5,000 psi rated
Regenerative braking	Yes

Fueling and Maintenance Facilities

As part of the DOE Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Chevron built and operated the first hydrogen fueling station at AC Transit. At the conclusion of the project, Chevron and AC Transit identified a third party supplier to provide hydrogen between the time the Chevron station was decommissioned in August 2010 and the startup of AC Transit's new Emeryville station. AC Transit began searching for a new partner to provide permanent fueling for its growing fleet of hydrogen-fueled buses. The agency planned two stations: one to replace the station at the Seminary Division and a second at its Emeryville Division. Knowing there would be a gap in fuel availability while the new stations were constructed and commissioned, AC Transit entered into an agreement with Air Products and Chemicals, Inc. (APCI) to provide a mobile fueler for the fuel cell buses. By the end of August 2010, the Chevron station was decommissioned, the equipment was removed, and the APCI temporary fueling solution was put in place. Since that time, APCI has provided regular deliveries of hydrogen to fuel the buses. AC Transit has expressed appreciation to APCI for its support, without which the agency would have been forced to park its fuel cell bus fleet for one year.

APCI Mobile Fueler

The temporary hydrogen fueling from APCI includes a mobile fueler and two additional tube trailers. The fuel is replenished by regular deliveries of liquid hydrogen that is vaporized to fill the tanks. Figure 4 shows the APCI mobile fueler being filled by the tanker truck. When the fueler was first put into use, AC Transit only had a few of its buses delivered, and APCI was delivering fuel an average of twice a week. As the new buses arrived and were placed into service, the need for fuel increased. AC Transit now gets daily deliveries of hydrogen Monday through Friday to meet its fleet needs. The contract with APCI is scheduled to carry the agency through the interim period while the Emeryville station is built. The current mobile fueling capabilities allow AC Transit to fuel and operate up to nine fuel cell buses.

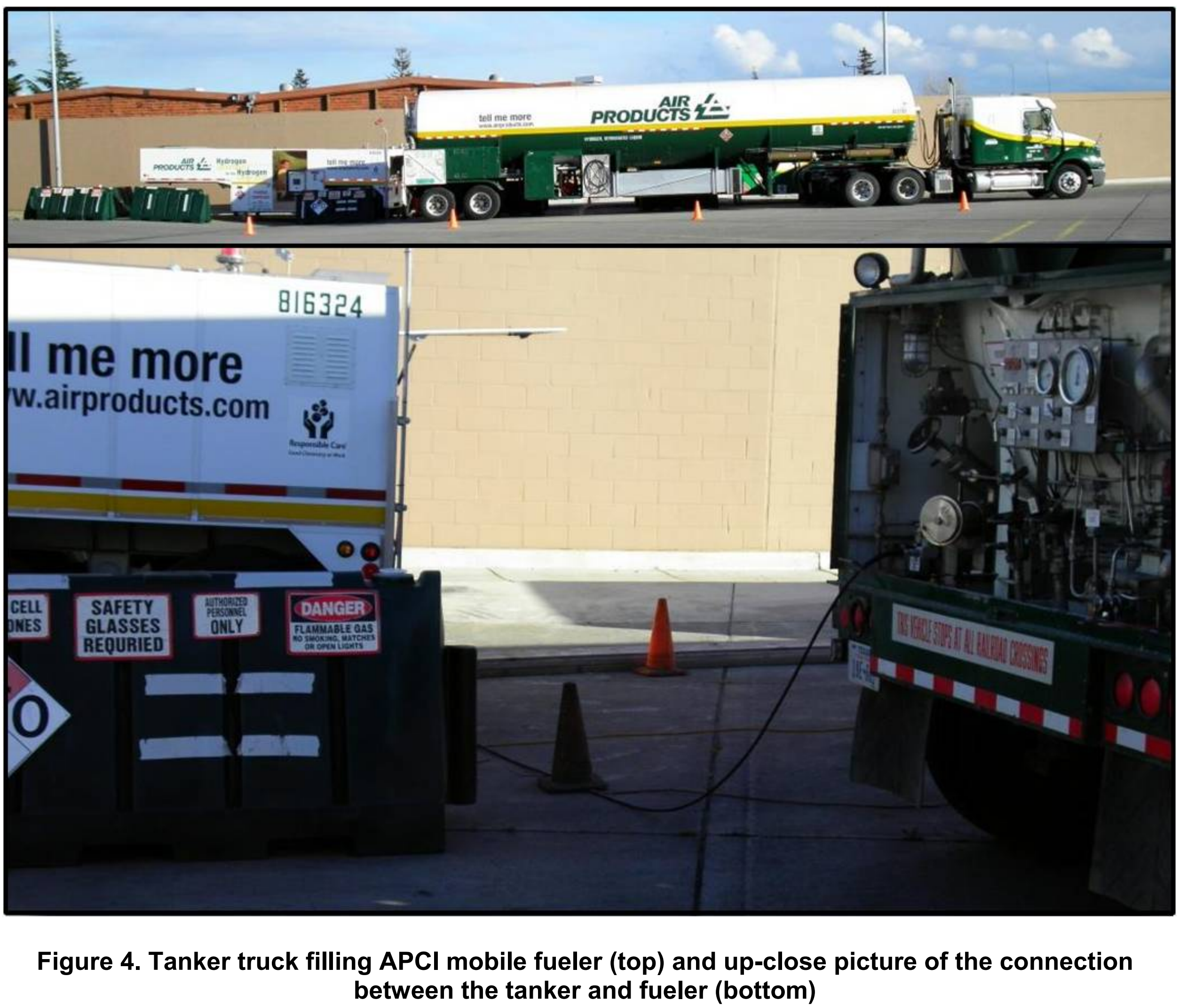

Figure 4. Tanker truck filling APCI mobile fueler (top) and up-close picture of the connection between the tanker and fueler (bottom)

