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Fuel Cell Buses in U.S. Transit Fleets: Current Status 2010

Technical Report
NREL/TP-560-49379
October 2010

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Acronyms and Abbreviations

AC Transit	Alameda-Contra Costa Transit District
APTA	American Public Transportation Association
BAAQMD	Bay Area Air Quality Management District
BC	British Columbia
CARB	California Air Resources Board
CATA	Centre Area Transportation Authority
CNG	compressed natural gas
CTE	Center for Transportation and the Environment
CTTRANSIT	Connecticut Transit
CUTE	Clean Urban Transport for Europe
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EDSP	Electric Drive Strategic Plan
EDTA	Electric Drive Transportation Association
FC	fuel cell
FCB	fuel cell bus
ft	feet
FTA	Federal Transit Administration
GEF	Global Environmental Facility
GGT	Golden Gate Transit
GVWR	gross vehicular weight rating
HCNG	hydrogen and compressed natural gas
HHICE	hydrogen hybrid internal combustion engine
HICE	hydrogen internal combustion engine
hp	horsepower
ICE	internal combustion engine
in	inches
kg	kilogram
kW	kilowatts
kWh	kilowatt-hours
lb	pounds
MBRC	miles between roadcalls
mpg	miles per gallon
mph	miles per hour
MTC	Metropolitan Transportation Commission
NAVC	Northeastern Advanced Vehicle Consortium
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
NYCT	New York City Transit
OEM	original equipment manufacturer
PEM	proton exchange membrane
psi	pounds per square inch
RC	roadcall

rpm	revolutions per minute
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SamTrans	San Mateo County Transit District
SFMTA	San Francisco Municipal Transportation Agency
SOC	state of charge
UNDP	United Nations Development Program
VTA	Santa Clara Valley Transportation Authority
WMATA	Washington Metropolitan Area Transit Authority
ZEB	zero-emission bus
ZEBA	Zero Emission Bay Area

Executive Summary

This past year has been one of transition for the introduction of fuel cell transit buses. The existing generation of fuel cell buses from Van Hool and UTC Power has continued to operate in service at three transit agencies. At the same time, a new generation of fuel cell bus from Van Hool and UTC Power transit bus has been developed, including 12 new buses for AC Transit and the Zero Emission Bay Area (ZEBA) demonstration group and 4 new buses for UTC Power with operation planned at Connecticut Transit (**CT**TRANSIT) and New York City Transit (NYCT). Delivery of these new buses has begun with 6 of the 16 buses between the two operating locations. During this reporting period for bus operation (August 2009 to July 2010), two of the five existing fuel cell buses from Van Hool and UTC Power were retired and one of the fuel cell power systems was installed into a new fuel cell bus.

At the same time, several new fuel cell bus designs have been introduced or are progressing toward introduction into service and demonstration. This includes the battery dominant Proterra fuel cell bus with fuel cell systems from Hydrogenics. One bus is in demonstration in Columbia, South Carolina and one in Burbank, California. New Flyer, ISE, and Ballard introduced their 20 new fuel cell buses in Vancouver, Canada in time for the Winter Olympics. One bus of this design has started service at SunLine Transit Agency during the reporting period in this report. Another demonstration at San Francisco Municipal Transportation Agency (SFMTA) is nearly ready to start with an Orion bus with hybrid propulsion from BAE Systems and new electric accessories and an auxiliary power unit fuel cell power system from Hydrogenics. A few more fuel cell bus designs are also expected in the next year.

This year's assessment report provides the results from the fifth year of operation of five Van Hool, ISE, and UTC Power fuel cell buses operating at AC Transit, SunLine, and **CT**TRANSIT. This will be the last assessment report solely focused on this fuel cell bus design. Two of the AC Transit fuel cell buses completed their service during the evaluation period in this report and the third bus is expected to be retired in the next year. The other two existing fuel cell buses operating at SunLine and **CT**TRANSIT will be operated until the buses are no longer serviceable or supported by the manufacturers.

The achievements and challenges of this bus design, implementation, and operation are presented in this report with a focus on the next steps for implementing larger numbers of fuel cell buses and new and different designs of fuel cell buses. The achievements and challenges are presented in six categories: Bus Operations, Reliability/Durability, Optimization of Components/Systems, Preparation for Market Introduction, Hydrogen Fueling, and Cost Reduction. The major positive result from nearly five years of operation is the dramatic increase in reliability experienced for the fuel cell power system. In preparation for the larger number of buses at AC Transit, two new fueling stations are being constructed with a design to accommodate up to 25 fuel cell buses being fueled nightly.

Next year's report will add the newer design fuel cell buses mentioned above and will include several new operating locations and the experience with fueling and infrastructure.

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Introduction

This status report is the fourth in a series of annual status reports from the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL).[1] It summarizes progress and accomplishments from demonstrations of fuel cell transit buses in the United States. Since 2000, NREL has evaluated fuel cell bus demonstrations, including buses, infrastructure, and each transit agency's implementation experience. These evaluations were funded by both DOE and the U.S. Department of Transportation's (DOT) Federal Transit Administration (FTA). This work is described in a joint evaluation plan.[2]

Scope and Purpose

This annual status report discusses the status and challenges of fuel cell propulsion for transportation and summarizes the introduction of fuel cell transit buses in North America. It provides an analysis of the combined results from fuel cell transit bus demonstrations evaluated by NREL with a focus on data from August 2009 through July 2010. NREL also evaluates the operating experience and costs of these demonstrations individually and posts reports at http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html. The "References" section lists these reports, each of which is an unbiased assessment of a transit agency's experience implementing fuel cell bus operations.

Because this report combines results for fuel cell transit bus demonstrations across the United States and discusses the path forward for commercial viability of fuel cell transit buses, its intent is to inform FTA and DOE decision makers regarding research and funding; state and local government agencies, such as the California Air Resources Board (CARB), that fund new propulsion technology transit buses; and interested transit agencies and industry manufacturers.

Organization

This report is organized into seven sections, beginning with this "Introduction". The section "Introduction of Fuel Cell Transit Buses" describes the status of fuel cell transit bus introduction in the United States. It summarizes existing demonstrations and lessons learned in the United States and provides an overview of FTA's National Fuel Cell Bus Program (NFCBP). The section "Current Status of Fuel Cell Bus Introductions: Achievements and Challenges" discusses the status and challenges of fuel cell propulsion for transportation.

The section "Update of Evaluation Results, August 2009 – July 2010" presents the results of the most recent NREL evaluations of three fuel cell transit bus demonstrations with comparisons for availability, fuel economy, and roadcalls. The section "What's Next" looks ahead to the expected results to be presented in next year's assessment report. The "References" section provides references for NREL's periodic evaluations of the individual fuel cell bus demonstrations. Finally, the "Appendix" provides summary fuel cell bus data from each of the three transit agencies.

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[1] Previous reports are *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status*, September 2007, NREL/TP-560-41967; *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008*, December 2008, NREL/TP-560-44133; and *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2009*, October 2009, NREL/TP-560-46490.

[2] *Fuel Cell Transit Bus Evaluations, Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*, 2010, NREL/TP-560-49342.

