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National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2



Alameda-Contra Costa Transit District
(AC Transit)



June 2010

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13. ABSTRACT (Maximum 200 words) This is an evaluation of hydrogen fuel cell transit buses operating at AC Transit in revenue service since March 20, 2006 compared to similar diesel buses operating from the same depot. This evaluation report includes results from November 2007 through February 2010. Evaluation results include implementation experience, fueling station operation, evaluation results at AC Transit (bus usage, availability, fuel economy, maintenance costs, and roadcalls), and a summary of achievements and challenges encountered during the demonstration.				
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Executive Summary

The Alameda-Contra Costa Transit District (AC Transit) has been operating three fuel cell buses in revenue service since March 20, 2006. This operation has been documented in previous evaluation reports from the U.S. Department of Energy (DOE), the U.S. Department of Transportation's Federal Transit Administration (FTA), and DOE's National Renewable Energy Laboratory (NREL). This report continues the evaluation at AC Transit; the funding for NREL's data collection and analysis was transitioned from DOE to the FTA. Specifically, this report presents the results of AC Transit's accelerated testing of its existing three fuel cell buses as part of the FTA's National Fuel Cell Bus Program (NFCBP).

Accelerated Testing

The accelerated testing project at AC Transit includes preparation and support to maximize operation of the three fuel cell buses, and support of the transition to the next phase of the fuel cell bus program. The maximized operation will help the manufacturers further validate the propulsion system by identifying the weakest areas, analyzing the root causes of failure, and making modifications and upgrades to increase durability and reliability.

The accelerated testing results in this report cover operation from November 2007 through February 2010 for the fuel cell buses, with a focus on fuel cell bus operations from the last installation of new fuel cell power systems (noted as the clean point). The diesel bus evaluation results are from January through December 2007. The evaluation results are summarized in Table ES-1. This report also describes the achievements and challenges from nearly 4 years of revenue service.

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell	Diesel
Number of Buses	3	6
Data Period	Clean Point – 2/10	1/07 – 12/07
Number of Months	~25	12
Total Mileage in Period	160,027	266,514
Average Monthly Mileage per Bus	2,101	3,702
Total Fuel Cell Operating Hours	16,403	N/A
Average Bus Operating Speed (mph)	9.8	N/A
Availability (85% is target)	66%	N/A
Fuel Economy (miles/kg)	6.01	N/A
Fuel Economy (miles/DGE ^a)	6.79	4.20
Miles between Roadcalls (MBRC) – All	1,185	4,299
MBRC – Propulsion Only	1,539 ^b	10,661
Total Maintenance (\$/mile) ^c	0.74	0.49
Maintenance – Propulsion Only (\$/mile)	0.19	0.10

^a Diesel gallon equivalent.

^b For fuel cell propulsion only, MBRC was 10,002.

^c Work order maintenance cost.

What's on the Horizon for AC Transit?

AC Transit is moving into the next phase of fuel cell bus development, demonstrating 12 new and advanced fuel cell buses. This demonstration is in response to the California Air Resources Board (CARB) Transit rule that requires several California agencies (including AC Transit) to purchase new and advanced fuel cell buses as part of their zero-emission bus regulations. Developed by UTC Power and Van Hool, the new buses incorporate the lessons learned during the demonstration of the current fuel cell buses.

AC Transit is the managing partner for a Zero Emission Bay Area (ZEBA) working group to respond to CARB's advanced fuel cell bus demonstration. The ZEBA group includes several Bay Area transit agencies:

- AC Transit
- Santa Clara Valley Transportation Authority
- Golden Gate Transit (GGT)
- San Mateo County Transit District
- San Francisco Municipal Transportation Agency (SF MTA).¹

AC Transit continues to work on developing hydrogen fueling infrastructure to support the new fuel cell buses. The Chevron station at the East Oakland Division that has been used for hydrogen fueling is scheduled for decommission in September 2010. AC Transit is working with Linde to construct new stations at East Oakland as well as its Emeryville depot (Division 2). The new Emeryville station will be a convenient fueling location for future bus operations by ZEBA partner transit agencies like GGT and SF MTA.

The current evaluation of accelerated testing at AC Transit was funded by FTA in conjunction with their NFCBP. With the completion of this report, the evaluation funding will be transitioned from FTA back to DOE. The DOE evaluation plans include all 12 of the new fuel cell buses for the planned ZEBA/CARB demonstration.

¹ SF MTA is a voluntary participant. Its fleet of trolley buses already meets CARB zero-emission bus regulations.

Table of Contents

Introduction and Background	1
National Fuel Cell Bus Program	1
AC Transit Fuel Cell Bus Operation and Evaluation	2
Accelerated Testing at AC Transit	3
What’s in this Evaluation Report?	4
Demonstration Achievements and Challenges	5
Bus Operations	5
Hydrogen Fueling	7
Facility Modifications	7
Training	8
Public Awareness	8
Coordination with Golden Gate Transit	8
Public Outreach	8
Passenger Survey Results	9
Ridership	9
Hydrogen Fueling	10
Fuel Cell Bus Operations—Evaluation Results	13
Route Descriptions	13
Bus Use and Availability	14
Fuel Economy and Cost	16
Maintenance Analysis	18
Roadcall Analysis	23
What’s Next for AC Transit?	24
Contacts	26
Acronyms and Abbreviations	27
Bibliography	28
AC Transit	28
City of Burbank	28
General	28
SunLine	28
Connecticut Transit	29
Santa Clara Valley Transportation Authority	29

Introduction and Background

The Alameda-Contra Costa Transit District (AC Transit) has been operating three fuel cell buses in revenue service since March 20, 2006. The early operation was documented in three previous evaluation reports from the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL).^{2,3,4} In November 2007, the funding for NREL's data collection and analysis transitioned from DOE to the FTA; the funding will return to DOE after publication of this report. This report covers the results of AC Transit's accelerated testing of its existing three fuel cell buses as part of FTA's National Fuel Cell Bus Program (NFCBP). NREL reported on the first half of the accelerated testing results in January 2009.⁵ The accelerated testing evaluation results in this report add operations from November 2008 through February 2010. This report completes NREL's accelerated testing and evaluation work for this fuel cell bus design. Under DOE funding, NREL will continue to work with AC Transit to evaluate the next-generation fuel cell bus project, which is expected to start when the first of 12 new buses is delivered in May 2010.

National Fuel Cell Bus Program

In 2006, FTA initiated the NFCBP,⁶ which supplied \$49 million over 4 years in competitive, 50-50 government-industry cost share grants to facilitate the development of commercially viable fuel cell bus technologies. This FTA program was funded as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)⁷. The objectives of the program include:



- Developing improved components and technologies for fuel cell buses, including fuel cell, energy storage, and power electronics technologies
- Demonstrating fuel cell buses equipped with these improved components and technologies
- Understanding the requirements of market introduction, including fuel supply, fueling infrastructure, supplier networks, maintenance, education, safety, and insurance
- Collaborating in developing design standards for fuel cell bus technologies.

On October 12, 2006, at SunLine Transit Agency, FTA awarded grants to three nonprofit consortia—CALSTART (Pasadena, California), Center for Transportation and the Environment (CTE, Atlanta, Georgia), and the Northeast Advanced Vehicle Consortium (NAVC, Boston,

² Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Preliminary Evaluation Results, February 2007, NREL/TP-560-41041, <http://www.nrel.gov/hydrogen/pdfs/41041.pdf>

³ Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Evaluation Results Update, October 2007, NREL/TP-560-42249, <http://www.nrel.gov/hydrogen/pdfs/42249.pdf>

⁴ Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Third Evaluation Report, July 2008, NREL/TP-560-43545-1, <http://www.nrel.gov/hydrogen/pdfs/43545-1.pdf>

⁵ National Fuel Cell Bus Program: Accelerated Testing Evaluation Report, January 2009, FTA-CO-26-7004-2009.1, <http://www.nrel.gov/hydrogen/pdfs/44820-1.pdf>

⁶ FTA Bus Research and Testing Web site: http://www.fta.dot.gov/assistance/technology/research_4578.html

⁷ www.fhwa.dot.gov/safetealu/

Massachusetts). Over a 4-year period, these consortia were funded to lead teams that develop and test components, conduct outreach, and demonstrate fuel cell buses in a variety of geographic locations and climates across the United States.

A portfolio of 14 projects (managed by the three consortia) was competitively selected by FTA to best advance fuel cell bus commercialization, including eight planned demonstration projects. Bus demonstration projects include both evolutionary and “clean sheet” approaches and incorporate multiple drive technologies and configurations, fuel cell stacks of different sizes, and various energy storage technologies. The buses being demonstrated incorporate components from four fuel cell power system manufacturers and various implementations of hybrid electric propulsion systems and energy storage—batteries and ultracapacitors.

For fiscal year 2010 into 2011, additional funding for the NFCBP was appropriated. This additional \$13.5 million will be competed among the three consortia already participating in the program under the same requirements as the other NFCBP projects. This new competition will focus on new projects that can advance project targets in the original program, contribute to the overall fuel cell bus research portfolio, and help further fuel cell bus commercialization in the near term.

Data collection, analysis, and reporting of the results of the demonstrations are all high priorities for FTA. As such, FTA is collaborating with DOE and NREL to ensure that data are collected on all fuel cell bus demonstrations in a complete and consistent manner. FTA tasked NREL as a third-party evaluator for the fuel cell buses developed and demonstrated under the NFCBP.

Under funding from DOE, NREL has been evaluating fuel cell buses to help determine the status of hydrogen and fuel cell systems in transit applications. NREL uses a standard data collection and analysis protocol that was established for DOE heavy-duty vehicle evaluations more than 10 years ago. In May 2008, NREL published *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*, which outlines the methodology and plans for both the DOE and FTA fuel cell bus evaluations⁸ to be performed by NREL. Appendix A is an overview of NREL’s transit bus evaluation activities for DOE and FTA.