Emeryville Hydrogen Fueling

AC Transit entered into a contract with Linde LLC in 2010 to build the hydrogen fueling station at Emeryville. This is a combined facility for light-duty fuel cell electric vehicles (FCEV) and fuel cell buses. Funding from the state of California made the light-duty FCEV fueling access possible – dispensers will be available to fuel at 350 and 700 bar pressure. Hydrogen is provided from two sources: liquid hydrogen delivery and a solar-powered electrolyzer. Hydrogen from both sources feeds into high pressure gaseous storage tubes for fueling buses and autos. A compressor boosts the pressure to 700 bar for FCEVs operating at the higher pressure. This new station will be a convenient fueling location for future bus operations by ZEBA partner transit agencies GGT and SFMTA. The current plan is for this station to be fully operational in August 2011. Figure 5 shows the progress in construction as of early June 2011.

Figure 5. Construction progress on the Emeryville hydrogen fueling station

Oakland Hydrogen Fueling

AC Transit has also contracted with Linde for the new station planned for the Seminary Division in Oakland. This station will be similar in design to the one at Emeryville. The primary differences are:

- Bus dispensers will be installed in-line with the diesel fueling island
- There will be no public access for light-duty FCEV fueling because the station is at the back of the property
- Hydrogen will be available at 350 bar pressure only
- The on-site electrolyzer will be powered by a solid oxide fuel cell fueled with directed biogas.[7]

[7] Directed biogas implies a process of purified biomethane (methane/natural gas developed from decaying organic matter) being injected into the natural gas pipeline. Designated customers of the biomethane do not use the identical biomethane, but can take credit for using the biomethane when using natural gas from the pipeline.

At the time of this report, the station is in the design phase. AC Transit's goal for completing the second station is by mid-2012. This station location will be more convenient for use by ZEBA partner agencies VTA and SamTrans.

When AC Transit first began operating fuel cell buses, the agency converted one of the maintenance bays at the Seminary Division to accommodate hydrogen-fueled buses. This bay will be available for the new fleet; however, the agency also has plans to upgrade a bay at the Emeryville Division in 2012 to make maintenance more convenient once there are buses operating from that location (planned to start in August 2011).

Implementation Experience

The new fuel cell buses were built at the Van Hool plant in Belgium. The manufacturer had two fuel cell power plants on-site for testing the buses. Once each bus was completed and tested, the test fuel cell power plant was removed and the bus was shipped to California. The bus was transported from the shipping port to AC Transit, where the maintenance staff and UTC Power engineer installed the fuel cell power plant. Currently, nine fuel cell buses have been delivered, and as of this report, seven of those buses are in revenue service as shown in Table 3. The delivery of the fuel cell buses has taken longer than originally anticipated; however, this was not a significant problem due to the delay in having the Emeryville fueling available and the nine-bus limitation of the APCI temporary fueling solution. The manufacturers also delivered another four fuel cell buses to UTC Power/CTTRANSIT during this timeframe.

The start date of evaluation for each bus, shown in Table 3, was chosen for convenience of the data analysis and results presentations. At a later date and in future reports, there will be a "clean point" chosen for the full NREL evaluation of the operation of these fuel cell buses and the hydrogen fueling infrastructure. That date will most likely occur after the Emeryville fueling is in full operation.

Table 3. Delivery and Start of Service for ZEBA Fuel Cell Buses

Bus Number	Arrived at AC Transit	Start Service	Evaluation Start
FC4	5/26/2010	9/9/2010	Sep 2010
FC5	8/19/2010	12/2/2010	Dec 2010
FC6	7/7/2010	8/23/2010	Sep 2010
FC7	8/17/2010	9/10/2010	Sep 2010
FC8	10/27/2010	2/2/2011	Feb 2011
FC9	2/11/2011	4/28/2011	May 2011
FC10	2/28/2011	4/25/2011	May 2011
FC11	4/27/2011	6/16/2011	July 2011
FC12	5/4/2011	6/29/2011	July 2011
FC14–FC16	Planned 8/15/2011		

As part of the NFCBP accelerated testing of the first three fuel cell buses at AC Transit, two of the three fuel cell power systems are still operating in new fuel cell buses; the power system from the bus operating in Belgium is also still in operation.

