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Alameda-Contra Costa Transit District (AC Transit)

Fuel Cell Transit Buses: Third Evaluation Report

Kevin Chandler, Battelle
Leslie Eudy, National Renewable Energy Laboratory

Link to Appendices

Technical Report
NREL/TP-560-43545-1
July 2008

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Prepared under Task No. H270.8200

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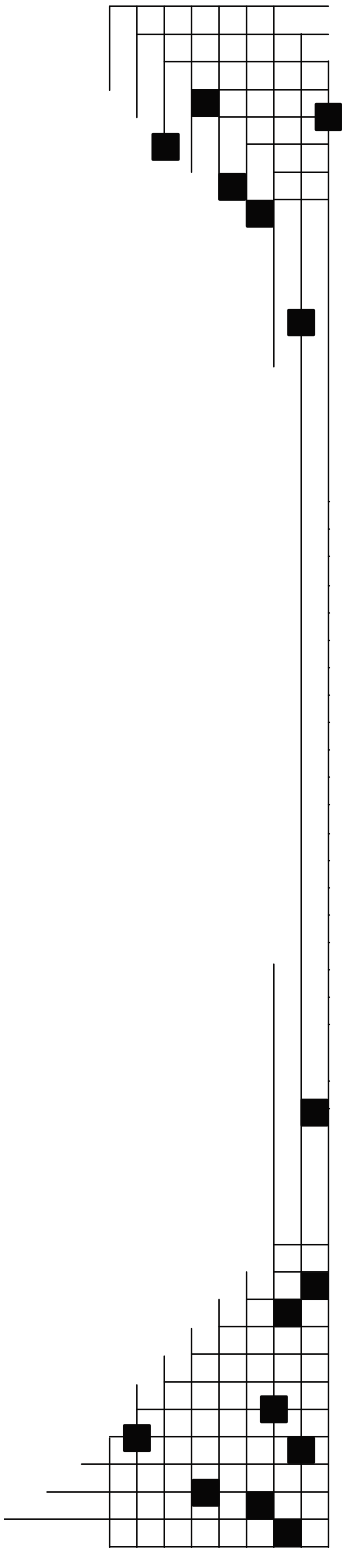

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Executive Summary

This report describes operations at Alameda-Contra Costa Transit District (AC Transit) for three prototype fuel cell buses and six diesel buses operating from the same location. This is the third evaluation report for this site, and it describes new results and experiences from September through December 2007. These results are an addition to those provided in the previous two evaluation reports. The evaluation periods presented in this report are as follows:

- **Fuel Cell Buses** – April 2006 through December 2007 (21 months of operation)
- **Diesel Buses** – April 2006 through December 2007 (21 months of operation)

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 provide opportunities to educate students, the general public in the Bay Area, and other interested parties such as federal and state government officials. AC Transit has been working with a team led by the Lawrence Hall of Science at the University of California, Berkeley to develop a curriculum to educate high school students and their teachers about hydrogen technologies. The operation of the fuel cell buses in revenue service also provides an opportunity for the public to experience the hydrogen fuel cell bus technology.

As resources allow, transit agency staff take the buses to outside events, provide on-site tours of the facility, and present information on the program. Since the beginning of the demonstration (January 2006 through December 2007), AC Transit estimates it has potentially reached over 520,000 people through various events and tours. 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 on March 20, 2006. The total estimate through December 2007 was 141,700 passengers.

Hydrogen Fueling

Hydrogen fuel is supplied at AC Transit by two steam methane reformers. The fuel is compressed and dispensed into vehicles at a final pressure of up to 5,000 psi. During the evaluation period, the AC Transit hydrogen station dispensed a total of 11,288 kg of hydrogen for the buses, with an overall average daily usage was 33.7 kg/day. The three buses were filled a total of 551 times during the evaluation period, with an average fill amount of 20.5 kg/fill and an average rate of 1.56 kg/min.

Evaluation Results

Table ES-1 provides a summary of results for several of the categories of data presented in this report.

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell	Diesel
Number of Buses	3	6
Data Period	4/06-12/07	4/06-12/07
Number of Months	21	21
Total Mileage in Period	62,191	389,473
Average Monthly Mileage per Bus	987	3,091
Availability (85% is target)	55%	N/A
Fuel Economy (Miles/kg)	6.23	N/A
Fuel Economy (Miles/DGE[a])	7.04	4.20
Miles between Roadcalls (MBRC) – All	1,296	4,582
MBRC – Propulsion Only	1,517[b]	10,526
Total Maintenance, $/mile[c]	0.57	0.44
Maintenance – Propulsion Only, $/mile	0.09	0.10

a. Diesel gallon equivalant
b. For fuel cell propulsion only, MBRC was 5,654
c. Work order maintenance cost

What's Next for AC Transit?

AC Transit has many hydrogen-related activities currently under way and in the planning stages as part of its HyRoad program. The existing fuel cell bus operation has nearly reached the originally planned two years of operation and evaluation. The current operation is now transitioning over to AC Transit's accelerated testing (starting November 1, 2007) as part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP). AC Transit plans to operate the three existing fuel cell buses in full revenue service to maximize usage for approximately two years.

At the same time, the California Air Resources Board (CARB) has required several California transit agencies (including AC Transit) to purchase new and advanced fuel cell buses as part of its zero-emission bus regulations. The Bay area is now required to have 12 new and advanced fuel cell buses in operation in 2009. AC Transit and UTC Power recently announced (May 6, 2008) an order for a minimum of eight new fuel cell power systems with options for an additional 13. These new fuel cell power systems are planned for delivery in 2009 and 2010. These systems are planned to be used in up to 20 fuel cell buses with one additional power system.

FTA is funding the evaluation of fuel cell buses for the accelerated testing at AC Transit. This means that the next two evaluation reports for AC Transit's program will be produced by and for FTA. Once the new buses for the CARB fuel cell bus demonstration start to arrive at AC Transit and the current three fuel cell buses are to be retired, the evaluation funding will be transitioned back to the U.S. Department of Energy (DOE). This is expected in mid-2009. The DOE evaluation plans include all 12 of the new fuel cell buses for the planned Bay Area CARB demonstration.

Table of Contents

Overview

The Alameda-Contra Costa Transit District (AC Transit) provides public transit service in the East Bay area including Oakland, California. 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 HyRoad. With a goal of demonstrating the viability of an emission-free transit system, this program includes operating fuel cell buses and passenger cars, 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 and intends to operate one of the fuel cell buses later in the program. GGT is a part of the Golden Gate Bridge, Highway, and Transportation District (GGBHTD), which is headquartered in San Francisco, California, and serves the North Bay area. Appendix A provides more information about AC Transit and GGT.