AC Transit Fuel Cell Bus Operation and Evaluation

AC Transit offers public transit service in the East Bay of the San Francisco, California, area, including Oakland. The AC Transit service area of 360 square miles includes 13 cities and adjacent unincorporated areas in Alameda and Contra Costa counties. Since 2000, AC Transit has developed and operated a fuel cell demonstration program called the HyRoad. With a goal of demonstrating the viability of an emission-free transit system, this program includes fuel cell bus and passenger car operation, on-site hydrogen production, fueling, vehicle maintenance, public outreach and education, and safety training.

Golden Gate Transit (GGT), headquartered in San Rafael, California, is participating in the AC Transit fuel cell bus demonstration—it operated one of the fuel cell buses for nearly a month, from February 19 to March 21, 2008, and again in early July 2009 for an event. GGT is a part of

⁸ Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-560-42781, May 2008, <http://www.nrel.gov/hydrogen/pdfs/42781-1.pdf>

the Golden Gate Bridge, Highway, and Transportation District, which is headquartered in San Francisco, and serves the North Bay area. Appendix B supplies more information about AC Transit and GGT.

The fuel cell bus development is the result of collaboration between Van Hool, ISE Corporation, and UTC Power. The buses use the PureMotion⁹ 120 Fuel Cell Power System manufactured by UTC Power in a hybrid electric drive system designed by ISE. The energy storage in this hybrid system consists of three ZEBRA (sodium/nickel chloride, high temperature) traction batteries. In addition to the three fuel cell buses at AC Transit, two other buses of the same design are operating at SunLine Transit Agency and Connecticut Transit (CTTRANSIT). Results from the operation of these two fuel cell buses are reported separately by NREL and DOE.

The evaluation in this report also presents results from the operation of six Van Hool diesel buses in revenue service at the same location as the fuel cell buses. The diesel buses, which are used in the evaluation as a baseline, are equipped with Cummins ISL engines. Other than the fuel cell and hybrid electric propulsion system on the fuel cell buses, the only significant difference with the diesel buses is that they do not have air conditioning. This is an important detail in the fuel economy analysis and comparison. Appendix C gives more detail about the buses and propulsion technologies in this evaluation. Appendix D contains information about the hydrogen fueling station and facilities modified for use with hydrogen. Updated information regarding hydrogen dispensing into the fuel cell buses is discussed later in this report.

Accelerated Testing at AC Transit

The accelerated testing project at AC Transit continues the partnership with UTC Power and Van Hool for ongoing demonstration of the three fuel cell buses. As mentioned previously, the NFCBP introduced nonprofit consortia leads for this FTA program. The accelerated testing project at AC Transit is managed through CALSTART in Pasadena, California. CALSTART works with public and private partners to accelerate the growth of advanced transportation technologies, including fuel cells. CALSTART was tasked with managing 5 of the 14 projects in the NFCBP, including fuel cell bus demonstrations (such as the AC Transit demonstration) and development of advanced components related to fuel cell propulsion systems.¹⁰

The accelerated testing project at AC Transit involves preparation and support for maximizing operation of the three fuel cell buses and then supporting the transition to the next phase of the fuel cell bus program. The maximized operation includes operating the fuel cell buses in revenue service 15 to 19 hours per day, up to 7 days per week, and is intended to accelerate planning for resources and training at AC Transit to prepare to support nearly full transit operation of the fuel cell buses. The maximized operation is intended to help the manufacturers further validate the propulsion system, identifying the weakest areas, analyzing the root causes of failure, and making modifications and upgrades to increase durability and reliability. The resulting design changes are being incorporated into the next-generation systems, which will be used in AC Transit's next phase of operation with 12 new fuel cell buses, with delivery starting in second quarter 2010.

⁹ PureMotion is a registered trademark of UTC Power.

¹⁰ CALSTART Web site: www.calstart.org

The 12 new fuel cell buses are a part of a multi-operator bus demonstration in the Bay Area to meet regulations promulgated by the California Air Resources Board (CARB). This new demonstration, designated the Zero Emission Bay Area (ZEBA) demonstration group, will be managed from AC Transit and will include participation by Golden Gate Transit (GGT), Santa Clara Valley Transportation Authority (VTA), San Mateo County Transit District (SamTrans), and San Francisco Municipal Transportation Agency (SF MTA).

What's in this Evaluation Report?

This accelerated testing evaluation report completes the analysis results for this fuel cell bus design and implementation from Van Hool, ISE Corporation, and UTC Power. These three fuel cell buses will be taken out of service as the first three new fuel cell buses from Van Hool and UTC Power arrive at AC Transit. The fuel cell power systems in the existing buses will be installed in the first three new fuel cell buses and will continue to operate at AC Transit. This transition is expected to begin in May 2010. NREL plans to evaluate these new fuel cell buses and will report on this transition in the first evaluation report for those new buses.

This evaluation report starts with a summary of the overall achievements and challenges during this demonstration at AC Transit. AC Transit has continued to support public outreach with their fuel cell bus program, and - ridership is summarized. The hydrogen fueling during the accelerated testing is summarized along with some statistics for life-to-date operation of the fueling station. This hydrogen station at AC Transit will be decommissioned and torn down, and a new station will be built as part of the new fuel cell bus demonstration (see What's Next for AC Transit?).

The bulk of this report contains summary results from the operation of the fuel cell buses from November 2007 through February 2010. The accelerated testing period was defined contractually to start with November 2007; however, the focus of the evaluation results is presented from the point at which the fuel cell power systems (CSAs—cell stack assemblies) were replaced for each of the three buses, as follows:

- **Fuel Cell Bus 1 (FC1)**—CSAs replaced on March 7, 2008, restarted service on March 18, 2008
- **Fuel Cell Bus 2 (FC2)**—CSAs replaced on January 31, 2008, restarted service on February 5, 2008
- **Fuel Cell Bus 3 (FC3)**—CSAs replaced on December 11, 2007, restarted service on December 13, 2007; the CSAs were replaced again on December 15, 2008, restarted service on December 31, 2008.

UTC Power reported that this last change of the CSAs incorporates many of the lessons learned from the previous operation of these fuel cell buses (and from the other operating locations), and previous early power-loss problems are believed to be resolved. The clean point period for the accelerated testing evaluation is the point that these fuel cell buses restarted service (FC1—March 2008, FC2—February 2008, FC3—December 2007) through the endpoint of February 28, 2010. This clean point evaluation period is used throughout the Evaluation Results section. The diesel bus baseline evaluation period is completed and includes data from January through December 2007.

This report concludes with a description of the next steps for the next phase of AC Transit's program, including the delivery of the 12 new fuel cell buses and construction of the two new hydrogen fueling stations.

Demonstration Achievements and Challenges

This section focuses on achievements during the demonstration of prototype fuel cell buses and fueling infrastructure at AC Transit since starting revenue service on March 20, 2006, through February 28, 2010. Many challenges were faced and resolved during this demonstration, and several challenges remain for the technology development. The lessons learned during this demonstration have been taken forward into an updated fuel cell bus and fuel cell power system design for the 12 new fuel cell buses at AC Transit and the four other San Francisco Bay area transit agencies. Four additional new fuel cell buses of the same design are to be delivered to UTC Power in Connecticut for operation at CTTRANSIT and New York City Transit.

Bus Operations

The current version fuel cell buses were designed and integrated over several years, from 2001 to 2004, and the first buses were delivered in late 2005. The specially modified Van Hool bus model has a fuel cell power system from UTC Power and a hybrid electric system from Siemens (the ELFA hybrid system). ISE Corporation completed the integration of this bus design and included ZEBRA high-temperature batteries for energy storage. This bus design was determined by a specification from AC Transit that required a bus with operational performance similar to that of their standard diesel buses. The main objective of the demonstration of fuel cell bus technology at AC Transit focused on proof of concept that a fuel cell bus could be implemented successfully into full transit service. Overall, this main objective of the demonstration has been achieved.

Table 1 is a summary of all revenue service evaluation results achieved during this demonstration. The fuel cell buses went into service in March 2006. During the early demonstration period, the agency limited operation of the buses while the agency became familiar with the technology. Two buses were used in service on weekdays for 8 hours per day; one bus was kept for use in training, maintenance, or events. AC Transit successfully ramped up service of the buses during the accelerated testing period: all three buses were planned to operate for two shifts each weekday for up to 19 hours a day. The buses also operated on weekends as needed. Through February 2010 (nearly 4 years), the buses had operated for nearly 225,000 miles and accumulated more than 22,400 hours on the fuel cell systems. Of those totals, 164,673 miles and 16,902 hours were accumulated during the accelerated testing period.

The age of this fuel cell bus design is important background information when considering the specific accomplishments of this design and implementation as well as what to expect with the next generation of fuel cell buses from Van Hool and UTC Power. Several of the challenges faced in this implementation and demonstration were resolved, and for those challenges that remain, the new design of the bus and propulsion system is focused on resolving these challenges or exploring a path to resolution.

Table 1. Summary of All Revenue Service Evaluation Results

Data Item	Fuel Cell Buses
Number of Buses	3
Data Period	3/20/2006–2/28/2010
Number of Months	47
Total Mileage in Period	224,871
Average Monthly Mileage per Bus	1,595
Total Fuel Cell Operating Hours	22,401
Average Bus Operating Speed (mph)	10.0
Availability (85% is target)	61%
Fuel Economy (miles/kg)	6.06
Fuel Economy (miles/DGE ^a)	6.85
Miles between Roadcalls (MBRC) – All	1,203
MBRC – Propulsion Only	1,530 ^b
Total Maintenance Cost, \$/mile ^c	0.70
Maintenance Cost – Propulsion Only, \$/mile	0.17

^aDiesel gallon equivalent.

^bFor fuel cell propulsion only, MBRC was 8,031.

^cWork order maintenance cost.