- The fuel cell power system from FC1 was installed into FC4 (May 2010) for testing and start of service activities and then replaced with a new fuel cell power system (August 2010).
- The fuel cell power system from FC2 was installed into FC7 (August 2010), and it is still in operation as the fleet leader with more than 9,000 hours of operation with no significant maintenance required.
- The fuel cell power system from FC3 was installed into FC8 (October 2010), and it is still in operation with more than 7,000 hours of operation with no significant maintenance required.
- The fuel cell power system from the bus operating in Belgium was installed into FC6 (August 2010), and it is still in operation with more than 5,000 hours of operation with no significant maintenance required.

Early in the demonstration of the first three fuel cell buses at AC Transit, the fuel cell power systems were at end of life before 2,000 hours; these results now indicate that 10,000 hours is within reach for one system. The fact that two more fuel cell power systems have 5,000 and 7,000 hours of operation indicates that this one system nearing 10,000 hours is not an anomaly, and it is a strong indicator of progress in the durability of the fuel cell power systems.

Bus-Related Issues

All new transit buses typically have a few issues that need to be resolved. These new fuel cell buses are no exception; however, only a few significant problems were experienced as follows:

- **Fuel line contamination** – Some of the stainless steel tubing used for the fueling system onboard the buses had process control issues. Some of the tubing was not properly cleaned out by the supplier before being delivered to Van Hool for installation, and the problem was not discovered until after the first few buses were delivered. The tubing was inspected and replaced as needed during October and November 2010.
- **Fuel flow issue** – A few of the fuel cell buses had a problem with the fuel supply valve restricting fuel flow. This problem was particularly pronounced on bus FC8 but was noted to some degree on all of the buses. The issue was resolved with bus FC8 in April 2011. The remainder of the buses will be repaired on a scheduled monthly basis.
- **Fire detection system** – In a couple of cases, the fire suppression system has indicated a fire and displayed system trouble alarms and dash lights causing the bus to be roadcalled. There was no indication of fire and the problem has been repaired and is being monitored and reviewed regularly to verify the resolution.

Fueling-Related Challenges

Although AC Transit gained valuable experience in planning for the original hydrogen fueling station in Oakland, several unforeseen problems caused delays in getting the Emeryville station constructed. When water was found during ground sampling early in the process, the agency was required to add stabilization to the area to prevent potential issues. The city required measures to adequately handle storm water runoff at the site. AC Transit personnel researched local businesses to determine which had had success with storm water mitigation. Once construction began, the area experienced an atypical weather pattern of back-to-back rain storms that turned the excavation into swimming pools. Other issues that were not expected included the need to remove several large trees and a local requirement for the use of art in the new construction. The agency was able to solve all these issues, but not without significant schedule delays and added expense.

Operations Plan

Once all of the buses are delivered and the Emeryville station is operational (planned for August 2011), the buses will be moved from the Seminary Division to the Emeryville Division. The entire fuel cell bus fleet will operate from Emeryville until the new hydrogen fueling station at Seminary is completed. At that time, the fleet will be split – six buses operating out of Seminary and six out of Emeryville. The ZEBA partner agencies will be able to operate as many as two buses each in their respective service area at prearranged times. GGT will be the first of the agencies to operate the new buses, primarily because the Emeryville station is located in closer proximity to their service area than to the other agencies. GGT is currently planning that operation and is working with AC Transit to finalize logistics of getting the buses back to Emeryville for daily fueling.

The SamTrans and VTA service areas are closer to the Seminary Division. Once the new station is operational at that division (planned for mid-2012), those partner agencies will explore the potential of operating fuel cell buses in their fleets.

Evaluation Results

The results presented in this section are early/preliminary information from the first five fuel cell buses that have been placed into service at AC Transit. The results period presented is from September 2010 through May 2011. These early results are presented as progress toward the full evaluation planned to begin once all of the buses go into service and hydrogen fueling is fully available for the entire fuel cell bus fleet.

Three diesel buses were selected as a comparison to the fuel cell buses. Similar route blocks have been selected for operation of the twelve fuel cell buses and three diesel buses operating from the Emeryville Division (August 2011).

Route Assignments

The fuel cell buses are currently operated from AC Transit's Seminary Division, which operates 15 local, 2 all-nighter, 10 transbay, and 14 school routes with a total of 179 buses (138 buses for peak service). The average bus operating speed for weekday service from this division is 14.3 mph. The fuel cell buses have been operating in service on AC Transit's local routes 21, 73, and 98. These route assignments are generally 160 to 190 miles in length and include 14 to 16 hours of operation time (around 12 mph average speed). The three baseline diesel buses have been operating from AC Transit's Emeryville Division on local routes 18 and 51B, which are 160 to 200 miles in length with 19 to 20 hours of operation (around 10 mph average speed). When the fuel cell buses move to the Emeryville Division, they will also operate on the 18 and 51B local routes.

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage may indicate downtime for maintenance or purposeful reduction of planned work for the buses. This section summarizes bus usage and availability for the two study groups of buses.

Table 4 summarizes average monthly mileage for the study buses through May 2011. Several of the fuel cell buses are just going into service, and overall the fuel cell buses have achieved 56% of the usage of the diesel buses.