Introduction of Fuel Cell Transit Buses

Introducing new types of buses into the transit industry is a well-understood, if sometimes challenging, process involving testing, demonstration, and limited production using increasingly greater numbers of vehicles. The three steps to introducing transit buses with fuel cell propulsion technology are:

Step 1. Operational field testing and design shakedown (one to three vehicles)

Step 2. Full-scale operational demonstration and fleet-ready reliability testing (5 to 20 vehicles at several locations)

Step 3. Limited production and full operation (50 to 100 vehicles at a small number of locations)

The number of fuel cell bus demonstrations has increased over the last few years. Some of the new demonstrations are introducing new designs of fuel cell buses in smaller numbers, placing those projects in step one. Several other demonstrations are beginning to field larger numbers of fuel cell transit buses, clearly moving the technology from step one into step two.

This section discusses the status of fuel cell buses planned and in operation in North America.

Fuel Cell Buses in Operation in the United States

Table 1 lists current fuel cell transit bus demonstrations in the United States. These demonstrations focus on identifying improvements to optimize reliability and durability. As of August 2010, 15 fuel cell buses were in service at seven locations in the United States. See the "References" section for details on the reports discussed.

NREL is currently evaluating the first eight demonstrations shown in Table 1. NREL's evaluation of the last demonstration in the table, VTA, was completed in 2005. NREL has not evaluated the University of Delaware or University of Texas[3] demonstrations.

- **Alameda-Contra Costa Transit District (AC Transit)**—Demonstration of three Van Hool buses with UTC Power fuel cell power system in a hybrid propulsion system. Data collection began in March 2006. NREL completed three evaluation reports for DOE with operations data through December 2007. As part of the National Fuel Cell Bus Program (NFCBP), AC Transit began accelerated testing of these three buses in late 2007. NREL completed two evaluation reports for FTA covering this accelerated operation through September 2009.

- **City of Burbank, BurbankBus—**Demonstration of one Proterra battery-dominant, plug-in hybrid bus with Hydrogenics fuel cells and lithium titanate batteries. This bus was delivered in April 2010 and was run through a series of tests by the bus operator and manufacturer. Data collection is scheduled to begin in September 2010 when the bus goes into service.

[3] Reported in *Heavy Hybrid Vehicles Technology Program, Final Report*, University of Texas at Austin, October 2008.

- **Central Midlands Regional Transit Authority (CMRTA) and the University of South Carolina (USC)—**Demonstration of one Proterra battery-dominant, plug-in hybrid bus with Hydrogenics fuel cells and lithium titanate batteries. This project is part of the NFCBP. After a short demonstration in Vancouver, British Columbia, during the 2010 Olympics, the bus was delivered to CMRTA and USC in March 2010. At the end of 2010, the bus will begin service at the second planned demonstration site in Austin, Texas. NREL has begun data collection and will report on the first year of demonstration in early 2011.

- **Connecticut Transit (CTTRANSIT)—**Demonstration of one Van Hool bus with UTC Power fuel cell power system in a hybrid propulsion system. Data collection began in April 2007. NREL completed three evaluation reports for DOE with operations data through October 2009.

- **Connecticut Transit (CTTRANSIT)—**Demonstration of four Van Hool buses with UTC Power fuel cell power system and a Siemens hybrid drive integrated by the bus manufacturer. This project is part of the NFCBP. The first of four buses was delivered in May 2010. **CT**TRANSIT will operate three of the buses, with the fourth planned for a year-long demonstration at New York City Transit. NREL will begin data collection as the buses are put into service.

- **SunLine Transit Agency—**Demonstration of one Van Hool bus with UTC Power fuel cell power system in a hybrid propulsion system. Data collection began in January 2006. NREL completed five evaluation reports for DOE with operations data through June 2009.

- **SunLine Transit Agency—**Demonstration of one New Flyer bus with an ISE hybrid system and a Ballard fuel cell. This bus went into service in May 2010 and data collection has begun. The first NREL report is planned for early 2011.

- **Zero Emission Bay Area (ZEBA) Demonstration Group led by AC Transit—**Demonstration of 12 next-generation Van Hool fuel cell hybrid buses with a fuel cell system by UTC Power. The first bus was delivered in May 2010. NREL has begun data collection and expects the first report in June 2011.

- **Santa Clara Valley Transportation Authority (VTA)—**Demonstration of three Gillig buses with Ballard fuel cell stacks in a non-hybrid propulsion system. NREL completed two evaluation reports for DOE with operations data from March 2005 through July 2006. These fuel cell buses have been retired and the hydrogen station decommissioned.

This report does not discuss the VTA demonstration further. The section "Update of Evaluation Results, August 2009 – July 2010" provides the most recent evaluation results for the three ongoing demonstrations at AC Transit, **CT**TRANSIT, and SunLine.

Table 1. Current Fuel Cell Transit Bus Demonstrations in the United States[a]

Bus Operator	Location	Total Buses	Active Buses	Technology Description
AC Transit	Oakland, CA	3	1	Van Hool bus with UTC Power fuel cell system, ISE hybrid system
BurbankBus	Burbank, CA	1	1	Proterra plug-in hybrid with Hydrogenics fuel cell
CMRTA/ University of SC	Columbia, SC	1	1	Proterra plug-in hybrid with Hydrogenics fuel cell
CTTRANSIT	Hartford, CT	1	1	Van Hool bus with UTC Power fuel cell system, ISE hybrid system
CTTRANSIT	Hartford, CT	4	2	Van Hool bus and hybrid system integration, UTC Power fuel cell
SunLine Transit Agency	Thousand Palms, CA	1	1	Van Hool bus with UTC Power fuel cell system, ISE hybrid system
SunLine Transit Agency	Thousand Palms, CA	1	1	New Flyer bus with ISE hybrid system and Ballard fuel cell
ZEBA (led by AC Transit)	San Francisco Bay Area, CA	12	4	Van Hool bus and hybrid system integration, UTC Power fuel cell
University of Delaware (Phase 1 & 2)	Newark, DE	2	2	Ebus battery dominant plug-in hybrid using Ballard fuel cells (22-ft)
University of Texas	Austin, TX	1	1	Ebus battery dominant plug-in hybrid using Ballard fuel cells (22-ft)
Santa Clara Valley Transportation Authority	San Jose, CA	3	0	Gillig bus with Ballard fuel cell stacks (non-hybrid)
	Total	**30**	**15**	

[a] Blue shaded rows indicate the project is part of the NFCBP

National Fuel Cell Bus Program (NFCBP)

In 2007, following the implementation of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU),[4] FTA initiated the National Fuel Cell Bus Program (NFCBP), a $49 million, multi-year, cost-share research program for developing and demonstrating commercially viable fuel cell technology for transit buses. The program included fuel cell bus demonstrations, component development projects, and outreach projects.

The demonstrations under FTA's NFCBP include developing new buses; expanding the fuel cell manufacturers beyond Ballard and UTC Power to include Hydrogenics and Nuvera; and exploring multiple bus sizes and hybrid propulsion designs. Because not all of the demonstrations received funding during the first year, the bus designs and development are in different stages. The demonstration projects that are currently underway are included in Table 1 (blue shaded rows). Table 2 lists the remaining demonstration projects that will field four more fuel cell buses by the end of 2011. The demonstration of these individual buses completes much of the research needed for step one for the introduction of fuel cell propulsion technology into transit.

[4] Signed into law in August 2005, SAFETEA-LU governs United States federal surface transportation spending.

The two component research projects, an integrated auxiliary module and a bi-directional converter, each for a fuel cell bus, are complete. One outreach project, *A Report on Hydrogen Bus Demonstrations Worldwide 2002-2007,*[5] is also complete. The remaining outreach projects are underway.