- Fuel Cell System Issues**—UTC Power monitors the performance of the fuel cell power system to analyze actual performance versus predicted performance. Early on in the demonstration, the cell stack assemblies (CSAs) showed power degradation during the operation of the buses. This early power degradation was reported with the fuel cell buses at other agencies as well, and UTC Power reported the problem as contamination within the CSAs causing the premature degradation (at about 800 to 1,200 hours of operation instead of the expected 4,000 hours or more). A new version of CSAs replaced the CSAs on the fuel cell buses at each agency. UTC Power reported that this early power degradation was resolved for these buses. The fact that two of the new-version fuel cell power systems have achieved more than 5,000 hours of service with no repairs indicates the issues have been resolved.
- Traction Battery Issues**—Managing the ZEBRA batteries in this design has proved to be the biggest challenge. The hybrid design on the bus includes three traction batteries operating in parallel. A cell in a ZEBRA battery typically will fail in short circuit. A battery with failed cells has reduced voltage even though it still can operate. Because the batteries operate with a direct parallel connection, when the number of failed cells within each battery is too different among the three batteries, the difference causes an unbalancing of the state of charge (SOC). This imbalance makes it difficult to keep the batteries in the recommended operating range. The present SOC balancing algorithm will disconnect a battery temporarily to keep the SOC balanced.

This situation may lead to overvolt errors in the propulsion system, causing a bus shutdown. UTC Power has been working closely with the battery manufacturer (MES-DEA) on the issue for some time. Because failed cells are related to a stress condition caused by the battery use, some progress was made with controller software changes to improve battery operation by refining some operational limits. Options for a balancing

strategy have been discussed. Additional replacement batteries are kept in stock to increase the number of available better-matched batteries and to reduce the amount of downtime of the fuel cell bus. MES-DEA also supplied training at AC Transit that was extremely helpful to the project team. The manufacturer also produced a manual that includes information and fault code definitions. This has been extremely helpful in understanding the battery and systems and how to troubleshoot and diagnose problems. To date, no permanent fix for these issues has been identified. The energy storage for the new design fuel cell buses has been changed to lithium ion batteries.

- **Fuel Economy**—During the accelerated testing period, AC Transit’s fuel cell buses achieved an average fuel economy of 6.0 miles per kilogram (kg), which equates to 6.8 miles per DGE (10.4 kg hydrogen/100 kilometers [km]). AC Transit’s diesel baseline fleet has an average fuel economy of 4.2 miles per gallon (mpg). Using this as a baseline, the fuel cell buses have a fuel economy that is 61% better than the diesel buses. The diesel buses used for this comparison do not have air conditioning and are more than 8,000 lbs lighter in weight. The fuel economy advantage for the new fuel cell buses is expected to increase, given the focus on optimization, new batteries, and use of a diesel baseline bus group with air conditioning.
- **Costs**—Fuel cell buses are following the typical trend of all prototype technology: capital costs are high in the early stages and begin to fall with increased production and further product development. The operating costs are also higher than those of conventional technology. This is also the typical trend for new technology introductions. Operating costs can be lower than expected in the first year while the buses are under warranty and maintenance is handled by the manufacturer’s on-site technicians. Then costs rise as the transit agency staff take over more maintenance and undergo a steep learning curve. Once the staff becomes more familiar with maintenance, these costs are expected to drop. AC Transit intends to be more involved in the maintenance of the newer design fuel cell buses, and a better understanding of future capital and operating costs is expected.

Hydrogen Fueling

AC Transit fuels its buses at the hydrogen station at the agency’s East Oakland Division. The fueling station, built and operated by Chevron, features a natural gas reformer, hydrogen storage, and two dispensers. During the entire demonstration, the three fuel cell buses were safely fueled more than 1,600 times, using more than 36,000 kg of hydrogen. This fueling station is to be decommissioned and demolished, and a replacement station will be constructed. AC Transit is installing another fueling station at its Emeryville Division to supplement fueling and operation at two locations and for easier use by other transit agencies in the Bay Area. Part of the new fueling station design is to incorporate the best way to green the hydrogen production and to consider what larger fleet needs will be for hydrogen production, storage, and dispensing.

Facility Modifications

AC Transit modified one of the maintenance bays at East Oakland for fuel cell bus maintenance. Because the maintenance bay is in the maintenance building, the fire marshal required that hydrogen fuel cell buses be defueled from 5,000 psi to 600 psi before entry into the maintenance bay for significant work. To reduce the loss of fuel from this process, AC Transit actively works

to plan service so that buses needing routine maintenance are as low on fuel as possible. In the future ZEBAs demonstration, AC Transit has secured funding and plans are being made to modify the bay to allow a fully fueled bus to be brought inside.

Training

From the onset of the project, AC Transit has been proactive with its training program. AC Transit and its project partners organized a comprehensive training program to ensure that the appropriate staff gained familiarity with hydrogen as a fuel and received detailed maintenance and operations information for the fuel cell bus. Working with various groups such as the College of the Desert and Schatz Energy Research Center, the agency developed training courses and videos to educate the public, transit staff, and first responders about fuel cell bus technology. These training programs will now be expanded to include the other transit agencies in the Bay Area that will potentially operate the new fuel cell buses.

Public Awareness

AC Transit reports a high level of interest in the local community and the region in the fuel cell bus demonstration. The agency receives requests to demonstrate the bus at various events and accommodates as many as possible. The agency has given tours of its East Oakland Division and fuel cell bus demonstrations to numerous individuals and groups from the United States and more than 12 different countries. The agency also surveyed passengers to measure the level of awareness and acceptance for fuel cell bus technology in the Oakland area. The survey results revealed a high level of interest in the technology, and passengers ranked the fuel cell bus performance much higher compared with conventional diesel buses.

Coordination with Golden Gate Transit

As an active demonstration partner, GGT wanted hands-on experience with the buses. The two agencies worked closely together to develop the agreements and process for allowing another agency to operate a bus in its service area. This was a major accomplishment and required a coordinated effort between the agencies. The effort involved developing a user's agreement, establishing a process for a potential emergency situation, planning logistics for transfer of the bus, and resolving the use of equipment differences between the agencies (e.g., farebox, head-sign, radios). GGT reports a positive experience in operating one of the fuel cell buses in its service. Because of the high average operating speed at GGT (22 miles per hour [mph]), the fuel economy during this operation was the highest recorded for the buses: 8.8 miles/kg or 10.0 miles/DGE.

With the arrival of the 12 new fuel cell buses, AC Transit will be coordinating with the four other participating transit agencies in the ZEBAs demonstration to operate, maintain, and fuel these fuel cell buses.

Public Outreach

AC Transit's hydrogen fuel cell vehicle program (HyRoad) has always had a significant focus on public awareness. One of the major objectives of the program has been to create opportunities to educate students, the general public in the Bay Area, and other interested parties such as federal and state government officials. Also, operating the fuel cell buses in revenue service is an opportunity for the public to experience hydrogen fuel cell bus technology. The agency continues

to accommodate as many requests for demonstration events as possible; the number of events decreased over time, however, as the agency increased the in-service time to accumulate more miles on the buses. During 2009, AC Transit participated in 37 events, which included environment-themed events, educational sessions for college and high school groups, fire department refresher training, and tours for U.S. and foreign officials.

Passenger Survey Results

The AC Transit passenger survey to gauge customer awareness and perceptions of the fuel cell bus operation received nearly 500 responses. The results are summarized in a previous report¹¹ for this accelerated testing at AC Transit.

Ridership

AC Transit, like most transit agencies, estimates ridership by counting ridership on the routes at different times of the day, days of the week, and times of the year. AC Transit's route ridership estimates were used to conservatively estimate the number of fuel cell bus revenue passengers since the buses went into service. From March 20, 2006, through the end of February 2010, each bus carried an average of 203,000 passengers; the total estimate is more than 609,000 passengers. Figure 1 shows the ridership estimate by month and as a cumulative total.

The passenger estimates were also supplemented by actual passenger counts from automated passenger counters installed on the buses. Actual counts on the buses started in 2008 for all three buses. These counts were also checked against the estimates from AC Transit to verify that they were consistent.

Note that the passenger count jumped significantly during the accelerated testing period (November 2007 through February 2010). More than three-quarters of the total passenger count occurred during the accelerated testing period—nearly 477,000 passengers. These data indicate that the bus operation during the accelerated testing is meeting the objective of significantly increased bus usage.

¹¹ National Fuel Cell Bus Program: Accelerated Testing Evaluation Report, January 2009, FTA-CO-26-7004-2009.1, <http://www.nrel.gov/hydrogen/pdfs/44820-1.pdf>