Table 4. Average Monthly Mileage (evaluation period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage
FC4	3,402	21,448	18,046	9	2,005
FC5	1,375	15,373	13,998	6	2,333
FC6	1,231	25,460	24,229	9	2,692
FC7	0	18,024	18,024	9	2,003
FC8	1,046	4,065	3,019	4	755
FC9	1,238	2,937	1,699	1	1,699
FC10	1,130	2,143	1,013	1	1,013
Fuel Cell			**80,028**	**39**	**2,052**
1209			33,804	9	3,756
1210			31,013	9	3,446
1211			34,645	9	3,849
Diesel			**99,462**	**27**	**3,684**

Another measure of reliability is availability—the percentage of days that the buses are planned for operation compared with the days the buses are actually available. Figure 6 shows availability for each of the fuel cell buses during the reporting period (October 2010 through May 2011). Table 5 summarizes the reasons for availability and unavailability for the fuel cell buses. During this reporting period, the average availability for the fuel cell buses was 63%. Bus-related maintenance is the reason for the highest percentage of unavailability (75% of all unavailable days).

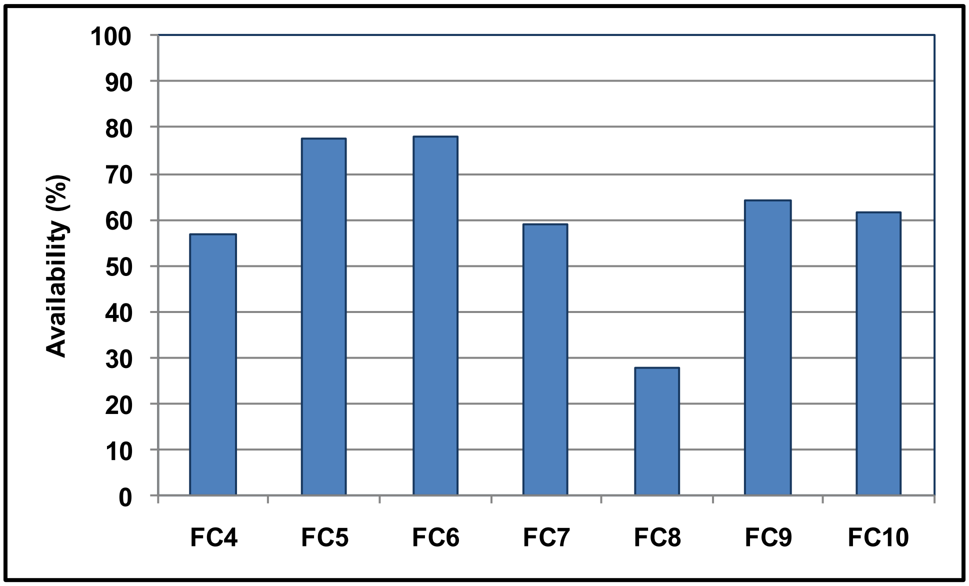

Figure 6. Availability for individual fuel cell buses

Table 5. Summary of Reasons for Availability and Unavailability of Buses for Service

Category	Group Total	
	Days	%
Planned work days	826	
Days available	519	63
Available	**519**	**100**
On route	460	89
Event/demonstration	7	1
Training	17	3
Not used	35	7
Unavailable	**307**	**100**
Fuel cell propulsion	22	7
Hybrid propulsion	3	1
Traction battery issues	29	9
Bus maintenance	230	75
Fueling unavailable	23	8

Fuel Economy and Cost

As discussed above, hydrogen fuel is currently provided by an APCI temporary fueling solution located at AC Transit's Seminary Division. The hydrogen is dispensed at up to 350 bar (5,000 psi). AC Transit employees performed nearly all fueling services for the hydrogen-fueled vehicles, and APCI electronically reported the fueling amounts. Currently, the hydrogen fuel dispensed is being measured based on the amount of fuel in the temporary fueling station and not with a direct mass flow measurement. In general, the hydrogen fueling amount measurements have not been as accurate as will be available from the permanent fueling station. These fuel consumption and economy measurements may change significantly when the new fueling station is brought online.

Table 6 shows hydrogen and diesel fuel consumption and fuel economy for the study buses during the reporting period. Overall, the fuel cell buses averaged 5.36 miles per kilogram of hydrogen, which equates to 6.05 miles per DGE. The energy conversion from kilograms of hydrogen to DGE appears at the end of Appendix A. (Appendix B contains the summary statistics in SI units.) These early results indicate that the fuel cell buses have an average fuel economy that is 52% higher than similar diesel buses.

Table 6. Fuel Use and Economy (evaluation period)

Bus	Mileage (fuel base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (gallon)	Miles per Gallon (mpg)
FC4	16,237	2,828.5	5.74	2,503.1	6.49
FC5	13,598	2,495.0	5.45	2,208.0	6.16
FC6	22,703	4,297.4	5.28	3,803.0	5.97
FC7	16,476	3,237.9	5.09	2,865.4	5.75
FC8	2,850	569.0	5.01	503.5	5.66
FC9	1,487	260.2	5.72	230.2	6.46
FC10	1,013	195.5	5.18	173.0	5.86
FCB Total	**74,364**	**13,883.4**	**5.36**	**12,286.2**	**6.05**
1209					
1210					
1211					
Diesel Total					**3.99**

Figure 7 shows monthly average fuel economy in both miles per kilogram and miles per DGE for the fuel cell buses. As the chart shows, starting in March 2011 a change in the software control of the battery energy storage (to allow more regenerative braking energy) has increased the fuel economy generally by about 20%.

