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Technical Report
NREL/TP-560-42249
October 2007

Alameda-Contra Costa Transit District (AC Transit)

Fuel Cell Transit Buses: Evaluation Results Update

Kevin Chandler, Battelle
Leslie Eudy, National Renewable Energy Laboratory

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Prepared under Task Nos. H270.8200

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Executive Summary

In early 2007, the National Renewable Energy Laboratory (NREL) published a preliminary evaluation results report[1] (April through November 2006) on hydrogen fuel cell and diesel buses operating at Alameda-Contra Costa Transit District (AC Transit) in Oakland, California. This report provides an update to the previous report and includes results and experience from December 2006 through August 2007. The evaluation covers three prototype fuel cell buses and six diesel baseline buses operating from the same AC Transit bus depot. The evaluation periods presented in this report are as follows:

- **Fuel Cell Buses** – April 2006 through August 2007 (17 months of operation)
- **Diesel Buses** – April 2006 through August 2007 (17 months of operation)

In March 2006, AC Transit kicked off the demonstration of three prototype fuel cell buses. The development of the fuel cell buses is the result of collaboration between ISE Corporation, UTC Power, and Van Hool. The buses use the PureMotion[2] 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.

This evaluation of prototype fuel cell transit buses at AC Transit is part of the U.S. Department of Energy's (DOE) Hydrogen, Fuel Cells & Infrastructure Technologies Program (HFCIT). This program integrates activities in hydrogen production, storage, and delivery with transportation and stationary fuel cell applications. The evaluation focuses on documenting progress and opportunities for improving the vehicles, infrastructure, and operating procedures. **There is no intent to consider the implementation of these hydrogen-fueled fuel cell transit buses as commercial (or full revenue transit service).**

Hydrogen Fueling Experience – Update

During the evaluation period, the Chevron-AC Transit hydrogen fueling station dispensed a total of 9,421 kg of hydrogen into buses. The station was used at least once per day to fill buses for 75% of the calendar days during the period. The overall average daily usage was 31.7 kg per day. The buses were filled a total of 418 times during the evaluation period, with an average fill amount of 20.2 kg. The average fueling rate was 1.50 kg/min and an average fueling takes 14 minutes.

Bus Experience – Update

In the preliminary evaluation results report for AC Transit, several issues were described for the fuel cell buses. The following discussion provides an update on those issues.

1. **ZEBRA batteries** – These batteries have had significant problems in this application. The main challenges have been accommodating cell failures and optimizing the state of charge (SOC) algorithm. The issues with using the three ZEBRA batteries have

[1] Alameda-Contra Costa Transit District, Fuel Cell Transit Buses: Preliminary Evaluation Results, March 2007, NREL/TP-560-41041, www.nrel.gov//hydrogen/pdfs/41041.pdf
[2] PureMotion is a trademark of UTC Power.

continued. AC Transit has started operating the fuel cell buses 14-16 hours per day. This has put excessive demands on these batteries. It has been difficult to keep the batteries charged and ready for service overnight between daily work assignments. ISE has been able to make more batteries available and ready for installation into a bus as needed.

2. **Air Conditioning** – During the summer of 2006, the air conditioning system had problems with failed evaporator and condenser motors. Since then, the motors have been changed. The summer of 2007 was uneventful as far as air conditioning failures for motor problems. This problem appears to be resolved at this point.

3. **UTC Power PureMotion 120 Fuel Cell Power System** – As reported in the preliminary evaluation results report, the cell stack assemblies (CSAs) for the fuel cell buses were replaced in late 2006 and early 2007. However, the CSA issues reported in the previous report have continued to impact each of the three buses in operation. Upgraded CSAs were provided by UTC Power and installed into FC1[3] and FC2 during June and August 2007 respectively. This has allowed AC Transit to start operating the fuel cell buses 14-16 hours per day. FC3 still has the previous version CSAs and had been taken out of service by the end of this evaluation period. This bus is expected to have CSA replacement in December 2007 with upgrades beyond those recently installed into FC1 and FC2.

Evaluation Results – Update

Table ES-1 provides a summary of results for many of the categories presented in this report. Note that fuel economy for the hydrogen-fueled buses is shown in miles per kilogram of hydrogen and in diesel gallon equivalent to compare with the diesel baseline buses.

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell	Diesel
Number of Buses	3	6
Data Period	4/06-8/07	4/06-8/07
Number of Months	17	17
Total Mileage in Period	54,404	277,408
Average Monthly Mileage per Bus	1,067	2,720
Availability (85% is target)	61%	N/A
Fuel Economy (Miles/kg)	6.17	
Fuel Economy (Miles/diesel gallon)	6.97	4.03
Miles between Roadcalls (MBRC) – All	1,395	4,474
MBRC – Propulsion Only	1,649	10,670
MBRC – Fuel Cell Related Only	5,440	
Total Maintenance, $/mile	0.59	0.44
Maintenance – Propulsion Only, $/mile	0.08	0.10

[3] AC Transit's fuel cell buses have been assigned the numbers: FC1, FC2, and FC3.

What's Next for This Demonstration?