Table 2. Remaining Fuel Cell Transit Buses Planned for the FTA NFCBP

Project	Location	Total Buses	Technology Description
American FCB – SunLine (NFCBP – CALSTART)	Thousand Palms, CA	1	Next-generation advanced design to meet ‘Buy America’ requirements
Compound FCB for 2010 (NFCBP – CALSTART)	San Francisco, CA	1	Daimler/BAE diesel hybrid with Hydrogenics fuel cell APU
Lightweight FCB Demo (NFCBP – NAVC)	Albany, NY	1	Lightweight bus with a GE hybrid system using advanced batteries and a Ballard fuel cell
Massachusetts FCB Demo (NFCBP – NAVC)	Boston, MA	1	Hybrid bus using Nuvera fuel cells and an advanced battery system

FTA is expanding the NFCBP with funding that was made available in FY 2010. An additional $13.5 million in Bus and Bus Facilities funding was made available in the FY 2010 DOT Appropriations Bill. With this new funding, FTA is expanding efforts under the existing NFCBP and has solicited project proposals for the $13.5 million in FY 2010 funds and additional funds that may become available to the program.

The Hiring Incentives to Restore Employment Act (HIRE) of March 18, 2010, extended program authority for FY 2010 and the first quarter of FY 2011 without changes to the original program criteria. The legislative language establishing the NFCBP required FTA to work with up to three geographically diverse non-profit organizations. Because of this, FTA accepted proposals for follow-on projects from the three existing consortia already selected through the original competitive process. The project proposals cover work in the following areas:

1. Extensions or enhancements to existing projects with existing teams
2. New development and demonstration projects
3. Outreach, education or coordination projects.

Once the final selections are announced, the new projects will be added to the program portfolio, thereby expanding the effort to facilitate development of fuel cell buses for transit.

Beyond the NFCBP, FTA funds fuel cell bus research at several universities and transit agencies around the country.

[5] Curtin, S.; Jerram, L.; Justice, L. (2009). *A Report on Hydrogen Bus Demonstrations Worldwide, 2002-2007*. FTA-GA-04-7001-2009.01

Current Status of Fuel Cell Bus Introductions: Achievements and Challenges

For advanced technology buses to be fully commercialized, they must be able to match the performance and durability of diesel buses. Demonstrations of the current-generation fuel cell buses have shown much progress toward meeting that goal, and manufacturers are taking the lessons learned and applying those to the new generation buses just now being placed into service. This section discusses the progress being made and the challenges that remain to bring fuel cell buses to the market.

Bus Operations

Early on in the demonstrations, transit operators limited the in-service hours on the fuel cell buses to weekdays during first shift. This ensured that the maintenance personnel trained to service the buses were available in case of a problem with the bus. Also, it allowed the agencies time to become familiar with the new technology and come up to speed with any operational differences. Agencies with multiple buses typically held one bus out of service to accommodate repair work, public/media events, and training activities.

As the demonstrations progressed, each agency has successfully ramped up in-service time to include multiple shifts and weekends. In particular, AC Transit worked to maximize operation of its three fuel cell buses as part of the FTA NFCBP. The project team set a goal for revenue service of 15 to 19 hours per day, up to 7 days per week, on all three buses. During this phase of the demonstration, the fuel cell buses successfully operated as many as 21 hours in a single day. The planned hours per day was reduced to a maximum of 19 hours, however, to allow sufficient time for overnight charging of the batteries. (A full charge for the batteries requires between 4 and 4.5 hours.) This maximized operation was intended to help the manufacturers 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. 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.

Reliability/Durability

FTA requirements for 40-ft diesel bus life are 12 years or 500,000 miles. Transit agencies typically keep these buses for as many as 14 years, rebuilding the diesel engines at approximately mid-life. To match this durability a fuel cell power system should be able to operate for half the life of the bus. FTA has set an early performance target of 4–6 years (or 20,000–30,000 hours) durability for the fuel cell propulsion system. Throughout the demonstration at all three sites, UTC Power has used the data to continually improve and optimize the system. Early on in the demonstration, the cell stack assemblies (CSAs) showed power degradation during the operation of the buses. The problem was reported 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). UTC Power replaced the CSAs at each agency with a newer version, reporting that this early power degradation was resolved. As of June 2010, two of the fuel cell systems accumulated a record number of hours without requiring repair or replacement of single fuel cells or cell stacks—one bus accrued more than 7,000 hours, and another more than 6,000 hours. These fuel cell systems continued to operate above minimum operational power.

Figure 1 illustrates the increasing reliability over time for these fuel cell systems. Tracking the transit industry measure of reliability, the blue line shows the monthly average miles between roadcall (MBRC) for all five buses (fuel cell system only). These data show a significant increase in fuel cell related MBRC after the installation of the new fuel cell systems. (The shaded area marks the timing of the fuel cell power system installations.) Overall reliability for the fuel cell system has increased by 41% since the new version was installed. The black dotted line (trailing 12-month average) clearly shows the upward trend over time.

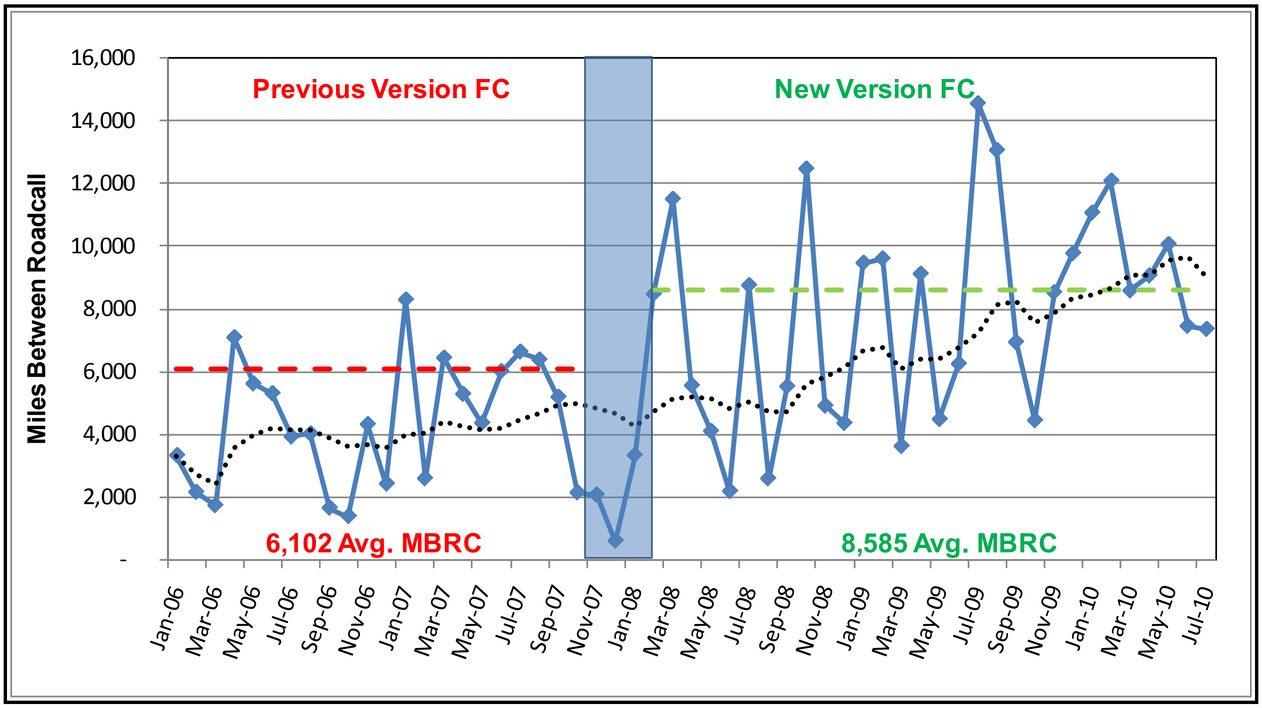

Figure 1. Average monthly MBRC for the fuel cell power system

Optimization of Components/Systems

All of the current-generation buses fall into stage one of commercialization, where manufacturers field test a smaller number of buses to refine the systems and determine what needs to be modified in the design. One of the greatest challenges encountered to date has been combining separate components and making them work well in a system. In the early stages of development and design, manufacturers used off-the-shelf components to cut costs. These off-the-shelf components may be cost effective, but sometimes they can't be made to fit into a system because of limitations such as size, power requirements, software control, or lack of adequate cooling.