When the new hydrogen fueling station comes online, the cost of hydrogen production as dispensed is expected to be between $6 and $8 per kg. The costs of operating the new hydrogen fueling stations are planned to be tracked and reported once the stations start operation. With hydrogen at $8 per kg, the fuel cost per mile is $1.49. Diesel fuel cost during the reporting period was $2.67 per gallon and that calculates to $0.67 per mile.

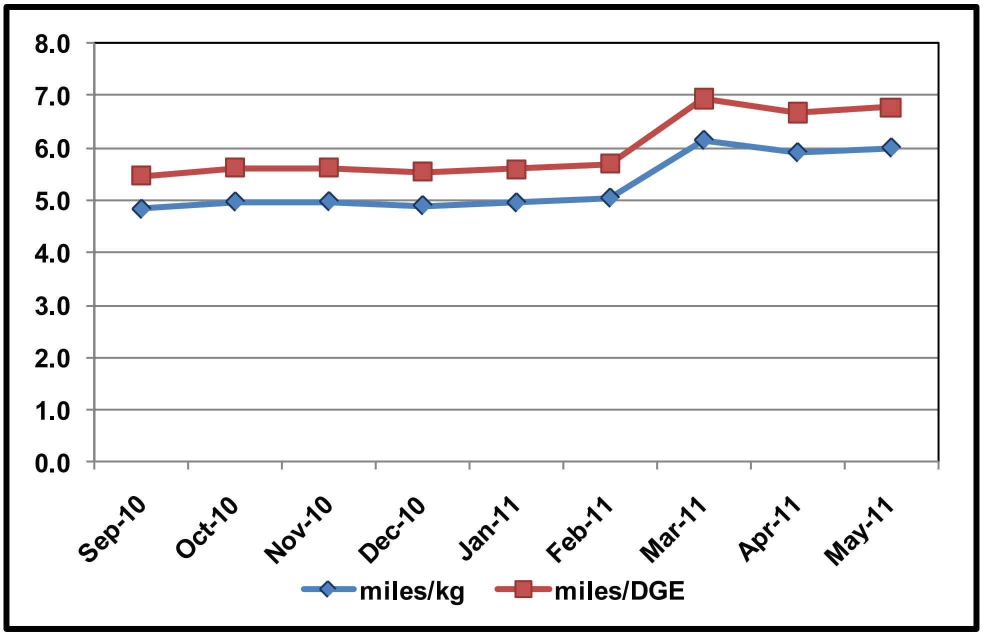

Figure 7. Average fuel economy for the fuel cell buses (evaluation period)

Maintenance Analysis

Warranty costs are not included in the cost-per-mile calculations. All work orders for the study buses were collected and analyzed for this evaluation. For consistency, the maintenance labor rate was kept at a constant $50 per hour; this does not reflect an average rate for AC Transit. This section first covers total maintenance costs and then maintenance costs by bus system.

Total maintenance costs – Total maintenance costs include the price of parts and 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 7 shows total maintenance costs for the fuel cell and diesel buses. Scheduled and unscheduled maintenance cost per mile is provided for each bus and study group of buses. Note that the fuel cell bus maintenance is supported by one of UTC Power's engineers at AC Transit. AC Transit has two mechanics/trainers assigned to maintain the fuel cell buses and provide training; a supervisor for the program (from a maintenance perspective); and plans to add another mechanic/trainer. In addition, AC Transit has resources from this program for cleaning, fueling, and performing body work and painting for the fuel cell fleet.

During the reporting period, the fuel cell buses had more than twice the cost per mile for maintenance compared to the three diesel buses.

Table 7. Total Maintenance Costs (evaluation period)

Bus	Mileage	Parts ($)	Labor Hours	Total Cost per Mile ($)	Scheduled Cost per Mile ($)	Unscheduled Cost per Mile ($)
FC4	18,046	2,811.07	527.7	1.62	0.30	1.32
FC5	13,998	1,183.77	334.7	1.28	0.18	1.10
FC6	24,229	3,694.45	512.6	1.21	0.20	1.01
FC7	18,024	1,088.10	551.9	1.59	0.26	1.33
FC8	3,019	677.91	228.3	4.01	0.17	3.84
FC9	1,699	0.00	17.0	0.50	0.00	0.50
FC10	1,013	893.78	41.2	2.91	0.00	2.91
Total Fuel Cell	**80,028**	**10,349.08**	**2,213.2**	**1.51**	**0.23**	**1.29**
1209	33,804	6,492.37	267.4	0.59	0.13	0.46
1210	31,013	8,246.53	367.4	0.86	0.12	0.74
1211	34,645	4,395.63	304.9	0.57	0.09	0.48
Total Diesel	**99,462**	**19,134.53**	**939.7**	**0.66**	**0.11**	**0.55**

Maintenance costs categorized by system – Table 8 shows maintenance costs by vehicle system and bus study group (without warranty costs). The vehicle systems shown in the table are as follows:

- **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, nonlighting 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**

Table 8. Maintenance Cost per Mile by System (Evaluation Period)

System	Fuel Cell		Diesel	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Cab, body, and accessories	0.66	44	0.27	40
Propulsion-related	0.50	33	0.17	25
PMI	0.19	13	0.08	12
Brakes	0.02	1	0.05	7
Frame, steering, and suspension	0.02	1	0.01	2
HVAC	0.03	2	0.04	6
Lighting	0.03	2	0.02	3
Air, general	0.06	4	0.01	2
Axles, wheels, and drive shaft	0.00	0	0.02	3
Tires	0.00	0	0.00	0
Total	**1.51**	**100**	**0.67**	**100**

The systems with the highest percentage of maintenance costs for the fuel cell and diesel buses were cab, body, and accessories; propulsion-related; and PMI.