This report covers AC Transit operation of the fuel cell and diesel baseline buses through August 2007. The next evaluation report for this site will include operational data through February 2008 and is planned for release around May 2008. This next evaluation report will include operational experience of one of the fuel cell buses on routes at Golden Gate Transit as well.

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 operates a fuel cell demonstration program called the HyRoad. With a goal of demonstrating the viability of an emission-free transit system, the HyRoad program includes operating fuel cell buses and passenger cars, on-site hydrogen production, fueling, and vehicle maintenance, and public education and safety training.

In March 2006, AC Transit kicked-off the demonstration of three prototype fuel cell buses. The development of the fuel cell buses is the result of collaboration between ISE Corporation, UTC Power, and Van Hool. The buses use the PureMotion 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.

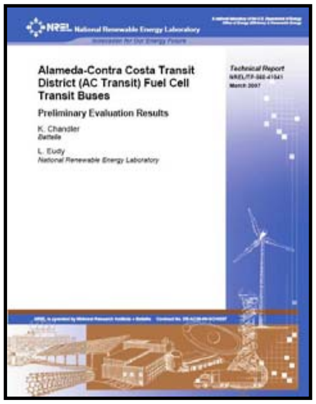
Figure 1. AC Transit fuel cell bus

Golden Gate Transit (GGT) 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. GGBHTD includes GGT and operates the Golden Gate Bridge and the Golden Gate Ferry operation. Figure 2 shows the coverage area of both AC Transit and GGT.

Demonstrations, such as the AC Transit HyRoad Program, are critical to understanding how these prototype systems and components perform in actual operation. The manufacturers use the data collected from demonstrations of this type to verify the results from controlled laboratory tests and to further optimize and improve their advanced propulsion systems for commercialization.

Figure 2. AC Transit and Golden Gate Transit operating area in California

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 a transit application. A preliminary data report was published in March 2007[4]. This report included descriptions of the technology, details on the early experiences, lessons learned, and eight months of preliminary operations data on the fuel cell buses. Evaluation results were also provided for diesel transit buses (Figure 1) as a baseline comparison to the fuel cell buses.



[4] Alameda-Contra Costa Transit District, Fuel Cell Transit Buses: Preliminary Evaluation Results, March 2007, NREL/TP-560-41041, www.nrel.gov//hydrogen/pdfs/41041.pdf

This evaluation results report provides results and experiences from December 2006 through August 2007, which is in addition to those provided in the preliminary evaluation results report. This data report includes results from the three prototype fuel cell buses and six similar diesel baseline buses operating from the same AC Transit bus depot. The evaluation periods presented in this report are as follows:

- **Fuel Cell Buses** – April 2006 through August 2007 (17 months of operation)
- **Diesel Buses** – April 2006 through August 2007 (17 months of operation)

Figure 1. Diesel bus at AC Transit

Infrastructure and Facilities

AC Transit operates its bus fleet from four divisions – Richmond, Emeryville, East Oakland, and Hayward. To demonstrate fuel cell buses (FCBs), the fleet needed to install hydrogen fueling infrastructure at one of these bus operating divisions. In March 2004, AC Transit partnered with Chevron Technology Ventures to design and build a hydrogen energy station at the East Oakland Division. Construction began in June 2005 and the station was operational by mid-December the same year. The Chevron – AC Transit Hydrogen Energy Station produces hydrogen through steam methane reforming. The station design includes two 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. Figure 4 provides pictures of the energy station including the reformer buildings, one of two dispensers, and the safety warning system.

AC Transit chose to modify an existing facility to enable staff to maintain the hydrogen-fueled buses safely. The required modifications (~$1.5 million) were completed and the maintenance bay was cleared for use in January 2006. The selected bay was isolated from the rest of the facility by a firewall. There is space for servicing two buses at a time. Figure 5 shows the bay with and without a fuel cell bus. Because the specially equipped maintenance bay is co-located with the rest of the maintenance building (and local fire code), maintenance staff is required to depressurize the buses prior to entering the facility. To accomplish this depressurization, the hydrogen in the tanks is vented down to 600 psi. The hydrogen removed from the vehicle is ultimately vented to the atmosphere in a controlled and safe manner. The fuel economy calculations presented later in this report exclude the hydrogen vented from the buses for this purpose.