These components (such as batteries, DC-DC converters/inverters) were usually developed for purposes other than what was needed. Some were easily incorporated into the design; others proved difficult to integrate and caused various issues affecting performance. The manufacturers have worked diligently to find solutions to the problems encountered. Some issues have been solved through improved software controls; others have required components to be replaced with different or newer design products. Some manufacturers have also brought component design work in-house for better control over the specifications and to avoid issues with access to proprietary data. The newest designs going into new demonstrations have been developed using lessons learned from previous iterations. This process was experienced in the development of commercial hybrid-electric transit buses, and the fuel cell buses are progressing and even being integrated into those essentially commercial hybrid-electric propulsion systems designed for the transit bus market.

Preparation for Market Introduction

The next step in introduction of fuel cell transit buses is to field larger fleets of vehicles, integrating them into standard transit routines and fully training staff to handle operation and maintenance. Over the past few years these demonstration project teams have been working toward those goals. All three transit agencies presented in this report have been proactive with training programs, providing familiarity training to the entire staff at each agency to educate and increase awareness of hydrogen and fuel cell technology. In the early stages of demonstration, only a handful of operators were trained to drive and handle start-up/shut-down of the buses. This number has increased at each site to avoid a bus being held from service because no trained operators are available. To prepare for its new fleet of buses, AC Transit has initiated programs to fully train all drivers at a specific depot to operate the buses.

Another important need to fully transition the technology into mainstream transit use is maintenance work. Agency staff has increasingly taken on more preventative maintenance and repair work on the fuel cell buses. Each agency has assigned existing maintenance staff or even hired additional staff specifically to learn to maintain the buses. Agencies are leveraging resources by sharing training with other agencies. For example, the ZEBA demonstration involves a shared program between five transit agencies. While AC Transit is the lead agency, the other agencies provide funding, participate in training activities, and periodically operate buses as part of the demonstration.

The transit agency partners continue to increase awareness of fuel cell technology among first responders and local fire/code officials, making it easier to gain permits for stations and facilities. Safety remains a priority for all the participants and as a result, no real safety issues occurred in the last five years of operation. Although several buses have been involved in traffic accidents, there have been no issues with hydrogen that have affected the safe operation of the buses.

Hydrogen Fueling

Access to hydrogen fueling, critical for introducing fuel cell buses into the market, still remains a major challenge. Early stations were costly and difficult to permit because of a lack of knowledge and understanding within some fire/building code jurisdictions (similar to the experience with the first CNG fueling stations). The first stations for transit agencies were specifically designed for smaller numbers of vehicles and were not necessarily designed to scale up to larger numbers of vehicles. Some of the fuel providers participating in the early demonstrations have made business decisions to move away from the market, possibly because of the economic downturn and lack of a near-term business case. Other companies have recently entered the market to fill this void with the newest technology for production and delivery of hydrogen.

The transit agencies are now beginning to rebuild older, outdated stations with the newest technology, taking into account larger fleets and the potential to scale up in size. These new fuel providers are learning more about the transit industry and its specific needs for fueling, such as fast fills, back-to-back fills, and long times between fueling sessions.

To aid in building the business case with higher throughput, some agencies are also working to include access for light-duty fuel cell electric vehicles. This is a challenge for most transit agencies because the fueling area is typically behind the fence with no easy access for vehicles outside the agency fleet. Most agencies have difficulty overcoming safety, security, and liability concerns. SunLine has been an exception to this because the agency's fueling station is on the edge of the property and already provided easy access for fueling CNG vehicles. When the agency added hydrogen-fueled vehicles to its fleet, the dispensers were placed in line with the existing CNG fueling. The agency has had public access for hydrogen fuel since November 2006. AC Transit is also taking steps to provide light-duty fuel cell electric vehicles access, with funding from the state of California. The new station at the agency's Emeryville Division will provide street access to hydrogen for light-duty fuel cell electric vehicles.

Cost Reduction

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. As mentioned in previous reports, purchase price has little relevance if the buses cannot meet performance standards. After fuel cell bus designs have proven performance and durability, the industry can investigate ways to reduce the cost of the buses and replacement components.

The operating costs are also higher than those of conventional technology, which is not unexpected for new technology introductions using a different fuel. 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 takes over more maintenance and undergoes a steep learning curve. Once the staff becomes more familiar with maintenance, these costs are expected to drop. As each agency becomes more involved in the maintenance of the fuel cell buses, we will gain a better understanding of actual future capital and operating costs.

Update of Evaluation Results, August 2009 – July 2010

Unless otherwise noted, the data presented below represent one year of bus operation, August 2009 through July 2010. Because the evaluation of AC Transit diesel baseline buses concluded in December 2007, data for these buses are from January 2007 through December 2007. The evaluation results for diesel baseline buses at **CT**TRANSIT were also for an earlier data period (November 2008 through October 2009). The Appendix summarizes information by demonstration location. This is the final report focused solely on this older fuel cell bus design from Van Hool, ISE, and UTC Power.

Prototype Demonstrations—The fuel cell transit buses presented in this section are prototype designs in the early demonstration and testing phase of development. The primary objective of fuel cell bus demonstrations is to learn from operational experience and incorporate the lessons learned into future designs. Demonstrations of prototype buses in real-world service are essential to validate technologies and identify modifications needed to increase reliability and durability for future commercial products. All manufacturers analyzed data from their particular designs and incorporated lessons learned into the next-generation fuel cell bus designs.

Lessons learned following almost five years of operation of the five Van Hool/UTC Power fuel cell buses at AC Transit, **CT**TRANSIT, and SunLine include the following:

- The demonstrations focused on proving that fuel cell transit buses can function in standard revenue transit service. The Van Hool/UTC Power fuel cell buses continue to be in standard revenue service since early 2006.

- The fuel cell power system manufacturer iterated its design, components, and implementation to explore reliability improvements and is implementing these improvements in its new products.

- The energy storage and amount of on-board hydrogen fuel storage selected for these demonstrations were not optimal. Energy storage was problematic because implementation was not optimized with the hybrid propulsion system, and manufacturing quality control and shipping requirements were lacking. Also, the amount of hydrogen onboard was more than was needed. The next-generation bus uses lithium ion batteries and carries less hydrogen onboard (50 kg on the older buses versus 40 kg on the newer buses). These changes have helped reduced the weight of the bus by nearly 5,000 lb. The next-generation bus is only 3,000 lb heavier than a standard diesel bus.

- Public outreach in a demonstration project is helpful gain acceptance. Demonstration participants expended great effort to educate the public about hydrogen and fuel cell propulsion in the locations where fuel cell transit buses were deployed. Two of the three locations surveyed their passengers to enhance public awareness of the buses and to obtain public impressions. Occasionally, the buses from all three locations were provided for display at public events.