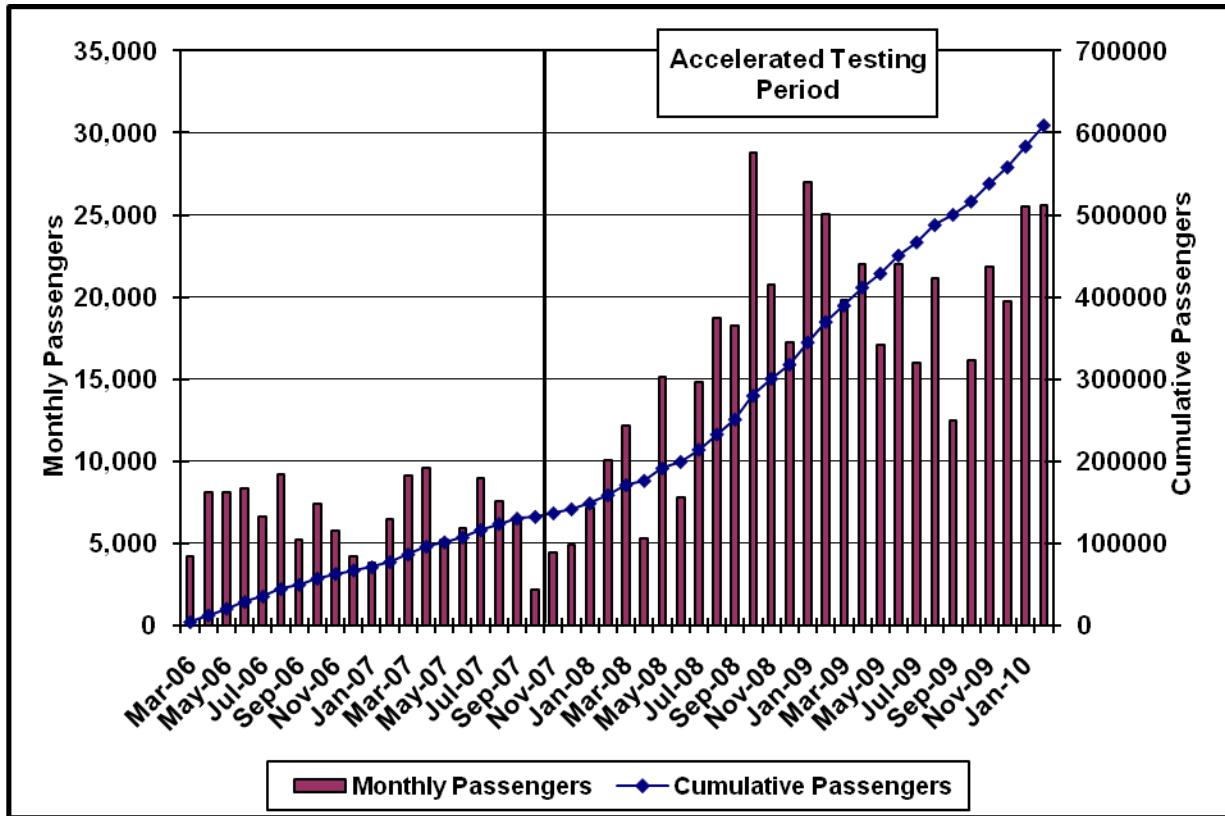


Figure 1. Ridership estimates for the fuel cell buses at AC Transit

Hydrogen Fueling

The hydrogen fueling station at AC Transit was designed by Chevron Technology Ventures and installed at Division 4 (East Oakland) in 2005. The station includes two steam methane reformers that can produce 150 kg of hydrogen per day. Total storage capacity at the station is 366 kg at up to 6,250 pounds per square inch (psi). The station was inaugurated in March 2006 just before the start of revenue service for the fuel cell buses. Figure 2 shows one of the fuel cell buses at the hydrogen fueling island and the fueling connections. A more detailed description of the hydrogen fueling and maintenance facilities at AC Transit is in Appendix C.

Figure 3 shows average monthly hydrogen usage from the station during the accelerated testing evaluation period (November 2007 through February 2010) for buses only. AC Transit also has a fleet of seven light-duty hydrogen vehicles that uses the station as well, but that fuel consumption is not accounted for in this analysis and discussion. The overall average usage for the buses during this period was 44.3 kg/day, or 988 kg/month. The calculation for this rate includes only the days in which hydrogen was dispensed into the buses from the station—73% of the calendar days during the period. In all, 27,668 kg of hydrogen was dispensed into buses during this period. Since the beginning of revenue service, the station dispensed 38,752 kg of hydrogen into buses (again excluding the light-duty fuel cell fleet).



Figure 2. Fueling at the Chevron hydrogen station (Photo credit: L. Eudy, NREL)

Figure 4 shows the distribution of hydrogen amounts per fill by bus. The three buses were filled 1,160 times during the accelerated testing evaluation period, at an average fill amount of 22.6 kg/fill. Figure 5 shows the cumulative fueling rate histogram for the AC Transit station during the accelerated testing period; the overall average fueling rate was 1.26 kg/minute. On average, it took approximately 18 minutes to fuel a bus.