Figure 4. The Chevron – AC Transit energy station

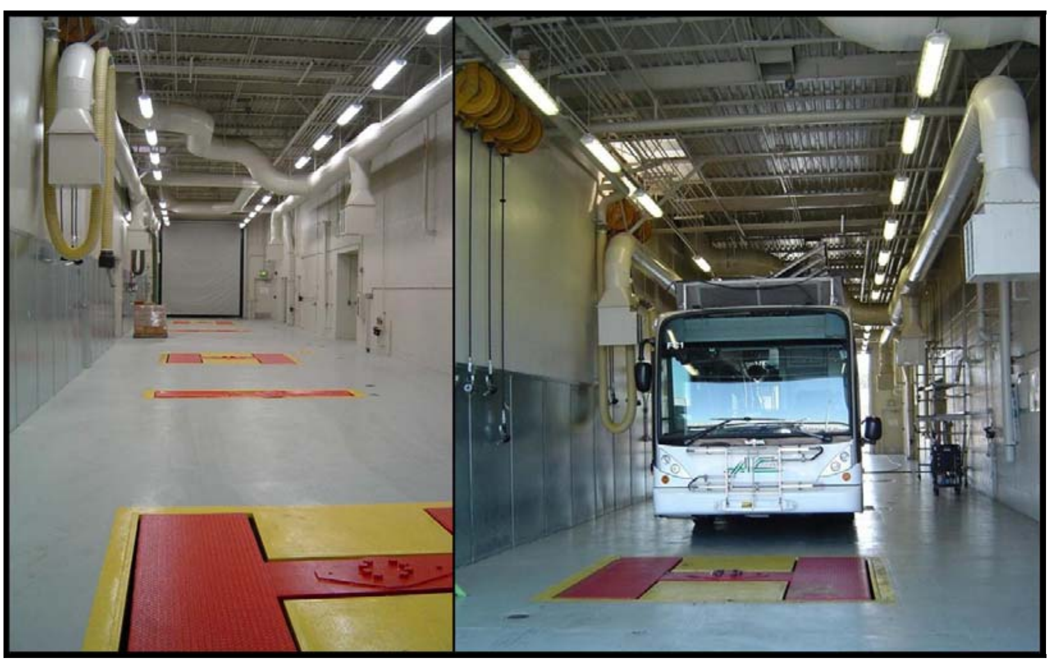


Figure 5. Modified maintenance bay at AC Transit East Oakland Division

Hydrogen Fueling Experience – Update: Figure 6 shows average daily hydrogen usage from the station during the evaluation period (April 2006 through August 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 in this period was 31.7 kg/day for buses. The calculation for this rate only includes the days in which hydrogen was dispensed from the station for buses – 75% of the calendar days during the period. A total of 9,421 kg of hydrogen were dispensed into buses during this period.

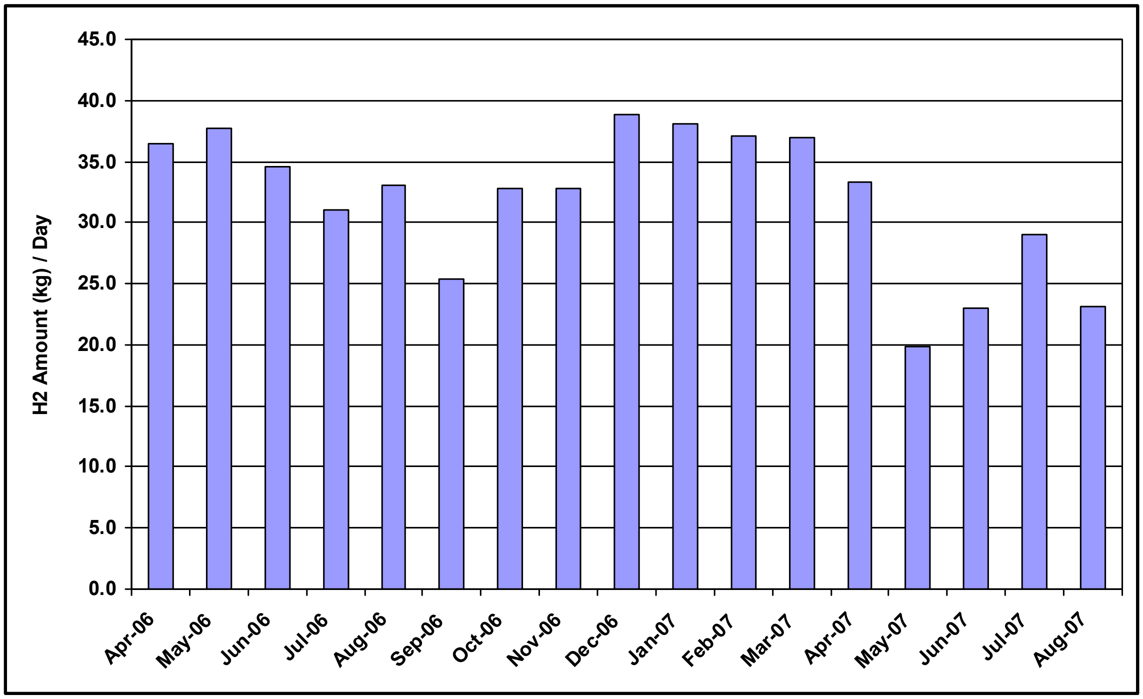


Figure 6. Average hydrogen use per day for the FCBs

Figure 7 shows the distribution of hydrogen amounts per fill. The three buses were filled a total of 418 times during the evaluation period, with an average fill amount of 20.2 kg/fill. Figure 8 shows the cumulative fueling rate histogram for the AC Transit station for the evaluation period. During this time, the overall average fueling rate was 1.50 kg/min. On average, it takes approximately 14 minutes to fuel a bus.

Currently, all hydrogen fueling is conducted by a Chevron technician. However, Chevron and AC Transit are working on training and certification so that AC Transit employees can qualify to perform the fueling function themselves. AC Transit staff (approximately 40 employees so far) completed classroom familiarization training for the fueling station and operation during the summer. 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). So far, three AC Transit employees have completed the certification process including the project manager, a trainer, and a service worker.