In March 2006, AC Transit kicked off its demonstration of three prototype fuel cell buses. The development of the fuel cell buses is the result of collaboration between Van Hool, ISE Corporation, and UTC Power. The buses use the PureMotion[1] 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) batteries. One of the fuel cell buses is pictured in Figure 1.

Figure 1. AC Transit fuel cell bus

This report describes operations at AC Transit for the three fuel cell buses and six Van Hool diesel buses in revenue service at the same location. The diesel buses (shown in Figure 2), which are used in the evaluation as a baseline, are equipped with Cummins ISL engines. Appendix B provides more detail about the buses and propulsion technologies included in this evaluation. Appendix C provides information about the hydrogen fueling infrastructure and facilities modified for use with hydrogen. Updated information regarding hydrogen dispensing into the fuel cell buses is discussed later in this report.

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

Figure 2. Diesel bus at AC Transit

The Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) is evaluating these buses to help determine the status of hydrogen and fuel cell systems and corresponding hydrogen infrastructure in transit applications. Appendix D provides a description of NREL's transit bus evaluation activities for DOE and the Federal Transit Administration (FTA). NREL has published two previous evaluation reports for this ongoing study at AC Transit.[2,3]

This third evaluation report describes results and experiences from April 2006 through December 2007. The newest data (September 2007 through December 2007) are highlighted when possible. The entire evaluation periods presented in this report are as follows:

- **Fuel Cell Buses** – April 2006 through December 2007 (21 months of operation)
- **Diesel Buses** – April 2006 through December 2007 (21 months of operation)

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 provide opportunities to educate students, the general public in the Bay Area, and other interested parties such as federal and state government officials. The operation of the fuel cell buses in revenue service also provides an opportunity for the public to experience hydrogen fuel cell bus technology.

Public Awareness

AC Transit continues to accommodate frequent requests for tours from various individuals and groups. As resources allow, transit agency staff take the buses to outside events, provide on-site tours of the facility, and present information on the program. Since the beginning of the demonstration (January 2006 through December 2007), AC Transit estimates it has potentially

[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

reached over 520,000 people through various events and tours. International interest has included visits by representatives from eight countries. Table 1 summarizes the public awareness events by category.

Table 1. Public Awareness Events by Category

Event Category	Number of Events	Number of People
Academic	15	3,176
General Public	54	515,663
Industry	13	32
International	18	104
Government	13	440
Partner Event	11	609
Total	**124**	**520,024**

During the latest data period (September 2007 through December 2007), AC Transit participated in 18 events that included nearly 178,000 people (included in the table above). A few of the events, tours, and presentations held since the last report was published include:

- **September 2007**: AC Transit provided tours of the hydrogen station and fuel cell buses for several events including Hayward Fire, a group from Australia, and the AC Transit Board and Chevron executives. Off-site events included a major local event called the Solano Stroll.
- **October 2007:** AC Transit provided fuel cell buses for two off-site events in Berkeley including the Spice of Life Festival and the Lawrence Hall of Science Community Day.
- **November 2007:** A fuel cell bus was provided for several off-site events including AC Transit's Uptown Transit Center Grand Opening and Alameda County's Veterans Day Parade.
- **December 2007:** During December, there were no tours or events that included the fuel cell buses or facilities. The buses were taken out of service for the holidays (December 22, 2007 through January 3, 2008).

AC Transit is also working in partnership with Lawrence Hall of Science at UC Berkeley and Schatz Energy Research Center at Humboldt State University to develop a 10-week science education curriculum for high schools around the country. The Hydrogen Technology and Education Curriculum (HyTEC) was funded in part by DOE to develop, test, and disseminate hydrogen and fuel cell curricula for high school students. AC Transit is funding the implementation of this curriculum in East Bay high schools served by AC Transit. The materials include hands-on kits to generate hydrogen from electrolysis, working fuel cells, and test equipment to measure results and efficiencies. Also included with the teaching materials are two videos. The first is a two-minute introductory film, and the second is an eight-minute piece that

describes various applications and associated challenges. The current status of this project was reported at the DOE Hydrogen Program 2008 Annual Merit Review[4].

Ridership

AC Transit, like most transit agencies, estimates their ridership. This is typically done by sampling ridership on the routes at different times of day, days of the week, and times of 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 December 2007, each of the buses carried between 45,000 and 50,000 passengers, with the total estimate being 141,700 passengers. Figure 3 shows the ridership estimate by month and as a cumulative total.

The passenger estimates have also been supplemented by actual passenger counts from an automated passenger counter (APC) installed in bus FC3. AC Transit has installed APCs in the other two fuel cell buses. The APCs are planned to be operational in early 2008.