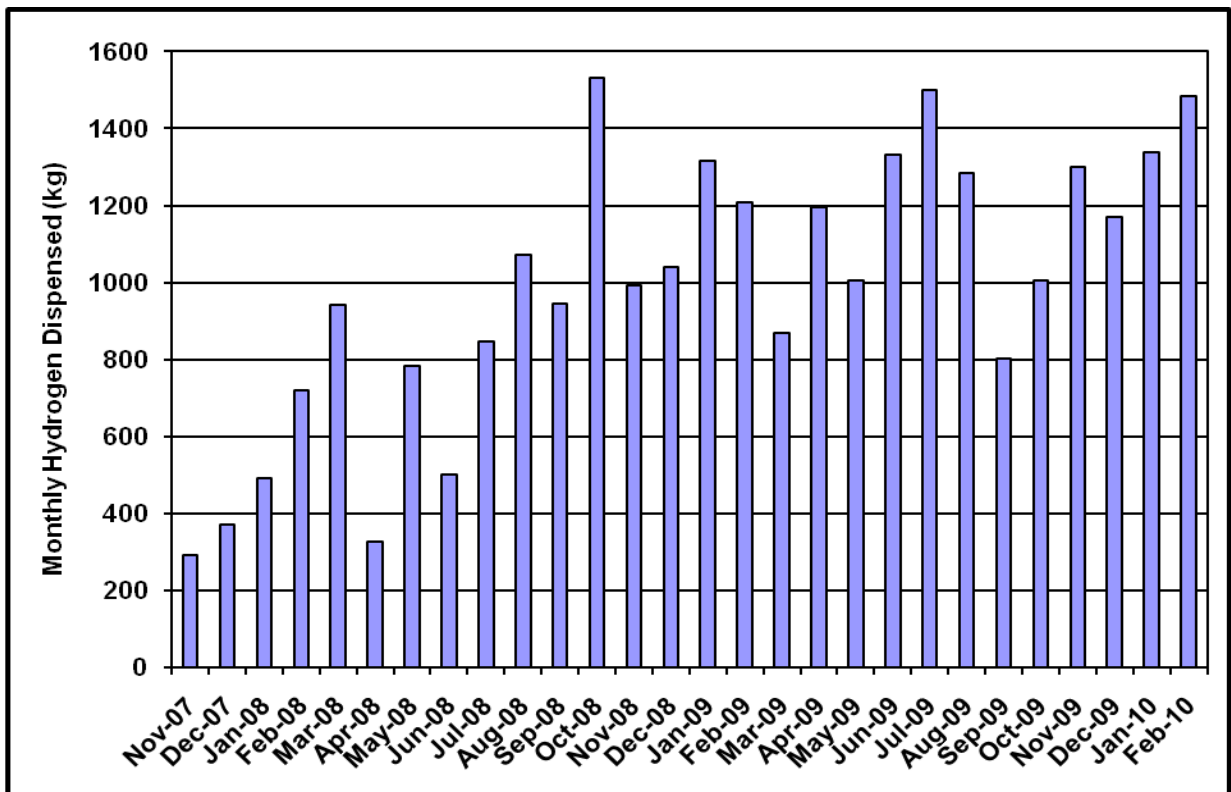


Figure 3. Average hydrogen use per month for AC Transit's fuel cell buses

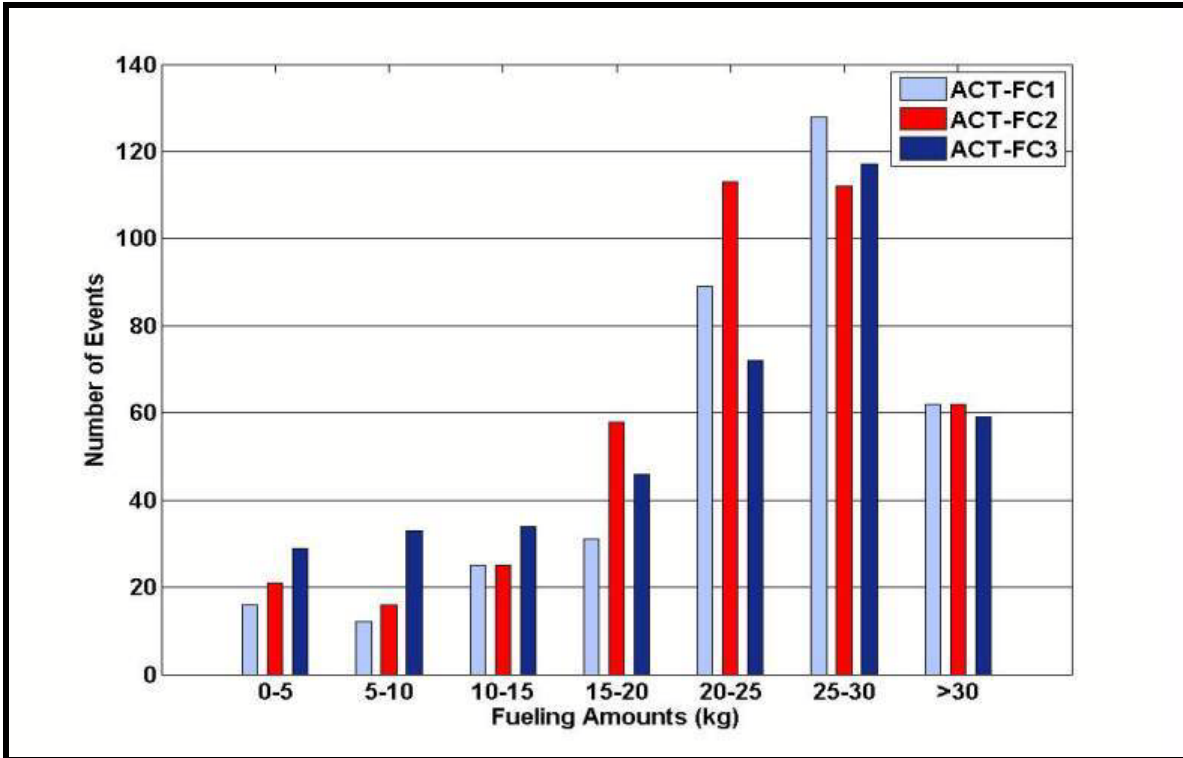


Figure 4. Distribution of fill amounts for the fuel cell buses

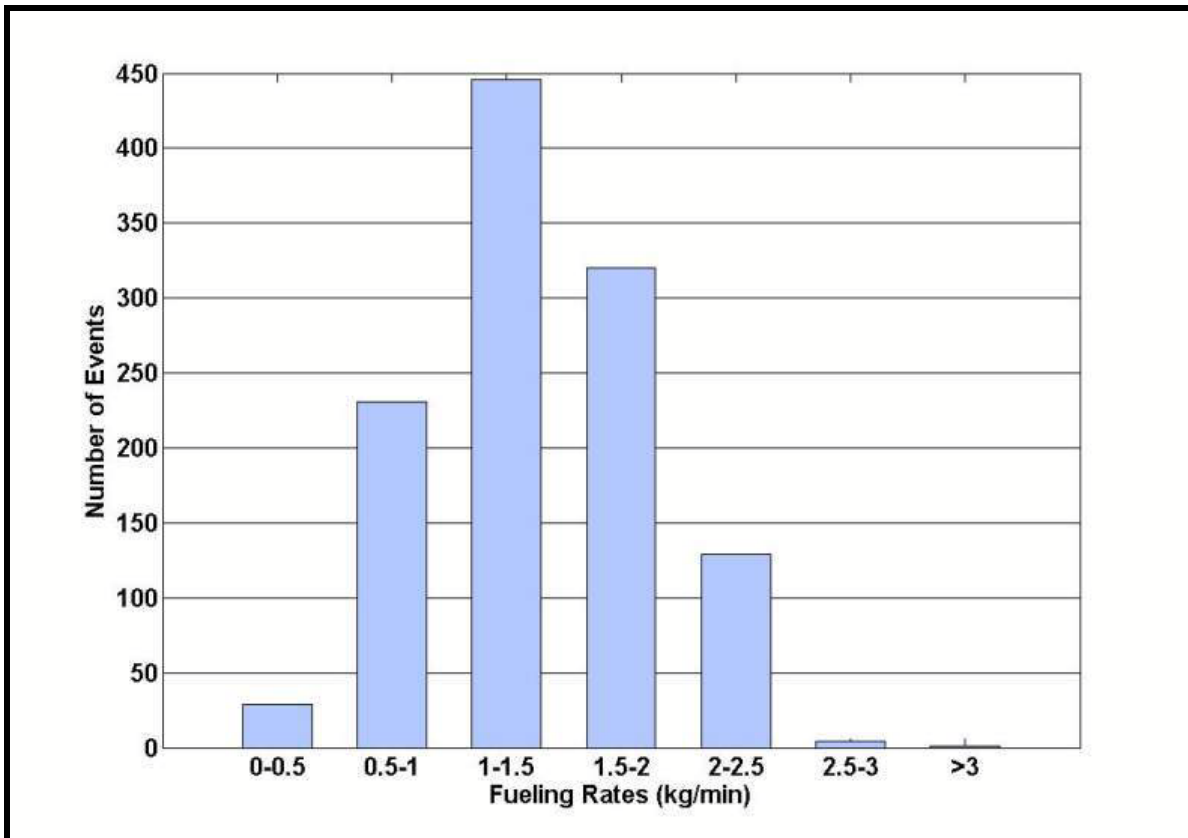


Figure 5. Fueling rate histogram for the AC Transit Hydrogen Energy Station (bus only)

Fuel Cell Bus Operations—Evaluation Results

For this demonstration, the fuel cell buses are considered to be prototype technology that is in the process of being commercialized. The analysis and comparison discussions with standard diesel buses serve as a baseline against which to measure the progress of the fuel cell bus technology. The intent of this analysis is to determine the status of this implementation and to document the improvements that have been made over time at AC Transit. There is no intent to consider this implementation of fuel cell buses as commercial (or full revenue transit service). This evaluation focuses on documenting progress and opportunities to improve the vehicles, infrastructure, and procedures.

The evaluation periods for the buses in this report are November 2007 through February 2010 (28 months) for the fuel cell buses and January through December 2007 (12 months) for the diesel buses. The accelerated testing evaluation period for the fuel cell buses focuses on a clean point period that starts with the last replacement of the CSAs for the fuel cell buses through February 2010. The start of the clean point evaluation period is as follows:

- **FC1**—CSAs replaced on March 7, 2008, restarted service on March 18, 2008
- **FC2**—CSAs replaced on January 31, 2008, restarted service on February 5, 2008
- **FC3**—CSAs replaced on December 11, 2007, restarted service on December 13, 2007; the CSAs were replaced again on December 15, 2008, restarted service on December 31, 2008.

The diesel Van Hool buses began operation in 2003–2004 but did not start operating at Division 4 (East Oakland) until July 2005. Data collection for these diesel buses has concluded, and a 12-month period of operation at AC Transit’s Division 4 was chosen for a baseline comparison with the fuel cell buses. As mentioned earlier, one significant difference of note is that the diesel buses do not have air conditioning, and this affects the fuel economy results comparison.

Route Descriptions

The fuel cell and diesel baseline buses are operated from AC Transit’s Division 4, 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.

At the beginning of revenue service, the fuel cell buses operated only during the week on two blocks of work created for testing the fuel cell and diesel baseline buses. This limited operation originally helped ensure that trained drivers and mechanics (and the manufacturer’s engineers) were available to work with the fuel cell buses when needed. Also, AC Transit decided to place only two of the three fuel cell buses into service on any given weekday to allow for maintenance, training, and special events with the third fuel cell bus.

As AC Transit and the manufacturer partners gained experience, operating the fuel cell buses more aggressively became a goal. As discussed earlier, the accelerated testing project is focused on maximizing the operation of all three of the fuel cell buses. This effort has taken significant planning and work on the part of AC Transit staff and the manufacturers. To maximize the

operation of the fuel cell buses, specific route blocks were defined so the fuel cell buses could attempt nearly full transit operation. During the accelerated testing evaluation period, the fuel cell buses operated on all of the route assignments shown in Table 2.

Table 2. Route Blocks of Work Created for Fuel Cell Bus Operation

Route Block	Pull-Out Time	Pull-In Time	Total Time	Total Miles	Average Speed (mph)
Weekday Operation					
18	6:06 a.m.	11:51 p.m.	17.8	171	9.6
18	5:22 a.m.	7:11 p.m.	13.8	140	10.1
57	7:01 a.m.	9:25 p.m.	14.4	150	10.4
Weekend Operation					
57	7:51 a.m.	8:00 p.m.	12.2	129	10.6
57	5:36 a.m.	9:01 p.m.	15.4	167	10.8

As stated previously in reports on this demonstration at AC Transit, meeting the long operation time of the route assignments is difficult because of the need to charge the batteries overnight before the next pullout. During the accelerated testing, the fuel cell buses operated on longer hours of operation; however, this time of operation was cut back slightly over time to ensure that overnight charging was sufficient for the next day's operation. A full charge for the batteries requires between 4 and 4.5 hours. During bus operation on the route, the batteries are kept at 50% to 60% SOC to allow for significant energy regeneration from braking back into the batteries. The diesel buses were not restricted to these special blocks of work. These diesel buses were allowed to operate on other work blocks during the week and on weekends as well. This operation is reflected in the bus use, which is discussed next.

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.

Usage for the fuel cell buses increased nearly 50% during the accelerated testing period as compared with the previous revenue operations (March 2006 through October 2007). For the entire accelerated testing period (November 2007 through February 2010), the fuel cell buses averaged 1,960 miles per month (each bus). The average monthly mileage results in Table 3 focus on the clean point periods for the fuel cell buses; the first partial month of operation after the last fuel cell power system replacement was removed from the calculation. The table shows that the average monthly mileage for the fuel cell buses was 2,129 miles per month. Compared with the diesel bus average mileage, the fuel cell buses have now achieved an average of 58% of full transit operation.

Table 3. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage
FC1	25,097	76,743	51,646	24	2,152
FC2	20,485	79,521	59,036	25	2,361
FC3	26,494	75,518	49,024	26	1,886
Fuel Cell			159,706	75	2,129
1043	111,443	155,982	44,539	12	3,712
1044	131,559	174,535	42,976	12	3,581
1045	142,518	186,774	44,256	12	3,688
1046	147,975	193,493	45,518	12	3,793
1047	128,064	173,870	45,806	12	3,817
1048	115,365	158,784	43,419	12	3,618
Diesel			266,514	72	3,702

The focus of the accelerated testing was to operate the fuel cell buses as much as the technology would allow. In addition, it was a key objective to operate the fuel cell power systems beyond 4,000 hours. This objective was accomplished. In fact, as of the end of February 2010, one bus accumulated more than 5,000 hours and another bus accumulated more than 6,000 hours. These same fuel cell power systems are expected to continue to operate in new buses starting in May 2010. The third fuel cell bus had the fuel cell power system replaced after a year of testing. The newer CSAs in the third bus are similar to the other two fuel cell buses.

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 monthly availability for each of the three fuel cell buses and an overall average availability for the group during the clean point evaluation period. The low availability months were generally caused by the need for traction battery replacements.

Table 4 summarizes the reasons for availability and unavailability for each of the three fuel cell buses. During the clean point evaluation period, the average availability for the fuel cell buses was 66%. The overall availability percentage by bus and overall average is highlighted in blue in the table. The two unavailability categories with the highest percentage were issues with the traction batteries (36% of all unavailable days) and AC Transit maintenance (35% of all unavailable days).

The traction battery issues include problems with matching SOC among the three traction batteries, the software to manage this SOC, and the interface between the propulsion system software and traction battery software. This problem improved during the evaluation period, but has never truly been resolved.

AC Transit maintenance includes scheduled and unscheduled maintenance performed for the fuel cell buses. In addition, there were several accidents that required body repairs. There was also one electrical system fire that caused significant unavailability for one of the buses. This fire was unrelated to the fuel cell power, hydrogen storage, or hybrid propulsion systems.