- Hydrogen fuel production and dispensing infrastructure has worked well for the three locations. However, scaling up for larger demonstrations and "greening" hydrogen production and delivery will require additional research and testing.

As it places new buses into service, AC Transit will remove its three buses with Van Hool/UTC Power fuel cells from service and send them to UTC Power. The fuel cell buses at SunLine and **CT**TRANSIT will continue in their current service so long as their existing fuel cell power systems are operational. Operational data from these buses allows UTC Power to continue assessing reliability and durability. Whether UTC Power will replace the power systems on these two buses after the end of their useful life is undetermined at this time.

As of the completion of this report two of the three older fuel cell buses at AC Transit were already taken out of service. AC Transit FC1 was removed from service on May 24, 2010 and FC2 was removed from service on August 27, 2010. Only FC3 continues in revenue service from the original three fuel cell buses at AC Transit. Both of the retired buses have had the fuel cell power system removed; one was transferred to a newer fuel cell bus operating at AC Transit and the other has been retired. The availability data collection was discontinued at AC Transit at the end of March 2010 due to this transition period from the older buses to the 12 new fuel cell buses.

Total Miles and Hours—Table 3 shows miles, hours, average speed, and average monthly miles per bus for the fuel cell buses at AC Transit, **CT**TRANSIT, and SunLine. At 13.0 mph, the SunLine bus had the highest average speed. AC Transit buses averaged 9.8 mph, and the **CT**TRANSIT bus averaged 6.1 mph. AC Transit's fuel cell buses have the highest average monthly usage, 2,239 miles per month. Compared to previous evaluation periods, two of three transit agencies show increased monthly mileage accumulation. Usage of the **CT**TRANSIT fuel cell bus decreased because of issues with the hybrid propulsion system and delays in acquiring parts for replacement of a door that was damaged in an accident.

Table 3. Miles and Hours for the Fuel Cell Buses

Site	Period	Months	No. of Buses	Miles	Hours	Avg. Speed (mph)	Avg. Monthly Miles
Early FC System Results							
AC Transit	4/06-10/07	19	3	60,198	5,499	10.9	1,023
SunLine	1/06-3/08	27	1	52,336	4,027	13.0	1,886
CTTRANSIT	4/07-12/07	10	1	4,554	886	5.6	516
New FC System Results							
AC Transit	11/07-7/10	~31	3	188,322	19,246	9.8	2,136
SunLine	4/08-7/10	28	1	53,315	4,018	13.3	1,904
CTTRANSIT	1/08-7/10	31	1	39,970	6,111	6.5	1,289
Report Results Period							
AC Transit	8/09-7/10	12	3	76,112	7,794	9.8	2,239
SunLine	8/09-7/10	12	1	25,537	1,965	13.0	2,128
CTTRANSIT	8/09-7/10	12	1	11,218	1,839	6.1	935

Bus Use—Figure 2 shows the average monthly bus use for the fuel cell buses and their respective baseline buses. The three transit agencies continue to operate their fuel cell buses fewer miles than they operate their baseline buses.

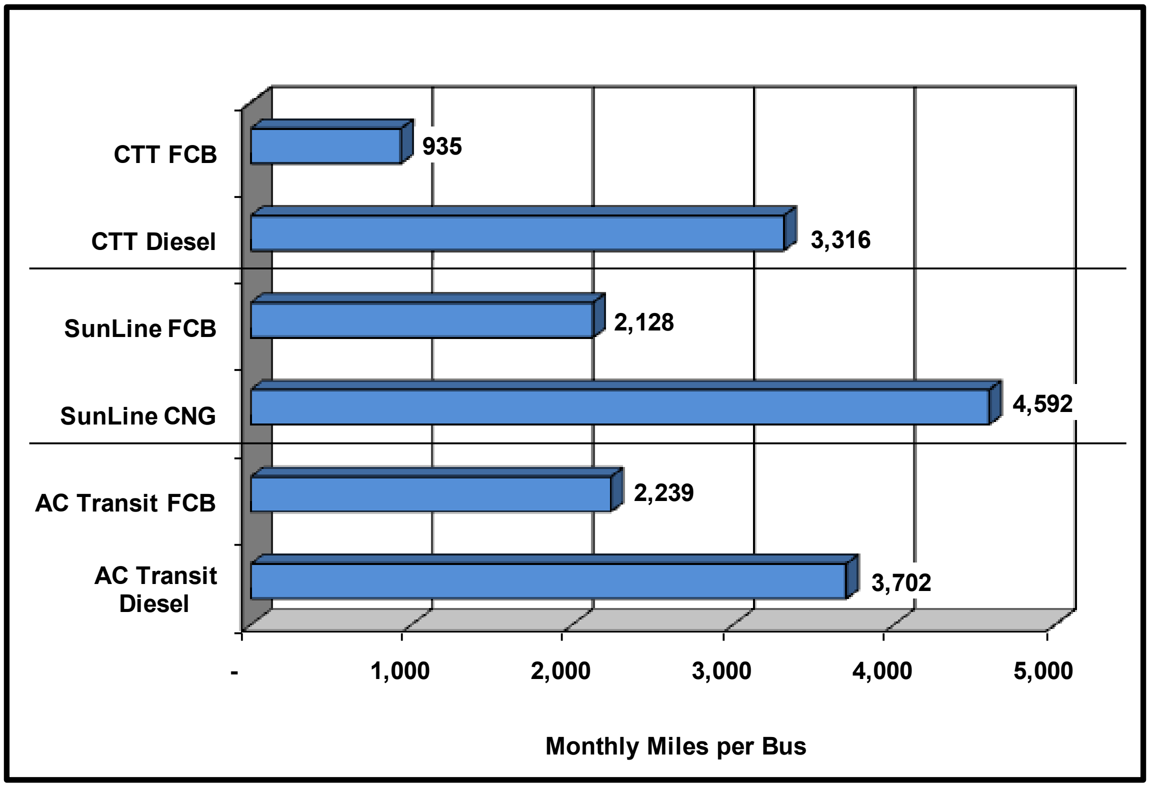

Figure 2. Average monthly miles per fuel cell and baseline buses

Availability—Availability is the percentage of days that buses are planned for operation compared to the percentage of days the buses are actually available. Table 4 summarizes the availability of the fuel cell buses at each transit agency. For this evaluation period, the fuel cell buses at AC Transit were available 68% of the time, the fuel cell bus at SunLine was available 69% of the time, and the fuel cell bus at **CT**TRANSIT was available 52% of the time. Figure 3 categorizes the reasons that the buses were not available by transit agency.

AC Transit's fuel cell buses were not available mostly due to transit-related repairs. AC Transit also had problems with the hybrid propulsion systems, primarily because of the batteries. Both SunLine's and **CT**TRANSIT's fuel cell buses had significant problems with the hybrid propulsion system and the traction batteries (both included in the hybrid propulsion category). As already mentioned, the **CT**TRANSIT bus was involved in an accident that required one of the doors to be replaced, and acquiring that door from Van Hool took more than a month. The bus was out of service for two months due to this accident.