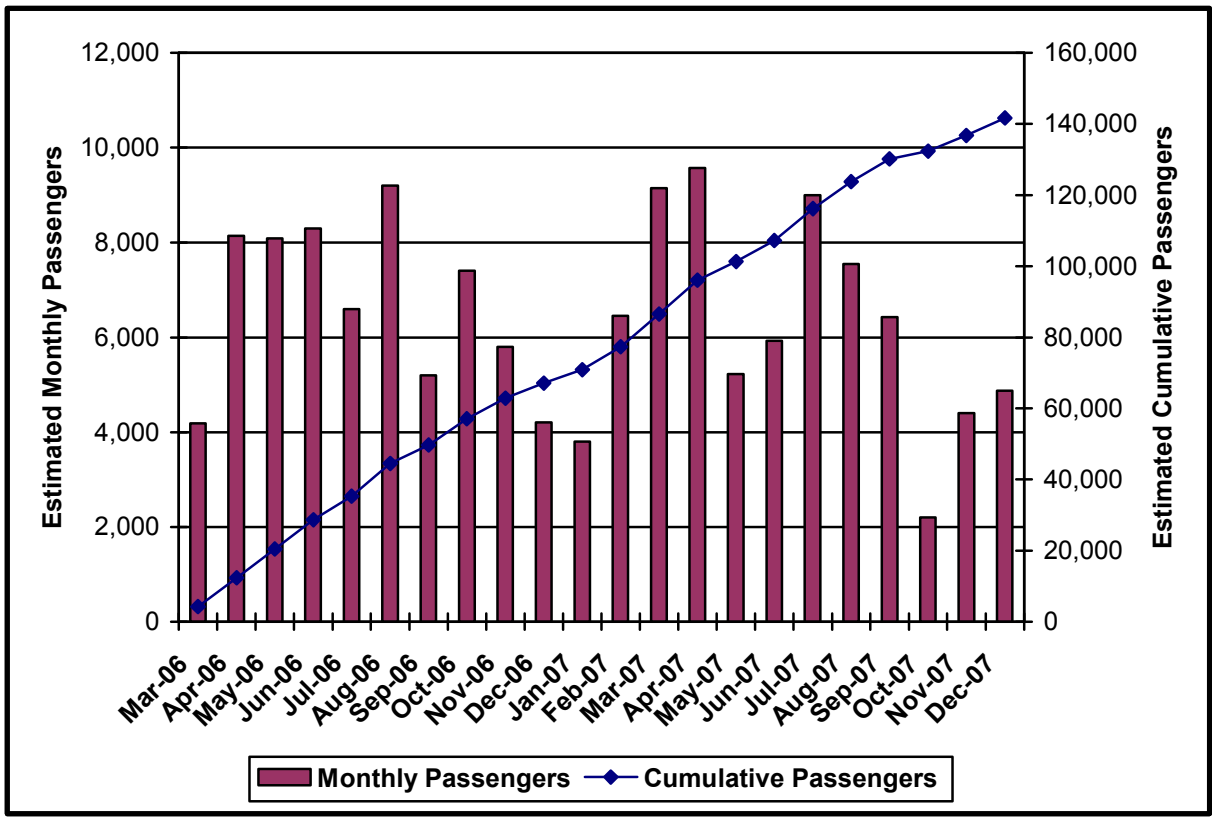

Figure 3. Ridership estimates for the fuel cell buses at AC Transit

[4] B. Nagle, *Hydrogen Technology and Energy Curriculum (HyTEC)*, DOE Hydrogen Program 2008 Annual Merit Review, June 2008, www.hydrogen.energy.gov/pdfs/review08/ed_6_nagle.pdf

Hydrogen Fueling

The hydrogen fueling station at AC Transit was designed by Chevron Technology Ventures and installed at the East Oakland division in 2005. The station includes two steam methane reformers that are capable of producing a total of 150 kg of hydrogen per day. Total storage capacity at the station is 366 kg of hydrogen at up to 6,250 psi. The station was inaugurated in March 2006 just prior to the start of revenue service for the fuel cell buses. Figure 4 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 provided in Appendix C.

Figure 4. Fueling at the Chevron Hydrogen Station

Figure 5 shows average daily hydrogen usage from the station during the evaluation period (April 2006 through December 2007) for buses only. AC Transit also has a fleet of seven light duty hydrogen vehicles that use the station as well, but that fuel consumption is not accounted for in this analysis and discussion. The overall average daily usage during this period was 33.7 kg/day for buses. The calculation for this rate only includes the days in which hydrogen was dispensed from the station for buses – 52% of the calendar days during the period. A total of 11,288 kg of hydrogen were dispensed into buses during this period.

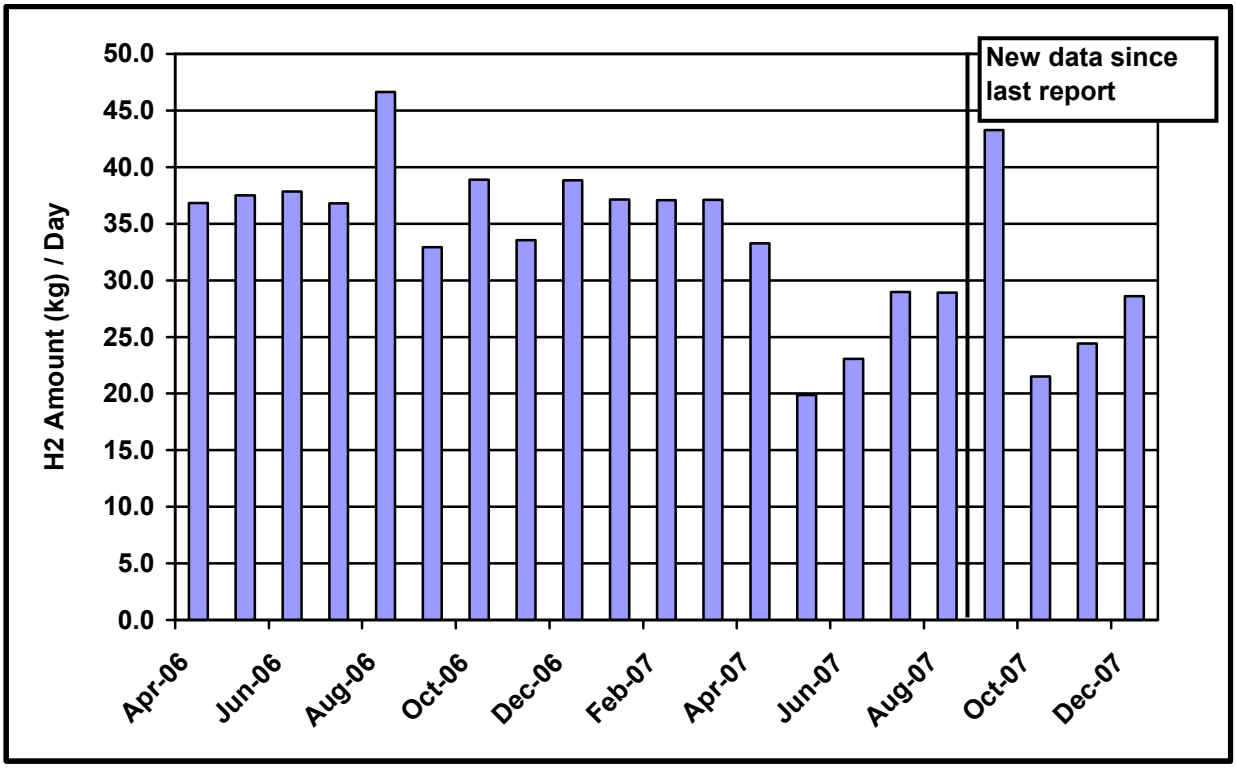

Figure 5. Average hydrogen use per day for AC Transit's fuel cell buses

Figure 6 shows the distribution of hydrogen amounts per fill. The three buses were filled a total of 551 times during the evaluation period, with an average fill amount of 20.5 kg/fill. Figure 7 shows the cumulative fueling rate histogram for the AC Transit station for the evaluation period. During this time, the overall average fueling rate was 1.56 kg/min. On average, it takes approximately 14 minutes to fuel a bus.

For most of the evaluation period, all hydrogen fueling was conducted by a Chevron technician. However, Chevron and AC Transit have been working on training and certification so that AC Transit employees are qualified to perform the fueling function themselves. Approximately 40 AC Transit employees completed classroom familiarization training for the fueling station and operation. Certification requires that each staff member complete 10 supervised fuelings (with the Chevron technician) along with the classroom training before being certified to fuel hydrogen on their own (with notification of Chevron and AC Transit).