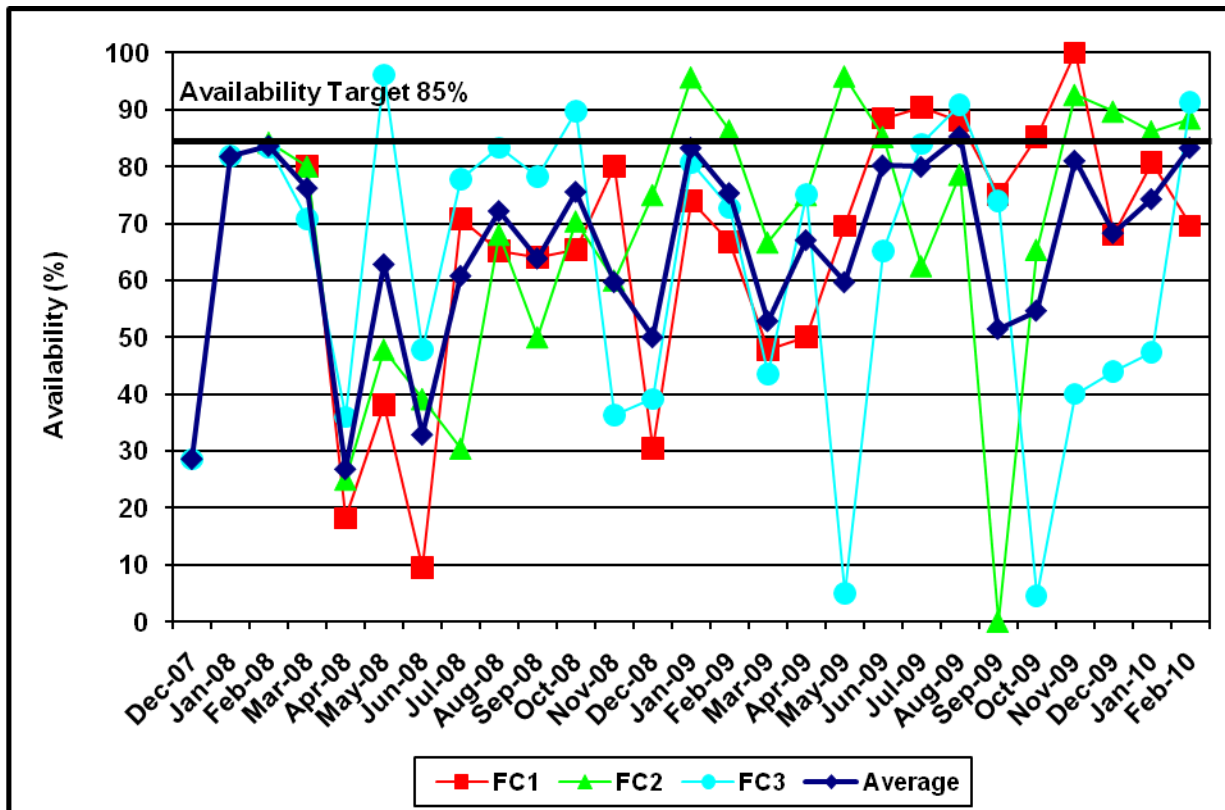


Figure 6. Availability for all three fuel cell buses and overall average

Table 4. Summary of Reasons for Availability and Unavailability of Buses for Service

Category	FC1		FC2		FC3		Group Total	
	Days	%	Days	%	Days	%	Days	%
Planned Work Days	568		620		620		1,808	
Days Available	379	67	427	69	396	64	1,202	66
Available	379	100	427	100	396	100	1,202	100
On Route	355	94	406	95	357	90	1,118	93
Event/Demonstration	11	3	10	2	23	6	44	4
Training	7	2	4	1	10	2	21	2
Not Used	6	1	7	2	6	2	19	1
Unavailable	189	100	193	100	224	100	606	100
Fuel Cell Propulsion	19	10	9	5	37	16	65	11
ISE Hybrid Propulsion	15	8	35	18	6	3	56	9
Traction Battery Issues	78	41	78	40	62	28	218	36
AC Transit Maintenance	55	29	58	30	97	43	210	35
Fueling Unavailable	22	12	13	7	22	10	57	9

Fuel Economy and Cost

Hydrogen fuel is supplied by the Chevron–AC Transit Hydrogen Energy Station at the East Oakland Division. The hydrogen is dispensed at up to 5,000 psi for the three fuel cell transit buses. During the accelerated testing evaluation period, AC Transit employees performed nearly all fueling services for the hydrogen-fueled vehicles, and Chevron electronically reported the fueling amounts.

Table 5 shows hydrogen and diesel fuel consumption and fuel economy for the study buses during the clean point evaluation period. Overall, the three fuel cell buses averaged 6.01 miles per kilogram of hydrogen, which equates to 6.79 miles/DGE. The energy conversion from kilograms of hydrogen to DGE appears at the end of Appendix E. (Appendix F contains the summary statistics in SI units.) It was also reported that approximately 536 kg of hydrogen were removed during the accelerated testing evaluation period so that the buses could be taken into the maintenance facility. This amount of hydrogen removed and vented equates to 2% of the hydrogen dispensed into the buses. AC Transit has been working to minimize the amount of hydrogen vented by managing the amount of bus operation and fueling before planned bus maintenance. The amount of hydrogen vented from the buses before maintenance has not been included in the fuel economy calculations.

As mentioned earlier, the buses are plugged in each night to recharge the batteries. This energy added to the fuel cell buses each night is not currently accounted for in the fuel economy calculation. AC Transit collects monthly total charging energy for the fuel cell buses. This charging energy represents 5% of the total energy used by the buses (based on the average of 22 months of data). To be accurate, the fuel cell fuel economy should be reduced by 5%, or reduced to 6.45 miles/DGE. This fuel economy would then be 54% higher than the fuel economy of the diesel buses. Note that the diesel buses do not have air conditioning, and this increases the fuel economy advantage of the fuel cell buses.

Table 5. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (fuel base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (gallon)	Miles per Gallon (mpg)
FC1	49,129	8,440.9	5.82	7,469.8	6.58
FC2	57,762	9,281.9	6.22	8,214.1	7.03
FC3	48,775	8,195.0	5.95	7,252.2	6.73
FCB Total	155,666	25,917.8	6.01	22,936.1	6.79
1043	43,835			10,765.1	4.07
1044	42,379			9,916.2	4.27
1045	44,256			10,381.1	4.26
1046	45,518			10,873.8	4.19
1047	45,673			10,744.5	4.25
1048	42,914			10,295.4	4.17
Diesel Total	264,575			62,976.1	4.20

Figure 7 shows monthly average fuel economy in both miles per kilogram and miles per DGE for the fuel cell buses as well as the baseline diesel bus average of 4.20 mpg. Note that the fuel economy for the fuel cell buses peaked in February and March 2008, which coincides with the GGT operation of one of the fuel cell buses. The GGT fuel cell bus operation and fuel economy were significantly higher than the AC Transit operation and influenced the overall fuel economy during the accelerated testing evaluation period. Also, this is a sufficiently long period of time to see the general degradation of the fuel cell power systems with usage (approximately 10% to 15% degradation over the evaluation period).

The operating cost for hydrogen production and dispensing for AC Transit is currently estimated at between \$6 and \$8/kg. This amount, which excludes capital expenses, was generated using

early data (not optimized operation) and conservative maintenance and operating estimates. The \$8/kg cost estimate for hydrogen fuel indicates a cost for the fuel cell buses of \$1.33/mile. The average diesel fuel cost during the evaluation period is \$2.29/gallon. This average indicates a \$0.55/mile cost. The diesel cost per mile is about 41% of the fuel cost per mile for the fuel cell buses.

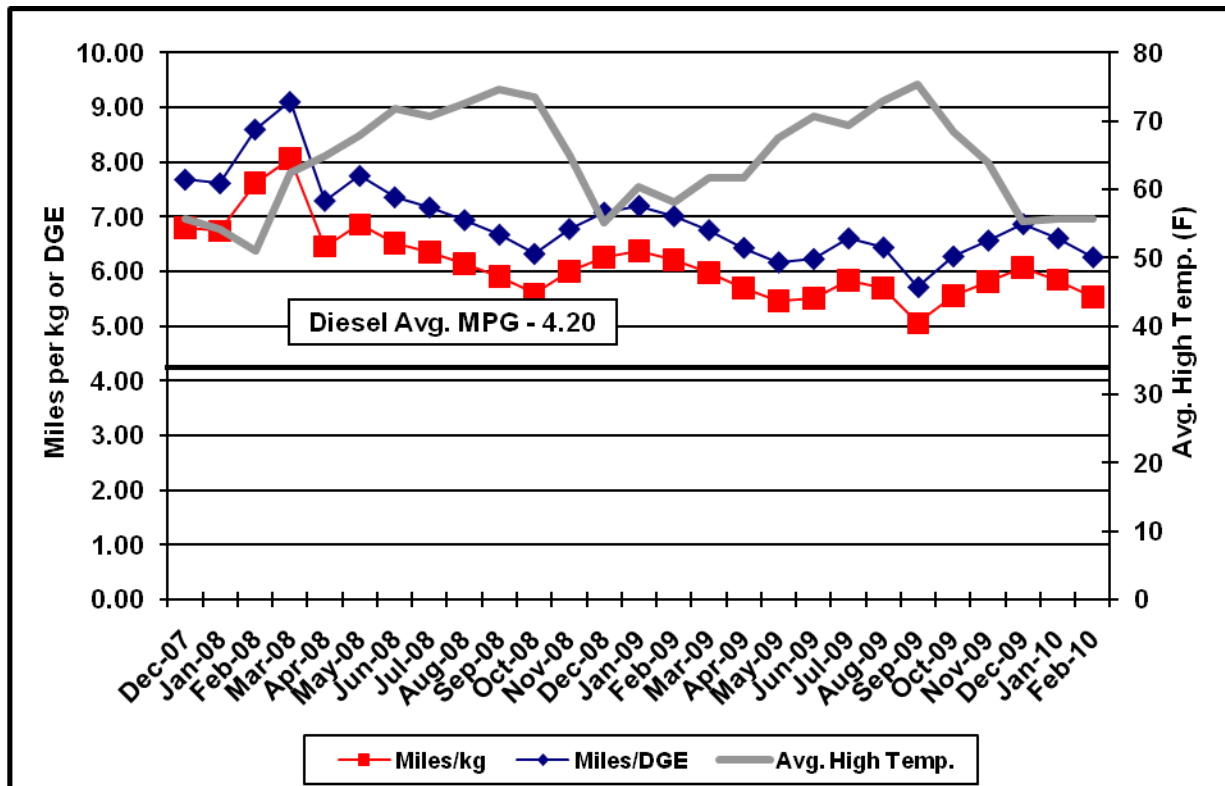


Figure 7. Average fuel economy (evaluation period)