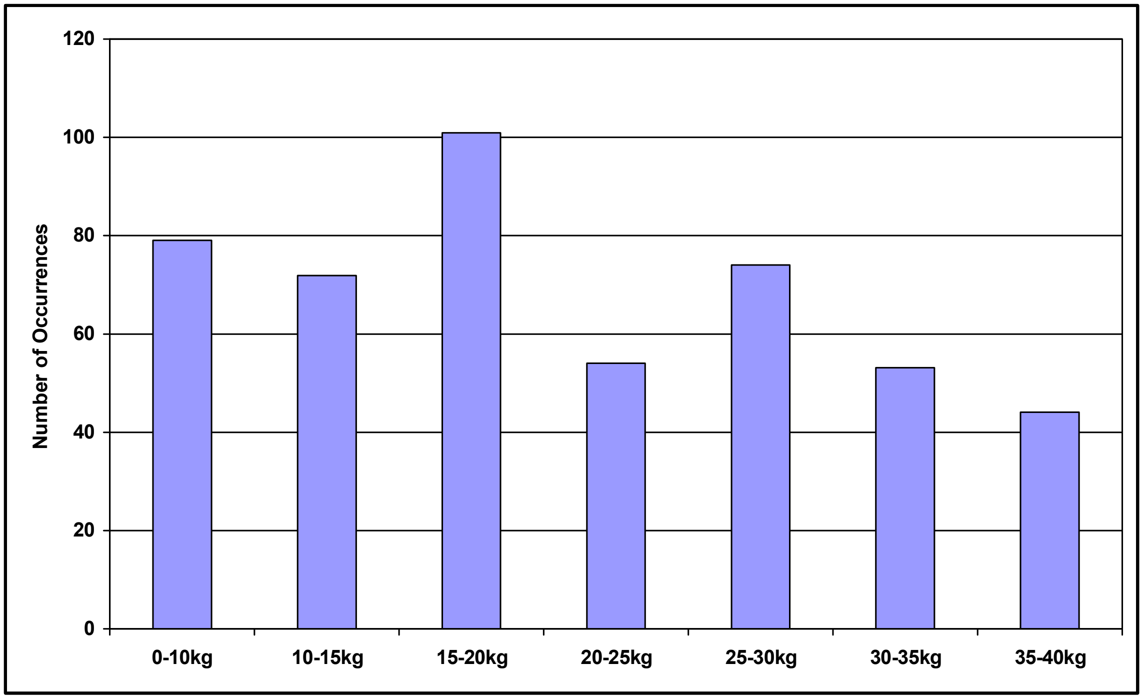


Figure 7. Distribution of average fill amounts

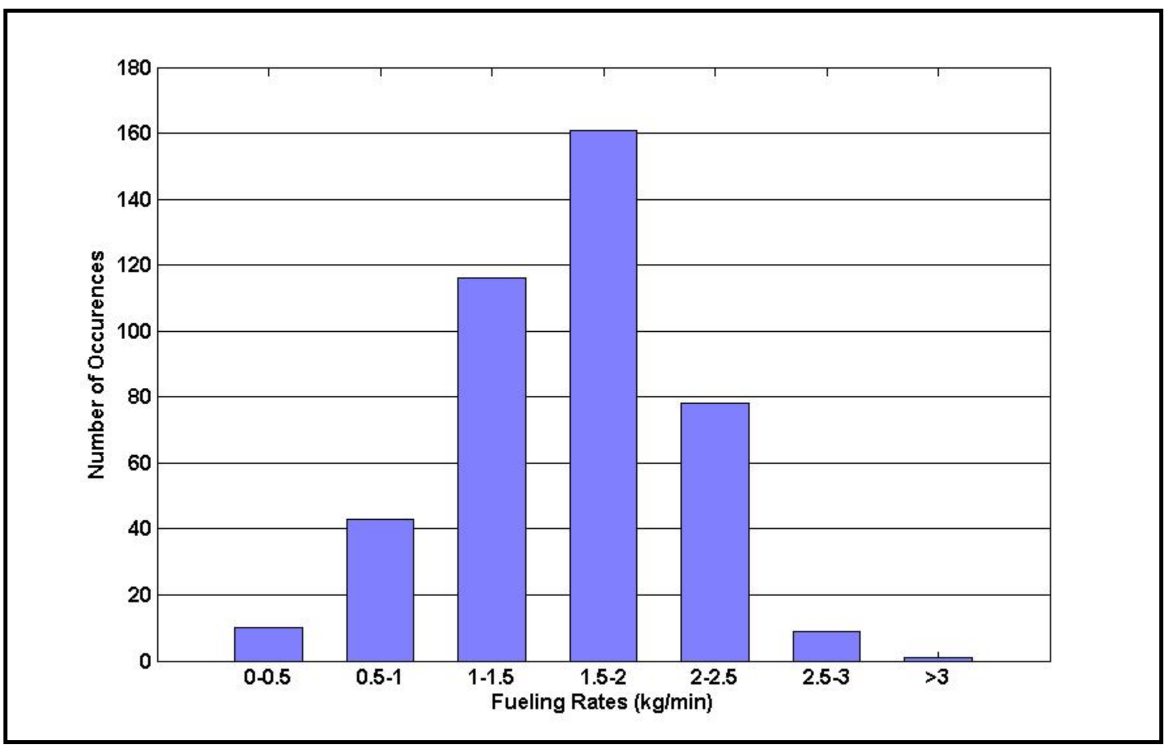


Figure 8. Fueling rate histogram for the AC Transit Hydrogen Energy Station (bus only)

Fuel Cell and Diesel Buses

Table 1 provides bus system descriptions for the fuel cell and diesel buses included in this evaluation. The buses began passenger service on March 20, 2006. For this evaluation, six Van Hool diesel buses were selected from buses of that type operating at the East Oakland Division. These six diesel buses are operated along side the fuel cell buses.