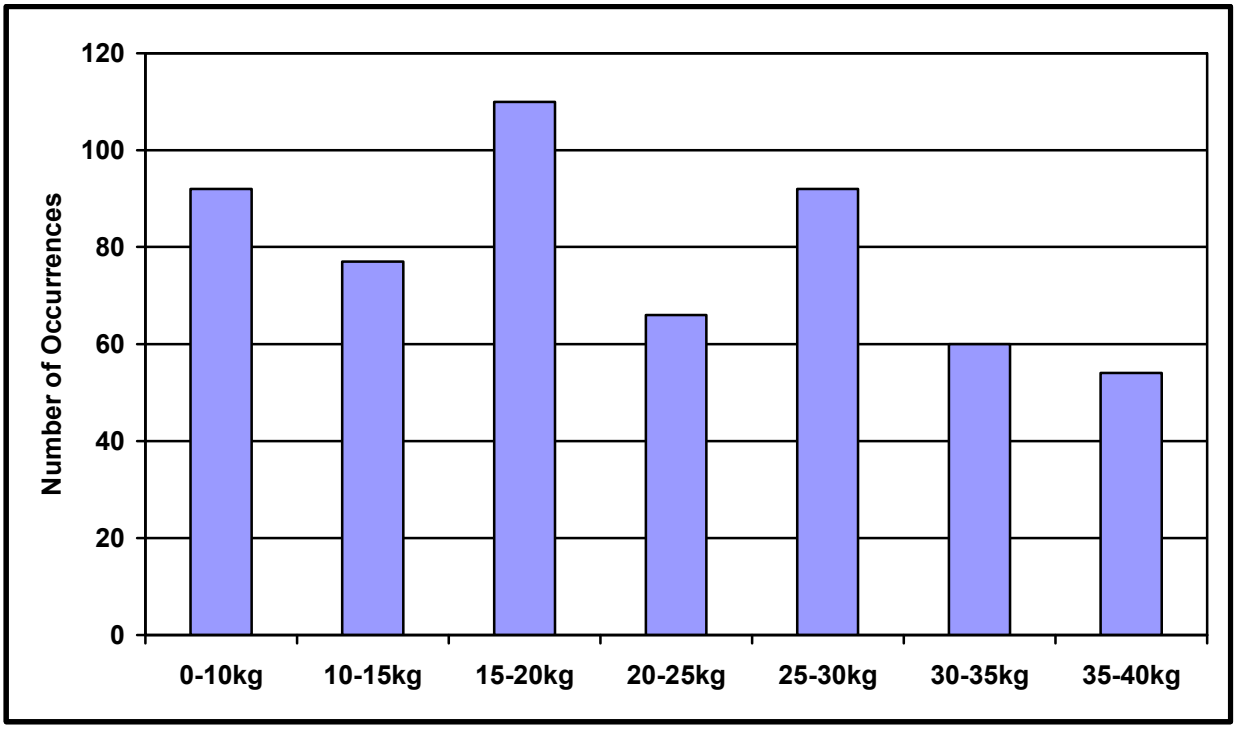

Figure 6. Distribution of average fill amounts for the fuel cell buses

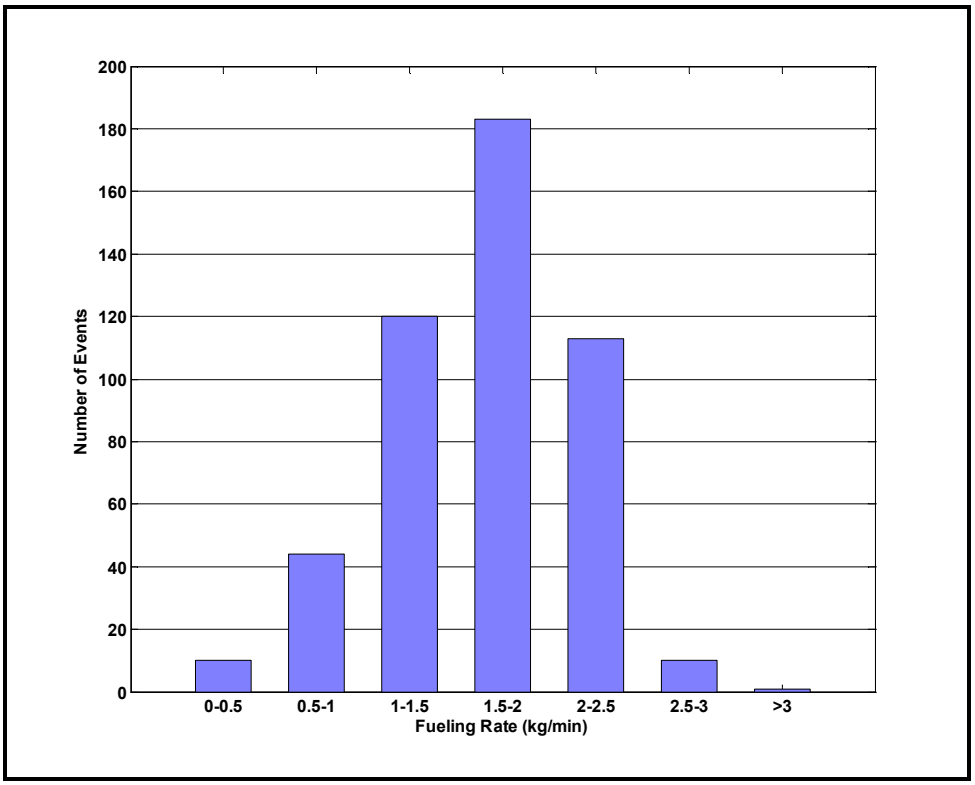

Figure 7. Fueling rate histogram for the AC Transit Hydrogen Energy Station (bus only)

Evaluation Results

The evaluation period for the fuel cell and diesel baseline buses for this report includes 21 months of operation from April 2006 through December 2007. The fuel cell buses started in revenue service on March 20, 2006, but the March 2006 data have not been included in the evaluation period to remove any early implementation/logistical issues. The diesel Van Hool buses are older and were in operation at AC Transit for some time prior to the evaluation period. The study group of diesel buses started operation in 2003-2004, but did not start operating at the East Oakland Division until July 2005. The evaluation period for the selected diesel buses is the same as that for the fuel cell buses.

In this third evaluation report, 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 help baseline the progress of the fuel cell bus technology. The intent of this analysis is to determine the status of this implementation and 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 for improving the vehicles, infrastructure, and procedures.

Route Descriptions

The fuel cell and diesel baseline buses are operated from AC Transit's East Oakland Division, which operates 15 local, two all-nighter, 10 transbay, and 14 school routes with 179 buses total (138 buses for peak service). The average bus operating speed for weekday service from the East Oakland Division is 14.3 mph.