Propulsion-related maintenance costs – Propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, nonlighting electrical, and transmission systems.

Table 9 shows the propulsion-related system repairs by category for the two study groups during the reporting period. The fuel cell buses had higher maintenance costs, which indicate the amount of AC Transit mechanic labor that goes to support and maintain the fuel cell buses. UTC Power still has an engineer on-site to supervise and complete maintenance of the fuel cell power system and related systems.

Table 9. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	80,028	99,462
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	1,511.78	7,262.74
Labor hours	771.6	186.15
Total cost ($)	40,092.78	16,570.24
Total cost ($) per mile	**0.50**	**0.17**
Exhaust System Repairs		
Parts cost ($)	0.00	0.00
Labor hours	0.0	4.5
Total cost ($)	0.00	224.50
Total cost ($) per mile	**0.00**	**0.00**
Fuel System Repairs		
Parts cost ($)	0.00	221.28
Labor hours	293.7	3.5
Total cost ($)	14,685.50	396.28
Total cost ($) per mile	**0.18**	**0.00**
Powerplant System Repairs		
Parts cost ($)	0.00	514.16
Labor hours	9.0	68.8
Total cost ($)	450.00	3,951.66
Total cost ($) per mile	**0.01**	**0.04**
Electric Motor and Propulsion Repairs		
Parts cost ($)	893.78	0.00
Labor hours	175.1	0.0
Total cost ($)	9,648.28	0.00
Total cost ($) per mile	**0.12**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	599.92	1,069.32
Labor hours	107.5	12.8
Total cost ($)	5,973.92	1,706.82
Total cost ($) per mile	**0.07**	**0.02**
Air Intake System Repairs		
Parts cost ($)	0.00	429.94
Labor hours	0.0	19.5
Total cost ($)	0.00	1,404.94
Total cost ($) per mile	**0.00**	**0.01**
Cooling System Repairs		
Parts cost ($)	0.00	4,972.70
Labor hours	0.0	66.7
Total cost ($)	0.00	8,305.70
Total cost ($) per mile	**0.00**	**0.08**
Transmission Repairs		
Parts cost ($)	0.00	55.33
Labor hours	4.0	9.5
Total cost ($)	200.00	530.33
Total cost ($) per mile	**0.00**	**0.01**

Roadcall Analysis

A roadcall or revenue vehicle system failure (as named in the National Transit Database[8]) 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.[9] If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a roadcall. The analysis described here includes only roadcalls that were caused by "chargeable" failures. Chargeable roadcalls include systems that can physically disable the bus from operating on route, such as interlocks (doors, air system), engine, or things that are deemed to be safety issues if operation of the bus continued. They do not include roadcalls for things such as problems with radios or destination signs.

Table 10 shows the roadcalls and MBRC for each study bus categorized by all roadcalls and propulsion-related-only roadcalls. The diesel buses have better MBRC rates for both categories; however, the fuel cell power system has only had two roadcalls and has an MBRC of 40,014.

Table 10. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC	Fuel-Cell-Only MBRC
FC4	18,046	7	2,578	2	9,023	
FC5	13,998	4	3,500	3	4,666	
FC6	24,299	4	6,075	1	24,299	
FC7	18,024	8	2,253	6	3,004	
FC8	3,019	3	1,006	3	1,006	
FC9	1,699	1	1,699	1	1,699	
FC10	1,013	1	1,013	1	1,013	
Total FCB	**80,028**	**28**	**2,858**	**17**	**4,708**	**40,014**
1209	33,804	5	6,761	0		
1210	31,013	9	3,446	5	6,203	
1211	34,645	15	2,310	6	5,774	
Total Diesel	**99,462**	**29**	**3,430**	**11**	**9,042**	

[8] National Transit Database website: www.ntdprogram.gov/ntdprogram/

[9] AC Transit defines a significant delay as 6 or more minutes.

What's Next for ZEBA

AC Transit continues to operate the fuel cell buses from the Seminary Division. The final three buses are scheduled to arrive by early September 2011 and will be placed in service soon after. The hydrogen fueling station at Emeryville is under construction and scheduled for commissioning in August. Once the station is operational, the buses will be moved to that location. The entire fleet of fuel cell buses will be operated from the Emeryville Division until the new Oakland hydrogen fueling station is built. Once that station is complete, AC Transit will operate six buses out of each division.