The diesel and fuel cell buses at AC Transit are the same bus model, but the diesel buses are slightly older. The fuel cell bus is a little more than 8,000 lbs heavier than the diesel bus, and this has reduced the passenger capacity. The price of the fuel cell bus is essentially ten times more than the diesel bus.

Table 1. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	Operation from East Oakland Division	
	Fuel Cell Bus	Diesel Bus
Number of Buses	3	6
Bus Manufacturer and Model	Van Hool A330 Low Floor	Van Hool A330 Low Floor
Model Year	2005	2003
Length/Width/Height	40 ft/102 in/139 in	40 ft/102 in/121 in
GVWR/Curb Weight	43,240 lb/36,000 lb	40,800 lb/27,800 lb
Wheelbase	228 in	235 in
Passenger Capacity	30 seated or 26 seated and two wheelchairs 15 standing	32 seated or 28 seated and two wheelchairs 53 standing
Engine Manufacturer and Model	UTC Power PureMotion 120 Fuel Cell Power System	Cummins ISL
Rated Power	Fuel cell power system: 120 kW Two Electric Drive Motors: 170 kW total (continuous)	280 hp @ 2200 rpm
Accessories	Electrical	Mechanical
Emissions Equipment	None	Diesel Oxidation Catalyst
Transmission/Retarder	Gearbox/Flenders Regenerative braking	Voith Integrated retarder
Fuel Capacity	50 kg hydrogen	92 gal
Bus Purchase Cost	$3.2 million	$323,000

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

Table 2. Additional Electric Propulsion System Descriptions

Propulsion Systems	Fuel Cell Bus
Manufacturer/Integrator	ISE Corporation
Hybrid Type	Series, charge sustaining
Drive System	Siemens ELFA/ISE
Propulsion Motor	2-AC induction, 85 kW each
Energy Storage	Battery – 3 modules/216 cells sodium/nickel chloride ZEBRA; 53 kWh capacity
Fuel Storage	Eight, roof mounted, SCI, type 3 tanks; 5,000 psi rated
Regenerative Braking	Yes

Bus Experience – Update: In the preliminary evaluation results report for AC Transit, we described several issues for the fuel cell buses. The following discussion provides an update on those issues from the last report and an additional topic.

1. **ZEBRA batteries** – These batteries have had significant problems in this application. The main challenges have been accommodating cell failures and optimizing the state of charge (SOC) algorithm. The issues with using the three ZEBRA batteries have continued. AC Transit has started operating the fuel cell buses 14-16 hours per day. This has put excessive demands on the batteries. It has been difficult to keep the batteries charged and ready for service overnight between daily work assignments. ISE has been able to make more of the batteries available and ready for installation into a bus as needed.

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3. **UTC Power PureMotion 120 Fuel Cell Power System** – As reported in the preliminary evaluation results report, the cell stack assemblies (CSAs) for the fuel cell buses were replaced in late 2006 and early 2007. However, the CSA issues reported in the previous report have continued to impact each of the three buses in operation. Upgraded CSAs were provided by UTC Power and installed into FC1 and FC2 during June and August 2007 respectively. This has allowed AC Transit to operate the fuel cell buses 14-16 hours per day. FC3 still has the previous version CSAs and was taken out of service by the end of this evaluation period. This bus is expected to have CSA replacement in December 2007 with upgrades beyond those recently installed into FC1 and FC2.

4. **Charging** – In preparation for full-day fuel cell bus operation, AC Transit upgraded their electrical access for charging the ZEBRA batteries overnight to allow faster charging. These upgrades were completed in June 2007. Each fuel cell bus is plugged into a charge station (shown in Figure 9) overnight to balance the charge between batteries, top off the charge, and provide heat for the batteries and freeze protection for the fuel cell when temperatures are 20° C or less.

Figure 9. Fuel cell bus/battery charging station at AC Transit

Training and Public Awareness

AC Transit is taking a proactive stance in its training program. The agency has provided hydrogen familiarization training to the majority of its staff. This training included information on the AC Transit HyRoad Fuel Cell Bus Program, general characteristics of hydrogen, and hydrogen safety.

The training for maintenance workers and operators is more extensive. For this training, maintenance staff at AC Transit and GGT has been learning light diagnostics and preventative maintenance for the FCB powertrain. ISE provided training that included a basic introduction to the hybrid fuel cell bus, descriptions of the drive system and components, preventive maintenance procedures, and instructions on safety aspects for maintaining the buses. UTC Power provided training on the fuel cell power system that included an introduction to the fuel cell system, descriptions of the various interfaces, and the necessary safety precautions for maintenance. AC Transit is working with the College of the Desert (Palm Springs, California) to develop a maintenance training class that will be incorporated into its apprenticeship program. AC Transit has also held several special training sessions for local fire fighters and emergency responders.