For most of the evaluation period, the fuel cell buses were operated only during the week on two blocks of work that were created for testing the fuel cell and diesel baseline buses. This was done originally to help ensure that trained drivers and mechanics (and the manufacturer technicians) were available to work with the fuel cell buses. 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.

As AC Transit and the manufacturer partners have gained experience, there has been a desire to operate the fuel cell buses in a more aggressive manner. Starting with the June 2007 service change at AC Transit, the fuel cell buses were planned to operate on two new standard blocks of work on the newly formed Route 18, which are essentially the same level of service as a typical diesel bus. These two route blocks of work are shown in Table 2.

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

Route Block	Pull Out Time	Pull In Time	Total Time	Total Miles	Average Speed
18	6:11 AM	11:43 PM	17.53	171	9.8
18	5:16 AM	12:23 AM	19.11	199	10.4

There have been issues with meeting the long operation time of the Route 18 blocks because of the need to charge the batteries overnight before the next pullout. 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% state of charge (SOC) to allow for significant energy regeneration from braking back into the batteries. AC Transit has not fully implemented Route 18 fuel cell bus operation because of problems with the ZEBRA batteries (discussed further as part of the next section).

The diesel buses are not restricted to these special blocks of work. These buses are allowed to operate on other work blocks during the week and on weekends as well. This 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 provides a summary of bus usage and availability for the two study groups of buses.

Table 3 summarizes the average monthly mileage accumulation by the fuel cell buses and the study group for the evaluation period. During this period, the fuel cell buses accumulated 62,191 miles (7,787 miles since the last evaluation report), and the fuel cell systems accumulated 5,765 hours (827 hours since the last evaluation report). These numbers indicate an overall average speed of 10.8 mph (9.4 mph since the last evaluation report), which is lower than the East Oakland Division operation speed of 14.3 mph.

The diesel buses operated a monthly average of 3,091 miles each as compared to the fuel cell buses, which operated a monthly average of 987 miles each. This indicates that the fuel cell buses operated only 32% of the miles that the diesel buses did in the same period. The fuel cell buses were limited to one eight-hour shift per weekday for most of the evaluation period. The diesel buses were used in typical service, up to seven days per week and 16-20 hours per day.

Another measure of reliability is availability – the percent of days that the buses are planned for operation compared to the days the buses are actually available. Figure 8 shows monthly availability for each of the three fuel cell buses and an overall average availability for the group during the evaluation period. For the first five months of the evaluation period, the availability for the group was between 80% and 90%. Starting in September 2006, the availability for the group dropped to around 60% due to problems with the ZEBRA batteries and changeouts of the fuel cell stack assemblies (CSAs). The ZEBRA batteries have continued to be an issue for availability and the CSAs were replaced in all three of the buses between April and August 2007 and again between September and December 2007. The length of time for shipping parts from remote locations also had an adverse effect on downtime for both issues.

The most recently installed UTC Power CSAs in the fuel cell buses are a newer/upgraded version of the power system. This newer power system is expected to be much more durable than the previous versions. Plans for more aggressive operation with these new power systems at AC Transit are discussed further in the last section of this report (What's Next for AC Transit?).

Table 3. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage	Fuel Cell System Hours
FC1	5,164	25,061	19,897	21	947	N/A
FC2	778	19,461	18,683	21	890	N/A
FC3	3,153	26,494	23,611	21	1,124	N/A
Fuel Cell			**62,191**	**63**	**987**	**5,765**
1043	91,534	155,982	64,448	21	3,069	N/A
1044	108,346	174,535	66,189	21	3,152	N/A
1045	125,972	186,774	60,802	21	2,895	N/A
1046	125,685	193,493	67,808	21	3,229	N/A
1047	108,336	173,870	65,534	21	3,121	N/A
1048	94,092	158,784	64,692	21	3,081	N/A
Diesel			**389,473**	**126**	**3,091**	**N/A**

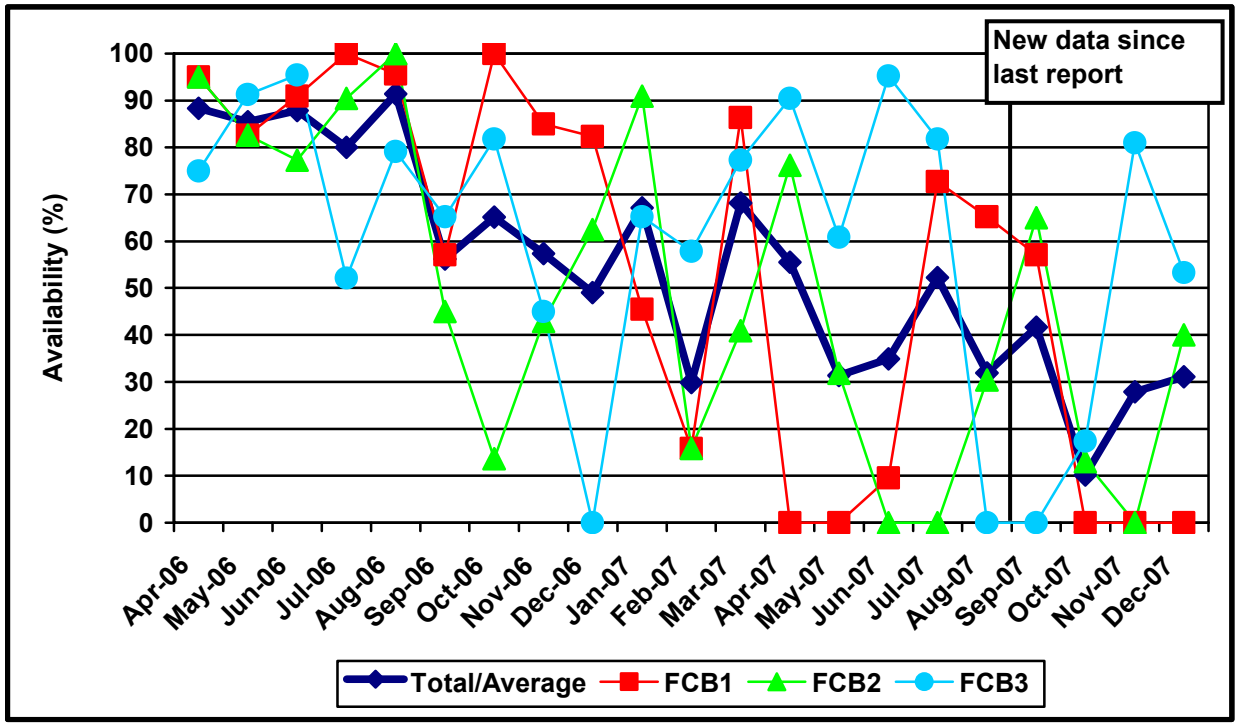

Figure 8. Availability for all three fuel cell buses and overall average

Table 4 summarizes the reasons for availability and unavailability for each of the three fuel cell buses. During the evaluation period, the average availability for the fuel cell buses was 55%. The overall availability percentage by bus and overall average is highlighted in blue in the table.