Table 4. Availability for the Fuel Cell Buses

Site	Period	Months	No. of Buses	Planned Days	Days Avail.	% Avail.
Early FC System Results						
AC Transit	4/06-10/07	19	3	1,246	720	58
SunLine	1/06-3/08	27	1	653	432	66
CTTRANSIT	4/07-12/07	10	1	192	87	45
New FC System Results						
AC Transit	11/07-4/10	~27	3	1,857	1,226	66
SunLine	4/08-7/10	28	1	746	500	67
CTTRANSIT	1/08-7/10	31	1	707	446	63
Report Results Period						
AC Transit	8/09-3/10	8	3	589	400	68
SunLine	8/09-7/10	12	1	327	226	69
CTTRANSIT	8/09-7/10	12	1	255	133	52

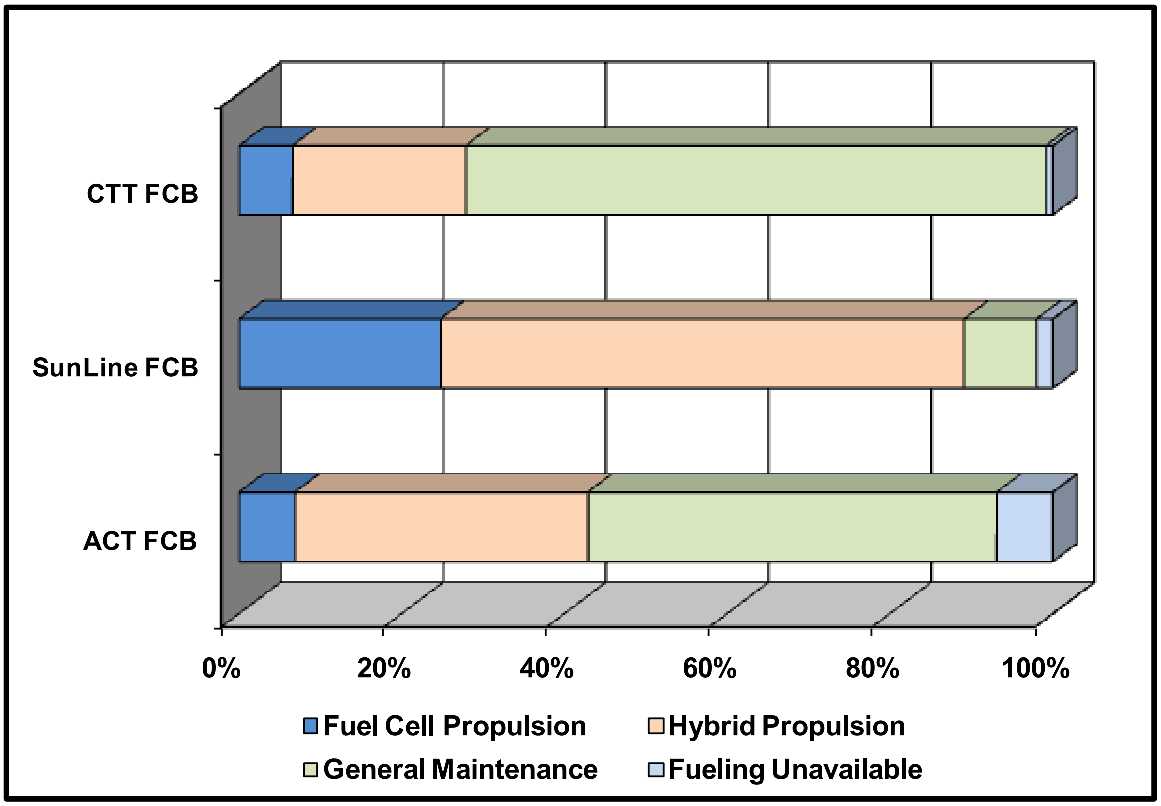

Figure 3. Reasons for unavailability of the fuel cell buses

Fuel Economy—Figure 4 shows the fuel economy in diesel energy equivalent gallons (DGE) for the fuel cell and baseline buses evaluated in this report. The fuel cell buses at the three locations showed fuel economy improvement ranging from 53% to 141% when compared to diesel and CNG baseline buses. AC Transit fuel cell buses have an overall fuel economy 53% higher than the AC Transit diesel buses.[6] For all revenue service at AC Transit, the fuel cell transit buses had

[6] Because the data collection on AC Transit's diesel baseline buses was completed previously, the chart includes the average fuel economy for one year of service.

a fuel economy average of 62% higher than the diesel buses. During the evaluation, the fuel cell buses reached more than twice the fuel economy of the diesel buses. Also, note that these diesel buses do not have air conditioning and the fuel cell buses do. In the next demonstration and evaluation at AC Transit, the diesel baseline buses will include air conditioning for a more accurate comparison. SunLine's fuel cell bus has a fuel economy 149% higher than its CNG buses. **CT**TRANSIT's fuel cell bus has a fuel economy 44% higher than its diesel buses. The **CT**TRANSIT diesel buses operate at twice the average speed as the fuel cell bus operating on the Star Route[7], which causes significantly lower fuel economy for its fuel cell bus compared to the fuel economies for the fuel cell buses at the other two transit agencies.

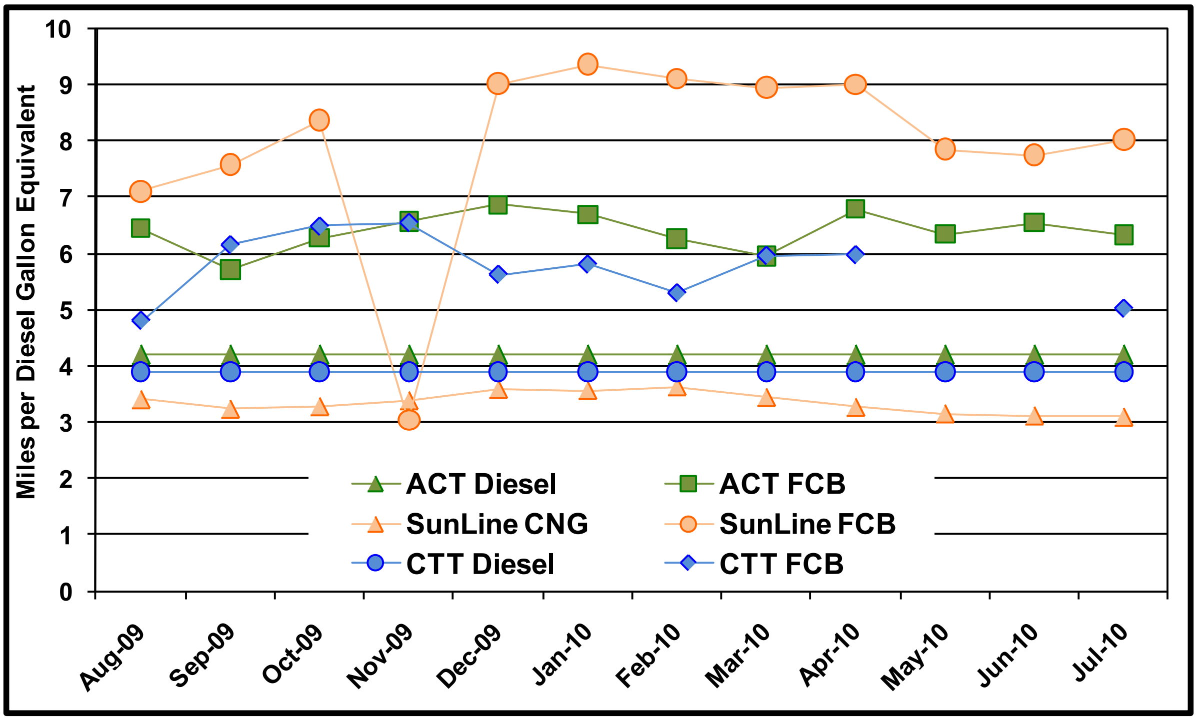

Figure 4. Fuel economy for fuel cell and baseline buses

Roadcalls—A roadcall (RC) or revenue vehicle system failure (see National Transit Database) is a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. If the bus is repaired during a layover and the schedule is maintained, then no RC is recorded. Figure 5 shows miles between roadcalls (MBRC) for all RCs, for propulsion-related-only RCs, and for fuel-cell-system-only RCs for the fuel cell and baseline bus groups at AC Transit, SunLine, and **CT**TRANSIT.