Maintenance Analysis

The maintenance cost analysis in this section is limited to the clean point evaluation period (last CSA/fuel cell power system replacement through February 2010). 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:

$$\text{Cost per mile} = [(\text{labor hours} * 50) + \text{parts cost}] / \text{mileage}$$

Table 6 shows total maintenance costs for the fuel cell and diesel buses. Note that the fuel cell bus maintenance was still being supported by on-site warranty work done by the manufacturer’s engineers at AC Transit. The AC Transit mechanics have supported the work done by the manufacturer’s engineers and have cleaned and maintained the bus (inside and outside). Some

support has been given for responding to roadcalls, and that effort is reflected in the maintenance discussion that follows. During the accelerated testing evaluation period, AC Transit personnel essentially took over all of the maintenance and support of the fuel cell buses except for maintenance by the UTC Power engineer.

Table 6. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts (\$)	Labor Hours	Cost per Mile (\$)
FC1	51,646	18,012.21	382.3	0.72
FC2	59,036	14,943.43	390.0	0.58
FC3	49,345	20,043.71	539.3	0.95
Total Fuel Cell	160,027	52,999.35	1,311.6	0.74
Avg. per Bus	53,342	17,666.45	437.2	--
1043	44,539	10,791.13	109.0	0.37
1044	42,976	12,104.40	156.3	0.46
1045	44,256	16,832.13	154.8	0.56
1046	45,518	12,102.17	169.3	0.45
1047	45,806	15,192.03	120.1	0.46
1048	43,419	19,613.14	167.4	0.64
Total Diesel	266,514	88,635.00	877.0	0.49
Avg. per Bus	44,419	14,772.50	146.2	--

AC Transit has expressed a strong desire to have its mechanics get more involved in all maintenance activities for the fuel cell buses so they gain experience. AC Transit assigned one project manager/supervisor and two mechanic trainers to work on the fuel cell buses. This addition of resources for fuel cell bus maintenance was necessary based on the desired increase in operation along with plans for more fuel cell buses. Figure 8 shows the monthly and cumulative labor hours assigned for maintenance of the fuel cell buses. The chart shows the maintenance labor increased significantly and then was lower in the last 6 to 8 months.

Maintenance issues for the fuel cell buses centered on problems with the traction batteries and fuel cell system on each of the buses. Brake relines were completed eight times, with some issues of smoking brakes that needed adjustment/break-in. FC3 was vandalized and needed windows replaced several times during the evaluation period. In addition, there were significant hours for accident damage body repairs and suspension repairs.

Maintenance issues for the diesel buses were mostly related to engine problems with the turbocharger (two buses), injectors and pump (two buses), and coolant surge tank (five buses). The diesel buses also had significant brake repair costs for standard relining (eight times). The other major maintenance costs were for accident repair and seat and window replacement (five buses).

The maintenance costs for the fuel cell buses reported here are generally higher than the costs reported previously, an indication of the added support from AC Transit maintenance personnel. This higher cost is especially reflected in the number of mechanic labor hours.

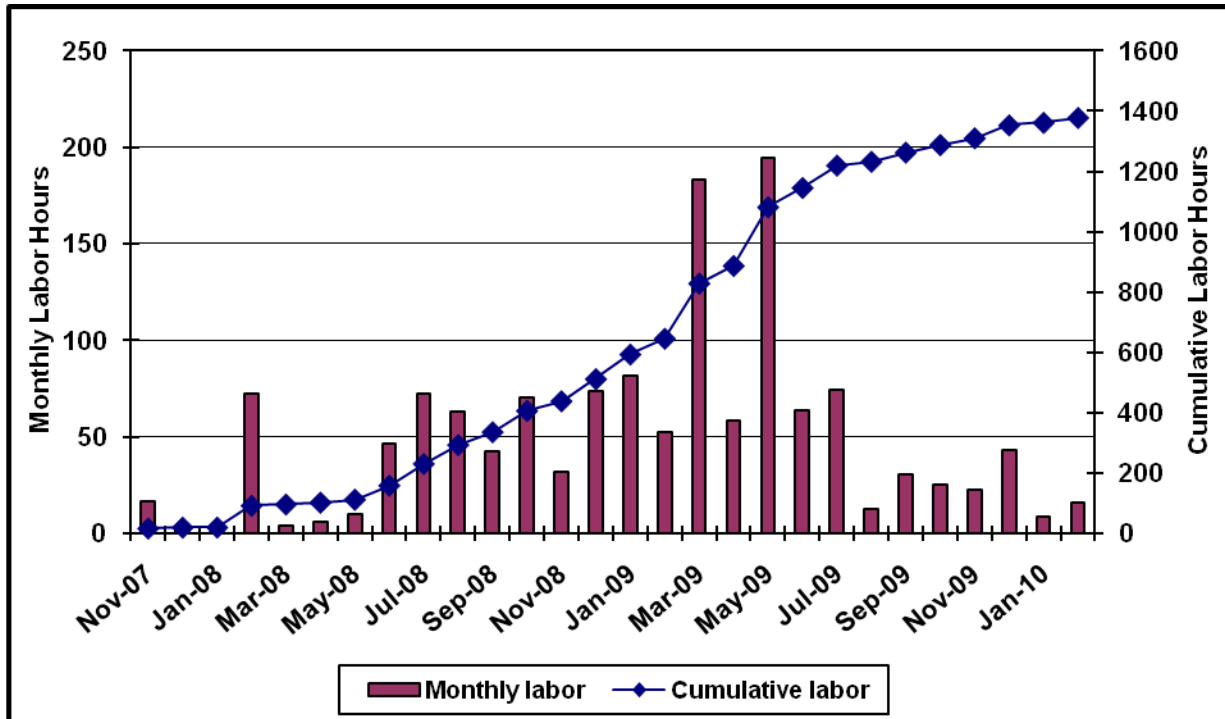


Figure 8. Monthly and cumulative AC Transit maintenance labor (evaluation period)

Maintenance Costs Categorized by System—Table 7 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 7. Maintenance Cost per Mile by System (Evaluation Period)

System	Fuel Cell ^a		Diesel	
	Cost per Mile (\$)	Percent of Total (%)	Cost per Mile (\$)	Percent of Total (%)
Cab, Body, and Accessories	0.17	23	0.16	32
Propulsion-Related	0.19	26	0.10	20
PMI	0.09	12	0.07	14
Brakes	0.21	29	0.11	22
Frame, Steering, and Suspension	0.04	6	0.02	4
HVAC	0.01	1	0.01	2
Lighting	0.01	1	0.01	2
Air, General	0.01	1	0.00	0
Axles, Wheels, and Drive Shaft	0.01	1	0.01	2
Tires	0.00	0	0.00	0
Total	0.74	100	0.49	100

^a Excludes warranty work costs

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

Propulsion-Related Maintenance Costs—Propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, nonlighting electrical, and transmission systems.

Table 8 shows the propulsion-related system repairs by category for the two study groups during the evaluation period (no warranty costs). The fuel cell buses had higher maintenance costs (50% higher), which indicate the amount of AC Transit mechanic activity 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 8. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	160,027	266,514
Total Propulsion-Related Systems (Roll-up)		
Parts cost (\$)	2,898.40	18,794.62
Labor hours	542.0	173.1
Total cost (\$)	29,996.90	27,448.12
Total cost (\$) per mile	0.19	0.10
Exhaust System Repairs		
Parts cost (\$)	0.00	5,091.03
Labor hours	8.0	28.0
Total cost (\$)	400.00	6,491.03
Total cost (\$) per mile	0.00	0.02
Fuel System Repairs		
Parts cost (\$)	0.00	2,561.24
Labor hours	4.0	17.8
Total cost (\$)	200.00	3,451.24
Total cost (\$) per mile	0.00	0.01
Powerplant System Repairs		
Parts cost (\$)	261.16	3,549.02
Labor hours	57.5	56.4
Total cost (\$)	3,136.16	6,368.52
Total cost (\$) per mile	0.02	0.02
Electric Motor and Propulsion Repairs		
Parts cost (\$)	28.82	0.00
Labor hours	318.5	0.0
Total cost (\$)	15,952.32	0.00
Total cost (\$) per mile	0.10	0.00
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost (\$)	1,499.95	1,809.52
Labor hours	137.0	33.4
Total cost (\$)	8,349.95	3,478.52
Total cost (\$) per mile	0.05	0.01
Air Intake System Repairs		
Parts cost (\$)	1,041.15	959.66
Labor hours	0.0	0.0
Total cost (\$)	1,041.15	959.66
Total cost (\$) per mile	0.01	0.00
Cooling System Repairs		
Parts cost (\$)	67.32	4,237.93
Labor hours	17.0	29.0
Total cost (\$)	917.32	5,687.93
Total cost (\$) per mile	0.01	0.02
Transmission Repairs		
Parts cost (\$)	0.00	451.46
Labor hours	0.0	2.5
Total cost (\$)	0.00	576.46
Total cost (\$) per mile	0.00	0.00

Roadcall Analysis

A roadcall or revenue vehicle system failure (as named in the National Transit Database¹²) 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.¹³ 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 9 shows the roadcalls and MBRC for each study bus categorized by all roadcalls and propulsion-related-only roadcalls. The diesel buses have much better MBRC rates for both categories. This lower rate is indicative of the prototype status of the fuel cell buses. The MBRC for the fuel cell power system, however, increased significantly over the evaluation period.