Raising public awareness for hydrogen and fuel cell technology continues to be an important part of the HyRoad program. In addition to introducing thousands of transit riders to the fuel cell buses in daily service, the agency has developed a Web site that provides information on the program. Visitors to the site can get general information on fuel cells and hydrogen, specifics on the demonstration, and keep up-to-date on the status of the project. The site also includes a Zero-Emission Hydrogen Fuel Cell Bus Operations Center, which provides near real-time tracking of the buses on-route. Displays include monitors for speed, power, emissions avoided, and a map pinpointing the location of the bus. The ISE-developed tracking center (Figure 10) uses global positioning system data from the buses to provide the second-by-second

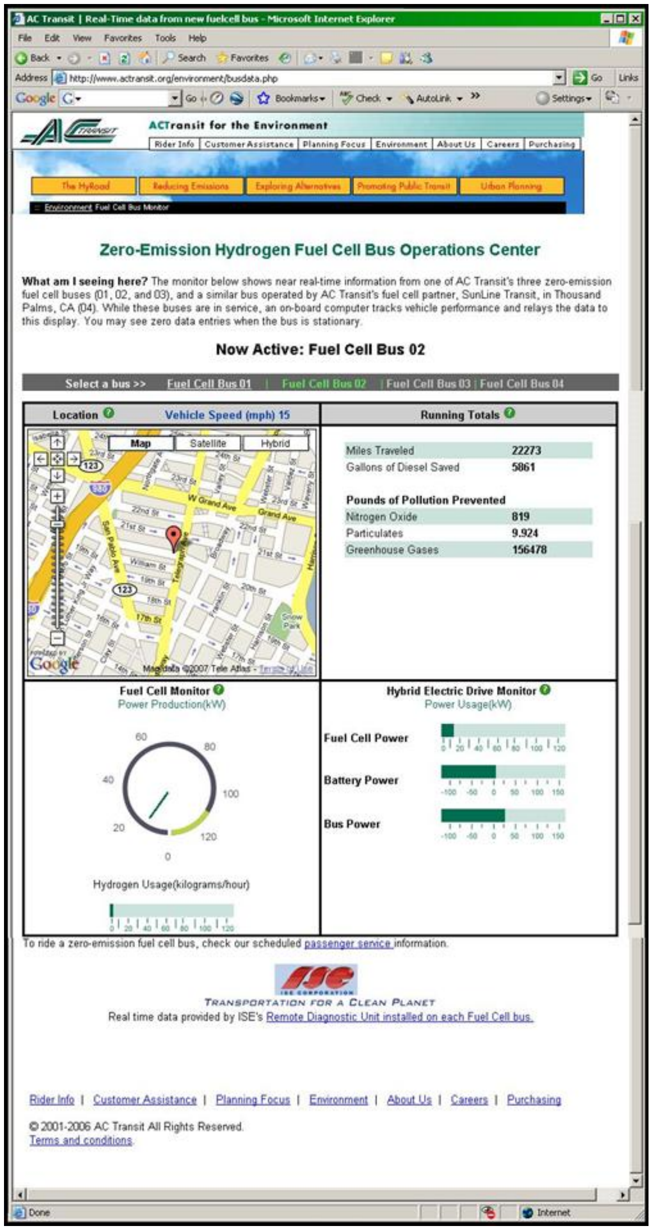

Figure 10. AC Transit's Fuel Cell Bus Tracking Center

status of the buses. The site allows the viewer to switch between any of four fuel cell buses. (Three at AC Transit and the fourth at SunLine in Thousand Palms, CA)

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 August 2007), AC Transit estimates it has potentially reached over 342,000 people through various events and tours. International interest includes representatives from eight countries. Table 3 summarizes those events by category.

Table 3. Public Awareness Events by Category

Event Category	Number of Events	Number of People
Academic	14	3,176
General Public	44	337,965
Industry	11	26
International	17	100
Government	11	385
Partner Event	9	591
Total	**106**	**342,243**

Events, tours, and presentations since the last report was published include:

- **December 2006**: AC Transit provided tours of the hydrogen station and fuel cell bus to A.P. Gianini Middle School and the Haas Energy Club.
- **January 2007:** AC Transit provided fuel cell buses for several off-site events including the inaugurations of the California Governor and Oakland Mayor, Berkeley's Ecopass Program event, a UTC Power event, and the Lawrence Hall of Science sponsored Bay Area Environmental Education Resource (BAEER) fair. Tours of the hydrogen station and bus were provided to representatives from DaimlerChrysler, EMCOR Group, and Chevron Technology Ventures.
- **February 2007:** AC Transit provided a fuel cell bus for a Climate Change event in Oakland, and hosted a meeting with representatives from the Weather Channel to discuss a study on climate change.
- **March 2007:** During the month, AC Transit hosted tours of the hydrogen facility and fuel cell bus to several groups including delegations from the U.S. – China Exchange Council and the Japan Gas Association. A fuel cell bus was provided for local events such as a Good Neighbor Breakfast, 2007 Sustainability Conference, and a Transportation and Land Use Choices Annual Summit.
- **April 2007:** AC Transit participated in several off-site events including the City of Oakland's Earth Day Celebration, the Cal Sustainable Transportation Fair, and Cal State East Bay Earth Day Event. Also during the month, AC Transit provided tours of the fuel cell bus and facilities to representatives from the California Transportation Commission, Bay Area Student Chapter of the Electrochemical Society, and Pacific Partners.