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	440		437		445		1,322	
Days Available	243	55	212	49	273	61	728	**55**
Available	**243**	**100**	**212**	**100**	**273**	**100**	**728**	**100**
On Route	172	71	183	86	191	70	546	75
Event/Demonstration	19	8	12	5	40	15	71	10
No Driver Available	13	5	7	3	4	1	24	3
Training	13	5	5	3	7	3	25	3
Not Used	26	11	5	3	31	11	62	9
Unavailable	**197**	**100**	**225**	**100**	**172**	**100**	**594**	**100**
Fuel Cell Propulsion	126	64	92	41	84	49	302	51
ISE Propulsion	1	1	6	3	3	2	10	2
ZEBRA Battery	34	17	80	36	36	21	150	25
Air Conditioning	3	1	3	1	3	2	9	2
AC Transit Maintenance	24	12	37	16	31	18	92	15
Event Preparation	4	2	5	2	10	5	19	3
Fueling Unavailable	5	3	2	1	5	3	12	2

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 evaluation period, Chevron employees provided nearly all fueling services for the hydrogen-fueled vehicles and electronically reported the fueling amounts.

Table 5 shows hydrogen and diesel fuel consumption and fuel economy for the study buses during the evaluation period. Overall, the three fuel cell buses averaged 6.23 miles per kg of hydrogen, which equates to 7.04 miles per diesel gallon equivalent (DGE). The energy conversion from kg of hydrogen to DGE is provided at the end of Appendix E. ISE also reported that the fuel cell buses had approximately 1,349 kg of hydrogen removed during the evaluation period so that the buses could be taken into the maintenance facility. This amount of hydrogen removed and vented equates to 12% of the hydrogen dispensed into buses.

The amount of hydrogen vented from the buses prior to maintenance has not been included in the fuel economy calculations. Also, 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 is now collecting the charging energy amounts. In future evaluation activities at AC Transit, we expect that estimates of charging energy per bus will be included in the fuel economy discussion.

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	19,897	3,138.2	6.34	2,777.1	7.16
FC2	18,683	3,024.2	6.18	2,676.3	6.98
FC3	23,611	3,819.6	6.18	3,380.1	6.99
FCB Total	**62,191**	**9,981.9**	**6.23**	**8,833.6**	**7.04**
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**

The diesel fuel consumption for the evaluation period is only available for January through December 2007. For this 12-month period, the six diesel baseline buses averaged 4.20 mpg, which indicates the fuel economy for the fuel cell buses is an overall 68% higher than that of the diesel buses.

Figure 9 shows a two-month rolling average fuel economy in both miles per kg and miles per DGE for the fuel cell buses as well as the diesel buses in miles per gallon. The chart shows a progression downward for the average fuel economy at the beginning of the period, indicating the first problems with the fuel cell systems. In the last four months of the evaluation period, the fuel cell fuel economy was back to the expected level. During the last few months of the evaluation period, the fuel economy started down again. This was caused by a combination of issues including the operating route, batteries, and additional air conditioning use.

The operating cost for hydrogen production and dispensing for AC Transit is currently estimated at between $6 and $8 per kg. This amount, which excludes capital expenses, was generated using early data (not optimized operation) and conservative maintenance and operating estimates. Using the $8 per kg cost estimate for hydrogen fuel indicates a cost per mile for the fuel cell buses of $1.28. The average diesel fuel cost per gallon during the evaluation period is $2.27 per gallon. This indicates a $0.54 per mile cost. The diesel cost per mile is about 42% of the fuel cell bus fuel cost per mile.

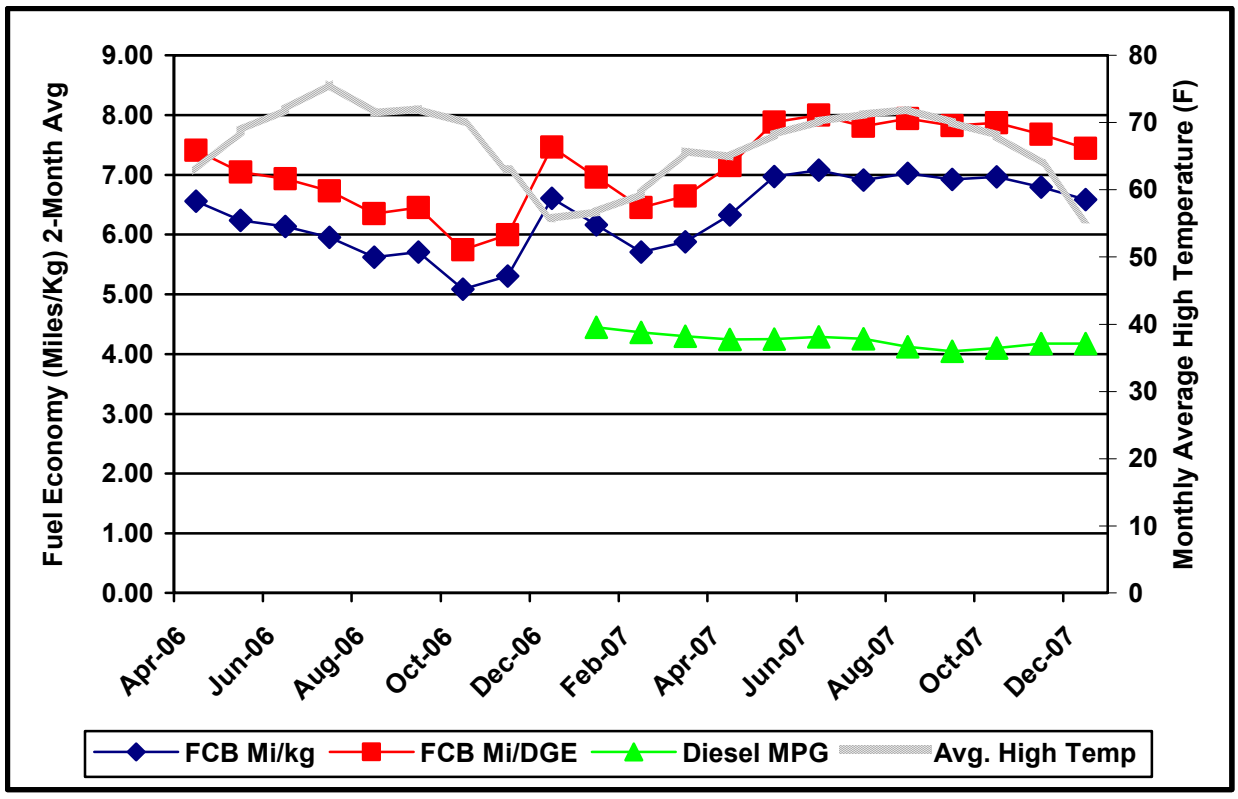

Figure 9. Two-month average fuel economy (evaluation period)

Maintenance Analysis

The maintenance cost analysis in this section is only for the evaluation period (April 2006 through December 2007). 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, then maintenance costs broken down by bus system.