MBRC rates for the fuel cell buses are significantly lower than the MBRC rates for the baseline buses. Clearly, fuel cell buses need improvement in reliability. Manufacturers and transit agencies are working to resolve the problems causing these low rates. Traction battery and hybrid propulsion control software problems accounted for most of the propulsion-related RCs

[7] CTTRANSIT operates its fuel cell bus on a downtown shuttle route—the Star Route—which is characterized by slow-speeds, multiple stops, and higher idle time.

(86%) across the five fuel cell buses evaluated. In addition, problems with UTC Power fuel cell systems made up 11% of propulsion-related RCs, which is a significant improvement from earlier in the demonstration of these buses.

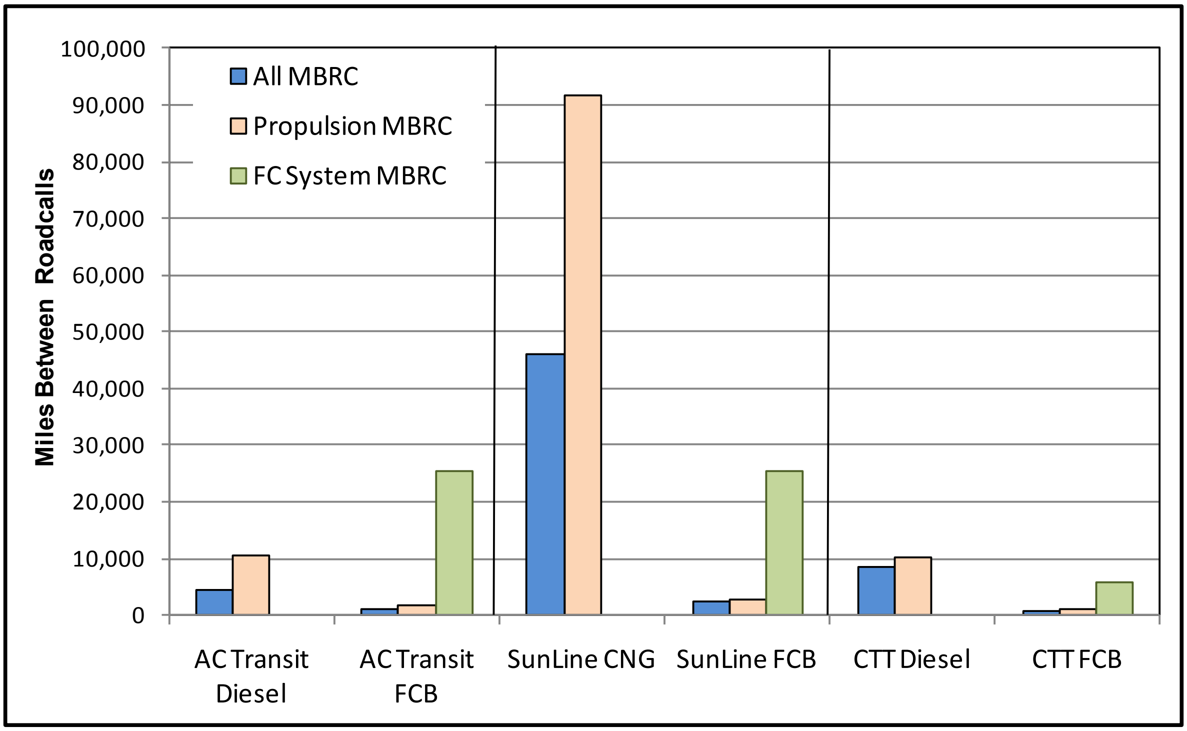

Figure 5. MBRC rates for fuel cell and baseline buses

Hydrogen Fueling—The fuel cell buses at these three transit agencies have been fueled with more than 67,000 kg of hydrogen over nearly five years with no fueling safety incidents. The fueling at each site is as follows:

- AC Transit—43,535 kg (March 2006 through July 2010)
- **CT**TRANSIT—9,286 kg (April 2007 through July 2010)
- SunLine—14,675 kg (December 2005 through July 2010)

In the last year of the data, the fueling times averaged 15 to 20 minutes per fill which equates to 1.3 kg per minute (from AC Transit and SunLine). Figure 6 shows a histogram of the fueling times at the two agencies. (Note: **CT**TRANSIT data is not included in the graph because the time provided includes set-up time.) These fill times are acceptable for a demonstration; however, in order to fuel more than a few fuel cell buses in one night, the capacity of the station needs to be significantly increased, and the fill time needs to be reduced to about 10 minutes per fill. The next-generation fueling stations being built at AC Transit will be a part of the ongoing demonstration and evaluation there. Figure 7 shows a histogram of the amount of hydrogen per fill for all three agencies. The average amount of hydrogen per fill during the entire demonstration period was 21 kg.