- **May 2007:** AC Transit provided a fuel cell bus for Keep Hayward Clean and Green event. Tours of the AC Transit facility and fuel cell bus were provided for several groups including Santa Clara Valley Transportation Authority, CalTrans, and the Indian government.
- **June 2007:** During the month, AC Transit hosted tours for Chevron's Mentoring Excellence in Technology program and representatives from SRI International.
- **July 2007:** AC Transit participated in 4th of July parades for Alameda and Freemont, as well as the Port of Oakland World Music Festival. A tour of the station and bus were provided to the mayor of San Leandro and staff and to a group of teachers for the HyTech program. A fuel cell bus was used in filming for an episode of DooF Kitchen, a PBS program aimed at teaching children about making healthy food choices.
- **August 2007:** AC Transit held a dedication for the solar power installation at the East Bay Division and hosted the filming of a documentary featuring Dave O'Reilly. A fuel cell bus was included in the Festival of India Parade, which was attended by approximately 40,000 people. AC Transit staff also provided tours to several groups including international students from Stanford's American Language and Cultural Program and delegations from Korea and Japan.

Evaluation Results

The evaluation period for the fuel cell and diesel baseline buses for this report includes 17 months of operation from April 2006 through August 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 have been in operation at AC Transit for some time. The study group of diesel buses started operation elsewhere 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 evaluation report, the fuel cell buses are considered to be a 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

Overall, AC Transit operates 107 fixed routes including 74 local, 27 transbay, and 6 all-nighter routes. In addition, there are 67 routes for school service in the East Bay area. AC Transit operates four bus divisions to serve these routes. The fuel cell and diesel baseline buses are operated only from the 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). For weekday service from the East Oakland Division, the average bus operating speed is 14.3 mph.

For demonstrating the advanced technology fuel cell buses, the fleet operates the buses only during the week on two blocks of work that were created for testing the fuel cell and diesel baseline buses. In addition, operating the fuel cell buses only in weekday service helps ensure that trained drivers and mechanics (and the manufacturer technicians) will be available to work with the fuel cell buses. The agency has also 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 in which one of the fuel cell buses may be included.

AC Transit developed two special bus blocks of work on each of two routes (Route 50 and Route 57) for operating the fuel cell and diesel baseline buses. These special bus blocks of work are shown in Table 5. The fuel cell buses were first operated on the two special blocks of work on Route 50 (Hegenberger) from March 20, 2006 to June 19, 2006 and again during March 2007 through June 2007. During these same timeframes, two of the diesel baseline buses were operated on two special blocks of work on Route 57 (40^{th} Street). Starting June 20, 2006 through March 2007, the fuel cell buses operated on Route 57 and the two baseline diesel buses operated on Route 50. This switch was done to ensure that fuel economy comparisons between the fuel cell and diesel baseline buses could eventually be made in the same duty cycle. AC Transit also operated the fuel cell buses for a short period of time during January 2007 on longer (15-hour) blocks on the Route 50 and 57.

Table 5. Route Blocks of Work Created for Fuel Cell Bus Evaluation

Route Block	Pull Out Time	Pull In Time	Total Time	Total Miles	Average Speed
50-12	5:26 AM	1:15 PM	7.82	127	16.2
50-21	12:55 PM	8:53 PM	7.97	127	15.9
57-20	6:27 AM	1:11 PM	6.73	76	11.3
57-21	1:02 PM	8:13 PM	7.18	82	11.4

Starting with the June 2007 service change at AC Transit, the fuel cell and diesel buses operated on two new special blocks of work on the newly formed Route 18 and Route 51. These two routes and blocks of work are shown in Table 6. There have been issues with meeting the long operation of the Route 18 blocks because of the need to be able to charge the batteries overnight before the next pullout. Another issue continues to be the need for tree trimming on the routes to ensure that the tall fuel cell buses do not get scratches around the roof.

Table 6. New Route Blocks of Work Created for Fuel Cell Bus Evaluation

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
51	5:10 AM	8:43 PM	15.55	148	9.5
51	5:32 AM	9:22 PM	15.84	148	9.3

The diesel buses are not restricted to just 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 indicated in the bus use that 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.

Figure 11 shows mileage and fuel cell power system operating hour accumulation for all three fuel cell buses from the start of testing at AC Transit in October 2005 through August 2007. As expected, usage began to accumulate faster after the buses went into passenger service in late March 2006. Use of the fuel cell buses was limited generally to weekdays and service within one eight-hour shift until the end of June 2007 when the work blocks were expanded. Other limiting factors included maintenance issues, availability of trained drivers, and availability of hydrogen fueling.