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

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

Table 6 shows total maintenance costs for the fuel cell and diesel buses. Note that the fuel cell bus maintenance costs shown in the table are significantly lower because of the on-site warranty work done by the UTC Power and ISE technicians physically located at AC Transit. These technicians have done nearly all unscheduled and scheduled maintenance on the fuel cell buses for the fuel cell power systems and hybrid drive systems during the evaluation period. The AC Transit mechanics have supported the work done by the manufacturer technicians and have done cleaning and maintenance of the bus (inside and outside). Some support has been provided for responding to roadcalls and that effort is reflected in the maintenance discussion that follows.

Table 6. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Cost per Mile ($)
FC1	19,897	2,229.98	139.7	0.46
FC2	18,683	3,510.46	149.1	0.59
FC3	23,611	5,284.15	193.0	0.63
Total Fuel Cell	**62,191**	**11,024.59**	**481.8**	**0.57**
Avg. per Bus	**20,730**	**3,674.86**	**160.6**	**--**
1043	64,448	13,950.38	203.9	0.38
1044	66,189	15,344.66	216.5	0.40
1045	60,802	18,561.89	224.7	0.49
1046	67,808	16,629.77	236.8	0.42
1047	65,534	19,152.69	220.8	0.46
1048	64,692	20,262.02	244.1	0.50
Total Diesel	**389,473**	**103,901.41**	**1,346.8**	**0.44**
Avg. per Bus	**64,912**	**17,316.90**	**224.5**	**--**

AC Transit has expressed a strong desire to have its mechanics get more involved in all maintenance activities for the fuel cell buses so that they get the experience. AC Transit has 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 will also be necessary based on the desired increase in operation along with the future plans for more fuel cell buses.

Maintenance issues for the fuel cell buses centered on problems with the traction batteries and the three replacements of the fuel cell system CSAs on each of the buses. In addition to those problems, there were two accidents that required significant work by the AC Transit mechanics – one for FC2 during February and March 2007; and one for FC3 in May 2007.

Maintenance issues for the diesel buses were mostly related to engine problems with the turbocharger (three buses), ECM (three buses), and coolant surge tank (three buses). The diesel buses also had significant brake repair costs for standard relining (eight times). The other major maintenance cost issues were for accident repair and replacing seats and windows (five buses).

The total maintenance costs, without warranty costs, are much lower for the diesel buses. The per-bus results for the fuel cell buses compared to the diesel buses are as follows:

- Usage/Mileage – The fuel cell buses are 68% lower than the diesel buses
- Parts Costs – The fuel cell buses are 79% lower than the diesel buses
- Labor Hours – The fuel cell buses are 28% lower than the diesel buses
- Cost per Mile (without warranty costs) – The fuel cell buses are 30% higher than the diesel buses

Maintenance Costs Broken Down by System—Table 7 shows maintenance costs by vehicle system and bus study group (without warranty costs). The vehicle systems shown in the table include the following:

- **Cab, Body, and Accessories**: Includes body, glass, and paint repairs following accidents; cab and sheet metal repairs on seats and doors; and accessory repairs such as hubodometers and radios

- **Propulsion-Related Systems**: Repairs for exhaust, fuel, engine, electric motors, fuel cell modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, and transmission
- **Preventive Maintenance Inspections (PMI)**: Labor for inspections during preventive maintenance
- **Brakes**
- **Frame, Steering, and Suspension**
- **Heating, Ventilation, and Air Conditioning (HVAC)**
- **Lighting**
- **Air System, General**
- **Axles, Wheels, and Drive Shaft**
- **Tires**

Table 7. Breakdown of Vehicle System Maintenance Cost per Mile (Evaluation Period)

System	Fuel Cell*		Diesel	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Cab, Body, and Accessories	0.28	49	0.14	32
Propulsion-Related	0.09	16	0.10	23
PMI	0.11	19	0.07	16
Brakes	0.07	12	0.08	18
Frame, Steering, and Suspension	0.00	0	0.02	5
HVAC	0.01	2	0.01	2
Lighting	0.01	2	0.01	2
Air, General	0.00	0	0.00	0
Axles, Wheels, and Drive Shaft	0.00	0	0.01	2
Tires	0.00	0	0.00	0
Total	**0.57**	**100**	**0.44**	**100**

* Excludes warranty work costs

The systems with the highest percentage of maintenance costs for the fuel cell buses were propulsion-related; PMI; cab, body, and accessories; and brakes. 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, non-lighting 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 and diesel buses had similar maintenance costs overall; however, these costs do not include the work done by the ISE and UTC Power personnel, which was covered under warranty.

Table 8. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	62,191	389,473
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	887.52	25,191.46
Labor hours	97.8	306.6
Total cost ($)	5,775.02	40,519.96
Total cost ($) per mile	**0.09**	**0.10**
Exhaust System Repairs		
Parts cost ($)	0.00	5,258.08
Labor hours	0.0	33.6
Total cost ($)	0.00	6,935.58
Total cost ($) per mile	**0.00**	**0.02**
Fuel System Repairs		
Parts cost ($)	0.00	3,238.31
Labor hours	11.4	49.8
Total cost ($)	570.50	5,728.31
Total cost ($) per mile	**0.01**	**0.02**
Powerplant System Repairs		
Parts cost ($)	126.68	7,689.35
Labor hours	15.0	98.2
Total cost ($)	874.68	12,598.85
Total cost ($) per mile	**0.02**	**0.03**
Electric Motor and Propulsion Repairs		
Parts cost ($)	238.39	0.00
Labor hours	66.4	0.0
Total cost ($)	3,557.39	0.00
Total cost ($) per mile	**0.06**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	220.19	1,888.56
Labor hours	2.0	45.8
Total cost ($)	320.19	4,177.56
Total cost ($) per mile	**0.01**	**0.01**
Air Intake System Repairs		
Parts cost ($)	294.45	1,408.08
Labor hours	0.0	0.0
Total cost ($)	294.45	1,408.08
Total cost ($) per mile	**0.01**	**0.00**
Cooling System Repairs		
Parts cost ($)	7.80	5,041.17
Labor hours	1.0	70.5
Total cost ($)	57.80	8,566.17
Total cost ($) per mile	**0.00**	**0.02**
Transmission Repairs		
Parts cost ($)	0.00	533.15
Labor hours	2.0	2.8
Total cost ($)	100.00	670.65
Total cost ($) per mile	**0.00**	**0.00**

Roadcall Analysis

A roadcall (RC) or revenue vehicle system failure (as named in the National Transit Database) 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[5]. If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a RC. The analysis provided here only includes RCs that were caused by "chargeable" failures. Chargeable RCs include systems that can physically disable the bus from operating on route, such as interlocks (doors, air system), engine, etc. or things that are deemed to be safety issues if operation of the bus continued. They do not include RCs for things such as problems with radios or destination signs.