Table 9. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC	Fuel Cell only MBRC
FC1	51,646	43	1,201	28	1,845	25,823
FC2	59,036	41	1,440	33	1,789	14,759
FC3	49,345	51	968	43	1,148	4,935
Total FCB	160,027	135	1,185	104	1,539	10,002
1043 Diesel	44,539	6	7,423	2	22,270	
1044 Diesel	42,976	15	2,865	5	8,595	
1045 Diesel	44,256	16	2,766	6	7,376	
1046 Diesel	45,518	7	6,503	3	15,173	
1047 Diesel	45,806	9	5,090	4	11,452	
1048 Diesel	43,419	9	4,824	5	8,684	
Total Diesel	266,514	62	4,299	25	10,661	

Most of the nonpropulsion roadcalls for the fuel cell buses were caused by problems with the brakes (13 roadcalls), air system (5 roadcalls), and suspension/leveling (5 roadcalls). When the brakes on the fuel cell buses are relined/replaced, there is a break-in period where the brakes give off a smell and “smoke,” resulting in several roadcalls. The smell and smoke come from a coating on the brake parts that is difficult to clean off before installation. This occurs only for a short period of time, but has caused some concern for the operators and passengers; however, this is not a safety issue.

The propulsion-related roadcalls for the fuel cell buses have been caused by problems with the hybrid propulsion system (49 roadcalls), traction batteries (34 roadcalls), and fuel cell power system (16 roadcalls). Many of the hybrid and battery roadcalls are related to a need to optimize the monitoring and management of the traction batteries and are not necessarily an indication of a component failure.

¹² National Transit Database web site: www.ntdprogram.gov/ntdprogram/

¹³ AC Transit defines a significant delay as 6 or more minutes.

What's Next for AC Transit?

AC Transit is moving into the next phase of fuel cell bus development with a demonstration of 12 new and advanced fuel cell buses. This demonstration is in response to the CARB Transit rule, which requires several California agencies (including AC Transit) to purchase new and advanced fuel cell buses as part of its zero-emission bus regulations. Developed by UTC Power and Van Hool, the new buses incorporate the lessons learned during the demonstration of the current fuel cell buses.

AC Transit is the managing partner for a ZEBAs working group to respond to CARB's advanced fuel cell bus demonstration. The ZEBAs group includes several Bay Area transit agencies:

- AC Transit
- Santa Clara VTA
- GGT
- SamTrans
- SF MTA.¹⁴

The new Van Hool fuel cell buses (purchase price is about \$2.5 million each) with power systems from UTC Power have an improved design from the current fuel cell buses. These buses are 5,000 lbs lighter weight and 3 inches shorter, and have a different battery/energy storage design (lithium ion). The first bus was delivered to AC Transit in May 2010.

AC Transit will own and maintain the 12 new fuel cell buses and will be responsible for managing the operation and demonstration; however, several of the ZEBAs partners may operate these buses for a period of time during the demonstration. Each ZEBAs transit agency is participating in the ongoing operations with financial and planning support. UTC Power has purchased an additional four new fuel cell buses from AC Transit's bus order to be operated in Connecticut and other selected areas (including at least one bus at New York City Transit) under the FTA's NFCBP.

AC Transit will continue to operate the three existing fuel cell buses in their accelerated testing project for FTA's NFCBP until the new buses arrive. As described earlier, once the new buses arrive, the plan is to remove the existing three fuel cell power systems and install them into the first three new fuel cell buses for operation at AC Transit. The existing/older fuel cell bus gliders are planned to be transferred to UTC Power. The other nine remaining fuel cell buses will arrive at AC Transit where new fuel cell power systems will be installed.

AC Transit continues to work on developing hydrogen fueling infrastructure to support the new fuel cell buses. The Chevron station at the East Oakland Division is scheduled for decommission in September 2010. The station was originally built to support the DOE Controlled Fleet Fuel Cell Vehicle Demonstration as well as the buses. Now that the DOE project is concluded, Chevron's commitment is complete. AC Transit is working with Linde to construct new stations

¹⁴ SF MTA is a voluntary participant. Its fleet of trolley buses already meets CARB zero-emission bus regulations.

at East Oakland as well as its Emeryville depot (Division 2). The Emeryville fueling station will be a combined facility for light-duty fuel cell vehicles and fuel cell buses. A solar-powered Proton Energy electrolyzer will generate up to 65 kg of hydrogen for the light-duty vehicles; liquid hydrogen delivery and storage will supply as many as six fuel cell buses with fuel. This new station will be a convenient fueling location for future bus operations by ZEBAs partner transit agencies like GGT and SF MTA.

NREL Evaluation of AC Transit Fuel Cell Buses—The current evaluation of accelerated testing at AC Transit was funded by FTA in conjunction with their NFCBP. With the completion of this evaluation report, the evaluation funding will be transitioned from FTA back to DOE. The DOE evaluation plans include all 12 of the new fuel cell buses for the planned ZEBAs/CARB demonstration.

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Acronyms and Abbreviations

AC Transit	Alameda-Contra Costa Transit District
CARB	California Air Resources Board
CSA	cell stack assembly
CTE	Center for Transportation and the Environment
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
FTA	Federal Transit Administration
GGT	Golden Gate Transit
HVAC	heating, ventilation, and air conditioning
kg	kilogram
MBRC	miles between roadcalls
min	minutes
mpg	miles per gallon
mph	miles per hour
NAVC	Northeast Advanced Vehicle Consortium
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
psi	pounds per square inch
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SamTrans	San Mateo County Transit District
SF MTA	San Francisco Municipal Transportation Agency
SOC	state of charge
VTA	Santa Clara Valley Transportation Authority
ZEBA	Zero Emission Bay Area

Bibliography

AC Transit

Chandler, K.; Eudy, L. (2009). *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report and Appendices*. NREL/TP-560-44646-1, NREL/TP-560-44646-2. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2008). *Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Third Evaluation Report and Appendices*. NREL/TP-560-43545-1, NREL/TP-560-43545-2. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2007). *Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Evaluation Results Update*. NREL/TP-560-42249. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2007). *AC Transit, Fuel Cell Transit Buses: Preliminary Evaluation Results*. NREL/TP-560-41041. Golden, CO: NREL.

NREL. (2006). *AC Transit Demos Three Prototype Fuel Cell Buses*. DOE/GO-102006-2286. Golden, CO: NREL.

City of Burbank

Eudy, L., (2010), *Fuel Cell Bus Takes a Starring Role in the Burbank Bus Fleet*, DOE/GO-102010-3035, Golden, CO: NREL.

General

Eudy, L.; Chandler, K.; Gikakis, C. (2009). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2009*. NREL/TP-560-46490. Golden, CO: NREL.

Eudy, L.; Chandler, K.; Gikakis, C. (2008). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008*. NREL/TP-560-44133. Golden, CO: NREL.

NREL. (2008). *Hydrogen and Fuel Cell Transit Bus Evaluations, Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*. NREL/MP-560-42781. Golden, CO: NREL.

Eudy, L.; Chandler, K.; Gikakis, C. (2007). *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status*. NREL/TP-560-41967. Golden, CO: NREL.

SunLine

Chandler, K.; Eudy, L. (2009). *SunLine Transit Agency, Fuel Cell Transit Bus: Fifth Evaluation Report and Appendices*, NREL/TP-560-46346-1, NREL/TP-560-46346-2. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2008). *SunLine Transit Agency, Fuel Cell Transit Bus: Fourth Evaluation Report and Appendices*, NREL/TP-560-44646-1, NREL/TP-560-44646-2. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2008). *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Third Evaluation Report and Appendices*. NREL/TP-560-43741-1, NREL/TP-560-43741-2. Golden, CO: NREL.

NREL. (2008). *SunLine Begins Extended Testing of Hybrid Fuel Cell Bus*. DOE/GO12008-2610. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2007). *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Evaluation Results Update*. NREL/TP-560-42080. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2007). *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Preliminary Evaluation Results*. NREL/TP-560-41001. Golden, CO: NREL.

NREL. (2006). *SunLine Tests HHICE Bus in Desert Climate*. DOE/GO-102006-2333. Golden, CO: NREL.

NREL. (2006). *SunLine Expands Horizons with Fuel Cell Bus Demo*. DOE/GO-102006-2287. Golden, CO: NREL.

Connecticut Transit

Chandler, K.; Eudy, L. (2010). *Connecticut Transit (CTTRANSIT) Fuel Cell Transit Bus: Third Evaluation Report & Appendices*. NREL/TP-560-47334-1 & NREL/TP-560-47334-2. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2009). *Connecticut Transit (CTTRANSIT) Fuel Cell Transit Bus: Second Evaluation Report & Appendices*. NREL/TP-560-45670-1 & NREL/TP-560-45670-2. Golden, CO: NREL.

Chandler, K.; Eudy, L. (2008). *Connecticut Transit (CTTRANSIT) Fuel Cell Transit Bus: Preliminary Evaluation Results*. NREL/TP-560-43847. Golden, CO: NREL.

NREL. (2008). *CT TRANSIT Operates New England's First Fuel Cell Hybrid Bus*. DOE/GO12008-2529. Golden, CO: NREL.

Santa Clara Valley Transportation Authority

Chandler, K.; Eudy, L. (2006). *Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Evaluation Results*. NREL/TP-560-40615. Golden, CO: NREL.

NREL. (2005). *VTA, SamTrans Look into Future with Bus Demo*. DOE/GO-102005-2147. Golden, CO: NREL.

Reports from DOE/NREL evaluations can be downloaded via the following Web sites:

Hydrogen and fuel cell related: www.nrel.gov/hydrogen/proj_fc_bus_eval.html

Hybrid and other technologies: www.nrel.gov/vehiclesandfuels/fleettest/publications_bus.html