GGT is planning to begin operating two of the buses by mid-summer. The agency will arrange to bring the buses to Emeryville to fuel each day. Because VTA and SamTrans are located in the southern Bay Area, those agencies will wait until the Seminary Division station is completed before they plan to operate any of the fuel cell buses. Although the SFMTA is not required to participate in the demonstration, the agency is exploring the possibility of operating one of the fuel cell buses in San Francisco.

NREL will continue to evaluate the buses in service at AC Transit and will collect data and experience from the other operators once they put buses in service. VTA and GGT also operate diesel hybrid-electric buses. NREL is planning to collect data on the hybrid buses to compare fuel efficiency to the fuel cell buses in similar service. The next report is expected in early 2012.

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Appendix A: Fleet Summary Statistics

Fleet Summary Statistics: ZEBA Fuel Cell Bus and Diesel Bus Groups and Evaluation Periods

Fleet Operations and Economics

	Fuel Cell Buses	Diesel Buses
Number of vehicles	3 up to 7	3
Period used for fuel and oil op analysis	9/10-5/11	9/10-5/11
Total number of months in period	9	9
Fuel and oil analysis base fleet mileage	74,364	N/A
Period used for maintenance op analysis	9/10-5/11	9/10-5/11
Total number of months in period	9	9
Maintenance analysis base fleet mileage	80,028	99,462
Average monthly mileage per vehicle	2,052	3,684
Availability	63%	N/A
Fleet fuel usage in H_2 kg/Diesel gal	13,883	N/A
Roadcalls	29	29
RCs MBRC	2,760	3,430
Propulsion roadcalls	18	11
Propulsion MBRC	4,446	9,042
Fleet miles/kg hydrogen	5.36	
(1.13 kg H_2/gal diesel fuel)		
Representative fleet MPG (energy equiv)	6.05	3.99
Hydrogen cost per kg	8.00	
Diesel gal cost		2.67
Fuel cost per mile	**1.49**	**0.67**
Total scheduled repair cost per mile	0.23	0.11
Total unscheduled repair cost per mile	1.29	0.55
Total maintenance cost per mile	**1.51**	**0.66**
Total operating cost per mile	**3.01**	**1.33**

Maintenance costs

	Fuel Cell Buses	Diesel Buses
Fleet mileage	80,028	99,462
Total parts cost	10,349.08	19,134.51
Total labor hours	2213.2	939.7
Average labor cost (@ $50.00 per hour)	110,660.50	46,984.00
Total maintenance cost	121,009.58	66,118.51
Total maintenance cost per bus		22,039.50
Total maintenance cost per mile	**1.51**	**0.66**