Table 9 shows the RCs and miles between roadcalls (MBRC) for each study bus categorized by all RCs and propulsion-related-only RCs. The diesel buses have much better MBRC rates for both categories. This is indicative of the low usage and prototype status of the fuel cell buses.

Table 9. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC	Fuel Cell only MBRC
FC1	19,897	16	1,232	14	1,422	4,974
FC2	18,683	19	1,131	16	1,440	4,671
FC3	23,611	13	2,008	11	2,232	7,870
Total FCB	**62,191**	**48**	**1,296**	**41**	**1,517**	**5,654**
1043 Diesel	64,448	9	7,161	4	16,112	
1044 Diesel	66,189	18	3,677	7	9,456	
1045 Diesel	60,802	22	2,764	9	6,756	
1046 Diesel	67,808	10	6,781	3	22,603	
1047 Diesel	65,534	14	4,681	9	7,282	
1048 Diesel	64,692	12	5,391	5	12,938	
Total Diesel	**389,473**	**85**	**4,582**	**37**	**10,526**	

[5] AC Transit defines a significant delay as six or more minutes.

What's Next for AC Transit?

AC Transit has many hydrogen-related activities currently under way and in the planning stages as part of its HyRoad program. The existing fuel cell bus operation has nearly reached the originally planned two years of operation and evaluation. The current operation is now transitioning over to AC Transit's accelerated testing as part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP). AC Transit plans to operate the three existing fuel cell buses in full revenue service to maximize usage for approximately two years.

At the same time, the California Air Resources Board (CARB) has required several California transit agencies (including AC Transit) to purchase new and advanced fuel cell buses as part of their zero-emission bus regulations. The Bay area is now required to have 12 new and advanced fuel cell buses in operation in 2009. AC Transit and UTC Power recently announced (May 6, 2008) an order for a minimum of eight new fuel cell power systems with options for an additional 13. These new fuel cell power systems are planned for delivery in 2009 and 2010. These systems are planned to be used in up to 20 fuel cell buses with one additional power system.

- **AC Transit's Accelerated Testing for FTA** – This activity plans to benchmark current fuel cell and hybrid systems in the three existing fuel cell buses at AC Transit. The three buses are now planned to operate in an accelerated manner – one block of the Route 18 on weekdays and three blocks of the Route 57 on weekdays and weekends. This accelerated testing started November 1, 2007, but had not been fully implemented by the end of the evaluation period in this report awaiting the installation of one of the fuel cell power systems and because of issues with availability of matched ZEBRA battery sets for each bus. Significant work has been completed at AC Transit to prepare for this accelerated testing, including training for all of the bus operators on the extra board (125 operators), addition of the two trainer mechanics assigned to the fuel cell bus program, and transition of hydrogen fueling from Chevron employees to AC Transit employees.

- **CARB Zero Emissions Bus Regulation** – CARB adopted a revision to their Zero Emission Bus (ZEB) rule in October 2006. Under this revision, the four Bay area transit agencies without zero-emission buses (AC Transit, GGT, Santa Clara Valley Transportation Authority – VTA, and San Mateo County Transit District – SamTrans) are required to establish a regional advanced fuel cell bus demonstration of 12 fuel cell buses by January 1, 2009. The regulation revision also extends a requirement deadline for procurement of 15% fuel cell buses for all new bus purchases for these transit agencies until January 1, 2011. As mentioned above, AC Transit has announced their purchase of eight new fuel cell buses from Van Hool and UTC Power for delivery in 2009 and 2010. These new buses (purchase price of $2.275 million each) have a slightly different design than the current fuel cell buses – they are 4,000 lbs lighter, three inches shorter in height, and different energy storage battery chemistry such as nickel metal hydride (NiMH) or lithium ion. The other four fuel cell buses for the Bay Area are to be purchased by VTA and their demonstration partner, SamTrans.

- **Next Evaluation Report** – This evaluation report covers AC Transit operation of the fuel cell and diesel buses through December 2007 and has been funded by DOE. The next evaluation report is funded by FTA as part of their National Fuel Cell Bus Program (NFCBP). Two evaluation reports are planned as part of AC Transit's accelerated testing starting with data from November 1, 2007 forward, which does overlap some with this report. The next evaluation report will also document preparations for and operation of one of the fuel cell buses at GGT. GGT personnel were trained in hydrogen and operation of the fuel cell buses. GGT also tested their planned operation with one of the fuel cell buses to make sure that trees were adequately trimmed to account for the taller bus and that there would not be any operational issues. One of the fuel cell buses was operated on weekdays for nearly 30 days at GGT during February and March 2008.

Once the new buses for the CARB fuel cell bus demonstration start to arrive at AC Transit and the accelerated testing is completed, the evaluation funding will be transitioned back to DOE. This is expected to happen in mid-2009. The DOE evaluation plans include all 12 of the new fuel cell buses for the planned Bay Area CARB demonstration.

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Acronyms and Abbreviations

AC Transit	Alameda-Contra Costa Transit District
APC	automated passenger counter
CARB	California Air Resources Board
CSA	cell stack assembly
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
ECM	electronic control module
FTA	Federal Transit Administration
GGBHTD	Golden Gate Bridge, Highway, and Transportation District
GGT	Golden Gate Transit
HyTEC	Hydrogen Technology and Education Curriculum
HVAC	heating, ventilation, and air conditioning
kg	kilogram
MBRC	miles between roadcalls
min	minutes
mpg	miles per gallon
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
NiMH	nickel metal hydride
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
psi	pounds per square inch
RC	roadcall
SamTrans	San Mateo County Transit District
SOC	state of charge
VTA	Santa Clara Valley Transportation Authority
ZEB	zero emission bus

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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

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