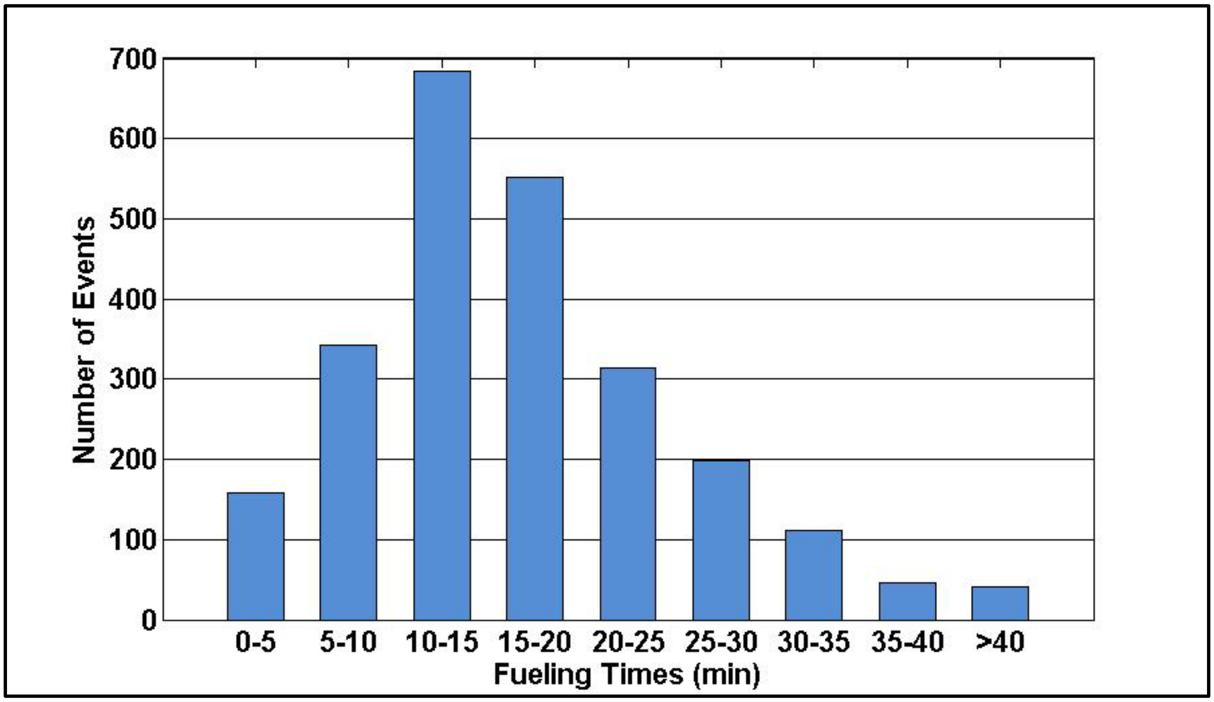

Figure 6. Histogram of fueling times for AC Transit and SunLine

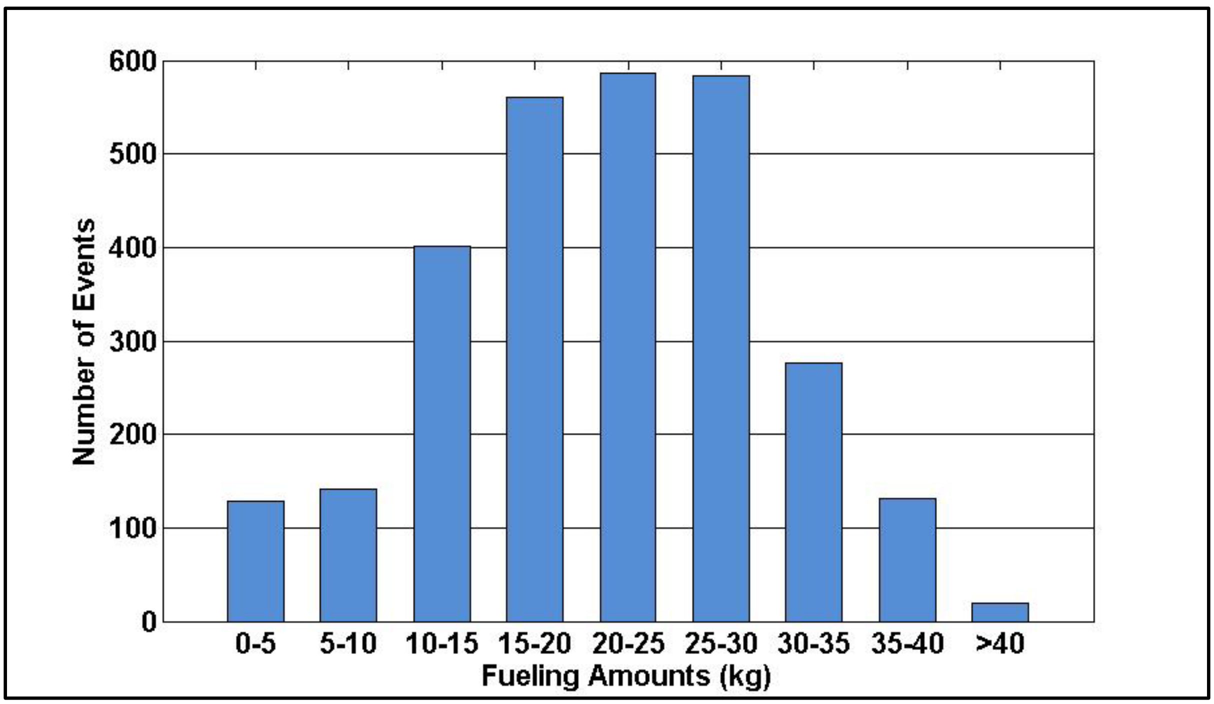

Figure 7. Histogram of amount per fill for the fuel cell buses at all three transit agencies

What's Next

In the next year, several demonstrations are expected to be up-and-running, and NREL is expecting to be monitoring and evaluating at each of those locations with funding from DOE and FTA. The addition of the new fuel cell bus designs and locations is expected to expand this assessment report's scope for determining the status of development. Several new evaluation reports are planned to present data and experiences from each of these sites.

The sites that are expected to be included in next year's assessment report are the following:

- ZEBA demonstration led by AC Transit: 12 Van Hool buses with UTC Power fuel cell power systems
- Nutmeg demonstration led by UTC Power: four Van Hool buses with UTC Power fuel cell power systems operating at **CT**TRANSIT and NYCT.
- One Proterra plug-in hybrid fuel cell (Hydrogenics) bus operating in Columbia, South Carolina, and transitioning to Austin, Texas
- A second Proterra plug-in hybrid fuel cell (Hydrogenics) bus operating in Burbank, California
- One New Flyer bus with hybrid integration by ISE using a Ballard fuel cell power system operating at SunLine
- One Orion bus with hybrid propulsion from BAE Systems with an auxiliary power unit using a Hydrogenics fuel cell power system and electric accessories operating at SFMTA

Additional buses that may begin operation and be available for the next report are a new bus from El Dorado, BAE Systems, and Ballard for operation at SunLine; a Nuvera fuel cell powered bus in Massachusetts; and another fuel cell bus planned in New York. These demonstrations may not have enough data available to be included in the next assessment report; however, a status update will be provided.

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Appendix: Summary Statistics

Table A-1. AC Transit Data Summary

	Early FC Version	New FC Version	Past Year
Data period	4/06 – 10/07	11/07 – 7/10	8/09 – 7/10
Number of buses	3	3	3
Number of months	19	~31	12
Total miles	60,198	188,322	76,112
Total FC hours	5,499	19,246	7,794
Average speed (mph)	10.9	9.8	9.8
Average miles per month	1,023	2,136	2,239
Availability	58%	66%	68%
Fuel economy (mi/kg)	6.22	5.95	5.69
Fuel economy (mpdeg)	7.03	6.73	6.43
All MBRC	1,281	1,223	1,171
Propulsion-only MBRC	1,505	1,583	1,691
FC system-only MBRC	5,017	10,463	25,371
Total hydrogen used (kg)	10,692	32,843	13,558

Table A-2. SunLine Data Summary

	Early FC Version	New FC Version	Past Year
Data period	1/06 – 3/08	4/08 – 7/10	8/09 – 7/10
Number of buses	1	1	1
Number of months	27	28	12
Total miles	52,336	53,315	25,537
Total FC hours	4,027	4,018	1,965
Average speed (mph)	13.0	13.3	13.0
Average miles per month	1,886	1,904	2,128
Availability	66%	67%	69%
Fuel economy (mi/kg)	7.20	7.20	7.34
Fuel economy (mpdeg)	8.14	8.13	8.29
All MBRC	1,495	2,221	2,322
Propulsion-only MBRC	1,636	2,962	2,837
FC system-only MBRC	7,477	6,664	25,537
Total hydrogen used (kg)	7,265	7,410	3,480

Table A-3. CTTRANSIT Data Summary

	Early FC Version	New FC Version	Past Year
Data period	4/07 – 12/07	1/08 – 7/10	8/09 – 7/10
Number of buses	1	1	1
Number of months	9	31	12
Total miles	5,157	39,970	11,218
Total FC hours	907	6,111	1,839
Average speed (mph)	5.7	6.5	6.1
Average miles per month	573	1,289	935
Availability	45%	63%	52%
Fuel economy (mi/kg)	4.82	4.82	4.97
Fuel economy (mpdeg)	5.44	5.44	5.62
All MBRC	573	957	863
Propulsion-only MBRC	737	1,148	1,122
FC system-only MBRC	5,157	5,741	5,609
Total hydrogen used (kg)	988	8,298	2,257