Breakdown of Maintenance Costs by Vehicle System

	Fuel Cell Buses	Diesel Buses
Fleet mileage	80,028	99,462
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)		
Parts cost	1,511.78	7,262.74
Labor hours	771.62	186.15
Average labor cost	38,581.00	9,307.50
Total cost (for system)	40,092.78	16,570.24
Total cost (for system) per bus		5,523.41
Total cost (for system) per mile	**0.50**	**0.17**
Exhaust System Repairs (ATA VMRS 43)		
Parts cost	0.00	0.00
Labor hours	0.0	4.5
Average labor cost	0.00	224.50
Total cost (for system)	0.00	224.50
Total cost (for system) per bus		74.83
Total cost (for system) per mile	**0.00**	**0.00**
Fuel System Repairs (ATA VMRS 44)		
Parts cost	0.00	221.28
Labor hours	293.7	3.5
Average labor cost	14,685.50	175.00
Total cost (for system)	14,685.50	396.28
Total cost (for system) per bus		132.09
Total cost (for system) per mile	**0.18**	**0.00**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts cost	0.00	514.16
Labor hours	9.0	68.8
Average labor cost	450.00	3,437.50
Total cost (for system)	450.00	3,951.66
Total cost (for system) per bus		1,317.22
Total cost (for system) per mile	**0.01**	**0.04**
Electric Propulsion Repairs (ATA VMRS 46)		
Parts cost	893.78	0.00
Labor hours	175.1	0.0
Average labor cost	8,754.50	0.00
Total cost (for system)	9,648.28	0.00
Total cost (for system) per bus		0.00
Total cost (for system) per mile	**0.12**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell Buses	Diesel Buses
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts cost	599.92	1,069.32
Labor hours	107.5	12.8
Average labor cost	5,374.00	637.50
Total cost (for system)	5,973.92	1,706.82
Total cost (for system) per bus		568.94
Total cost (for system) per mile	**0.07**	**0.02**
Air Intake System Repairs (ATA VMRS 41)		
Parts cost	0.00	429.94
Labor hours	0.0	19.5
Average labor cost	0.00	975.00
Total cost (for system)	0.00	1,404.94
Total cost (for system) per bus		468.31
Total cost (for system) per mile	**0.00**	**0.01**
Cooling System Repairs (ATA VMRS 42)		
Parts cost	0.00	4,972.70
Labor hours	0.0	66.7
Average labor cost	0.00	3,333.00
Total cost (for system)	0.00	8,305.70
Total cost (for system) per bus		2,768.57
Total cost (for system) per mile	**0.00**	**0.08**
Hydraulic System Repairs (ATA VMRS 65)		
Parts cost	0.00	0.00
Labor hours	0.0	0.0
Average labor cost	0.00	0.00
Total cost (for system)	0.00	0.00
Total cost (for system) per bus		0.00
Total cost (for system) per mile	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)		
Parts cost	0.00	84.85
Labor hours	97.0	18.0
Average labor cost	4,850.00	900.00
Total cost (for system)	4,850.00	984.85
Total cost (for system) per bus		328.28
Total cost (for system) per mile	**0.06**	**0.01**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell Buses	Diesel Buses
Brake System Repairs (ATA VMRS 13)		
Parts cost	12.70	2,254.99
Labor hours	28.0	49.0
Average labor cost	1,400.00	2,450.00
Total cost (for system)	1,412.70	4,704.99
Total cost (for system) per bus		1,568.33
Total cost (for system) per mile	**0.02**	**0.05**
Transmission Repairs (ATA VMRS 27)		
Parts cost	0.00	55.33
Labor hours	4.0	9.5
Average labor cost	200.00	475.00
Total cost (for system)	200.00	530.33
Total cost (for system) per bus		176.78
Total cost (for system) per mile	**0.00**	**0.01**
Inspections Only - no parts replacements (101)		
Parts cost	0.00	0.00
Labor hours	305.0	161.3
Average labor cost	15,251.00	8,062.50
Total cost (for system)	15,251.00	8,062.50
Total cost (for system) per bus		2,687.50
Total cost (for system) per mile	**0.19**	**0.08**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts cost	6,773.61	3,951.08
Labor hours	917.9	449.7
Average labor cost	45,897.00	22,485.00
Total cost (for system)	52,670.61	26,436.08
Total cost (for system) per bus		8,812.03
Total cost (for system) per mile	**0.66**	**0.27**
HVAC System Repairs (ATA VMRS 01)		
Parts cost	867.49	3,069.39
Labor hours	26.0	21.3
Average labor cost	1,300.00	1,062.50
Total cost (for system)	2,167.49	4,131.89
Total cost (for system) per bus		1,377.30
Total cost (for system) per mile	**0.03**	**0.04**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell Buses	Diesel Buses
Lighting System Repairs (ATA VMRS 34)		
Parts cost	1,183.52	729.23
Labor hours	17.2	24.0
Average labor cost	857.50	1,200.00
Total cost (for system)	2,041.02	1,929.23
Total cost (for system) per bus		643.08
Total cost (for system) per mile	**0.03**	**0.02**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts cost	0.00	442.63
Labor hours	39.0	13.8
Average labor cost	1,949.50	691.50
Total cost (for system)	1,949.50	1,134.13
Total cost (for system) per bus		378.04
Total cost (for system) per mile	**0.02**	**0.01**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts cost	0.00	1,339.60
Labor hours	3.8	16.5
Average labor cost	191.50	825.00
Total cost (for system)	191.50	2,164.60
Total cost (for system) per bus		721.53
Total cost (for system) per mile	**0.00**	**0.02**
Tire Repairs (ATA VMRS 17)		
Parts cost	0.00	0.00
Labor hours	6.0	0.0
Average labor cost	300.00	0.00
Total cost (for system)	300.00	0.00
Total cost (for system) per bus		0.00
Total cost (for system) per mile	**0.00**	**0.00**

Notes

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

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

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

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

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

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

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

7. Warranty costs are not included.

Appendix B: Fleet Summary Statistics – SI Units

Fleet Summary Statistics: ZEBA Fuel Cell Bus and Diesel Bus Groups and Evaluation Periods

Fleet Operations and Economics

	Fuel Cell Buses	Diesel Buses
Number of vehicles	3 up to 7	3
Period used for fuel and oil op analysis	9/10-5/11	9/10-5/11
Total number of months in period	9	9
Fuel and oil analysis base fleet kilometers	119,674	N/A
Period used for maintenance op analysis	9/10-5/11	9/10-5/11
Total number of months in period	9	9
Maintenance analysis base fleet kilometers	128,789	160,064
Average monthly kilometers per vehicle	3,302	5,928
Availability	63%	N/A
Fleet fuel usage in H2 kg	13,883	N/A
Roadcalls	29	29
RCs KMBRC	4,441	5,519
Propulsion roadcalls	18	11
Propulsion KMBRC	7,155	14,551
Fleet kg hydrogen/100 km	11.60	
(1.13 kg H2/gal diesel fuel)		
Rep. fleet fuel consumption (L/100 km)	38.86	59.29
Hydrogen cost per kg	8.00	
Diesel cost/liter		0.71
Fuel cost per kilometer	**0.93**	**0.42**
Total scheduled repair cost per kilometer	0.14	0.07
Total unscheduled repair cost per kilometer	0.80	0.34
Total maintenance cost per kilometer	**0.94**	**0.41**
Total operating cost per kilometer	**1.87**	**0.83**

Maintenance costs

	Fuel Cell Buses	Diesel Buses
Fleet mileage	128,789	160,064
Total parts cost	10,349.08	19,134.51
Total labor hours	2213.2	939.7
Average labor cost (@ $50.00 per hour)	110,660.00	46,985.00
Total maintenance cost	121,009.08	66,119.51
Total maintenance cost per bus		22,039.84
Total maintenance cost per kilometer	**0.94**	**0.41**