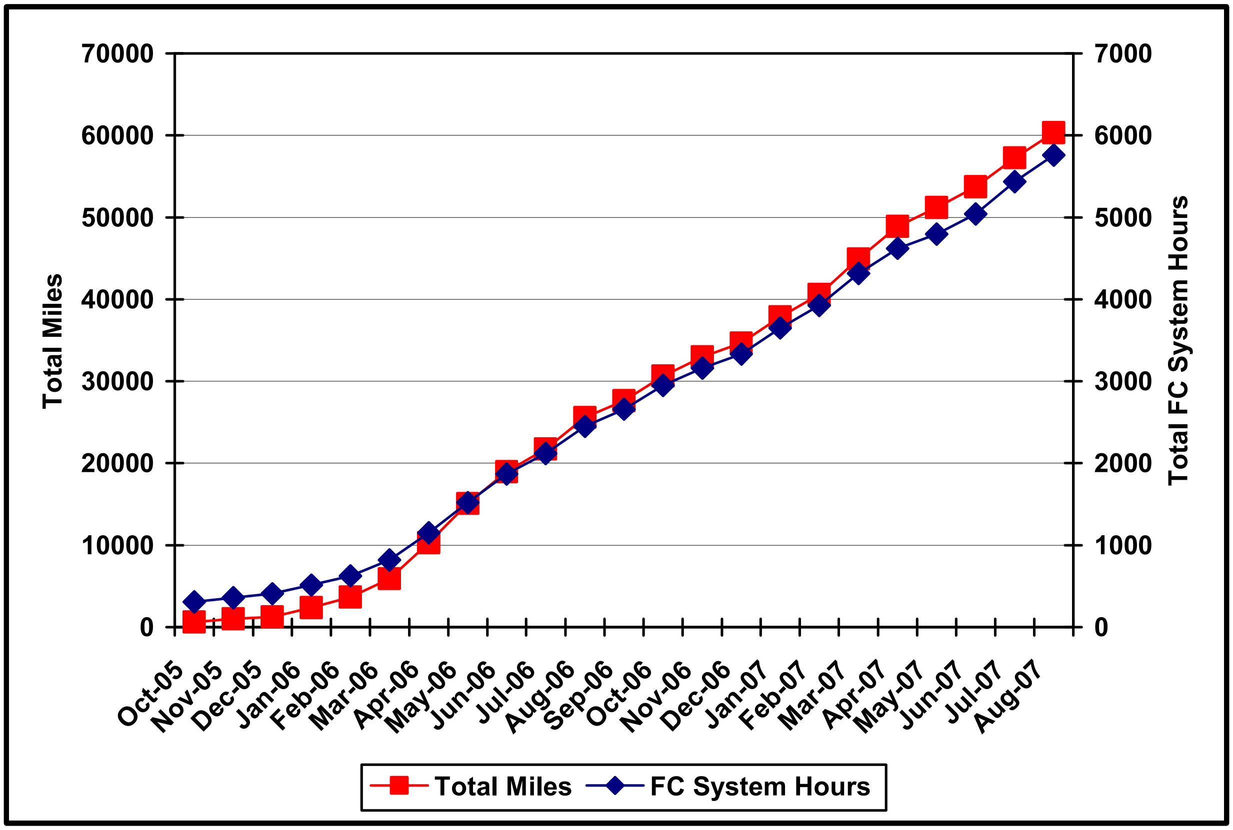

Figure 11. Cumulative mileage and fuel cell system hours for all three fuel cell buses

Table 7 summarizes average monthly mileage accumulation by bus and study group for the evaluation period. Since the start of operation, the fuel cell buses have accumulated over 60,000 miles. For the evaluation period (17 months), the fuel cell buses accumulated 54,404 miles and 4,938 fuel cell power system hours (this indicates an average speed of 11.0 mph during the evaluation period).

The diesel buses operated a monthly average of 2,720 miles each as compared to the fuel cell buses, which operated a monthly average of 1,067 miles each. This indicates that the fuel cell buses operated only 39% of the miles that the diesel buses did in the same period. The fuel cell buses were limited to only weekdays and 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.

Figure 12 shows monthly availability for each of the three fuel cell buses and an overall average availability for the group for 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), as described above. The ZEBRA batteries have continued to be an issue for availability and the CSAs were replaced again for all three of the buses. These problems are highlighted by the number of months that a bus had zero availability, especially during April through August 2007.

Table 7. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage	Fuel Cell System Hours
FC1	5,164	23,646	18,482	17	1,087	N/A
FC2	778	16,616	15,838	17	932	N/A
FC3	3,153	22,967	20,084	17	1,181	N/A
Fuel Cell			**54,404**	**51**	**1,067**	**4,938**
1043	91,534	136,883	45,349	17	2,668	N/A
1044	108,346	158,880	50,534	17	2,973	N/A
1045	125,972	170,293	44,321	17	2,607	N/A
1046	125,685	172,272	46,587	17	2,740	N/A
1047	108,336	155,502	47,166	17	2,774	N/A
1048	94,092	137,543	43,451	17	2,556	N/A
Diesel			**277,408**	**102**	**2,720**	**N/A**

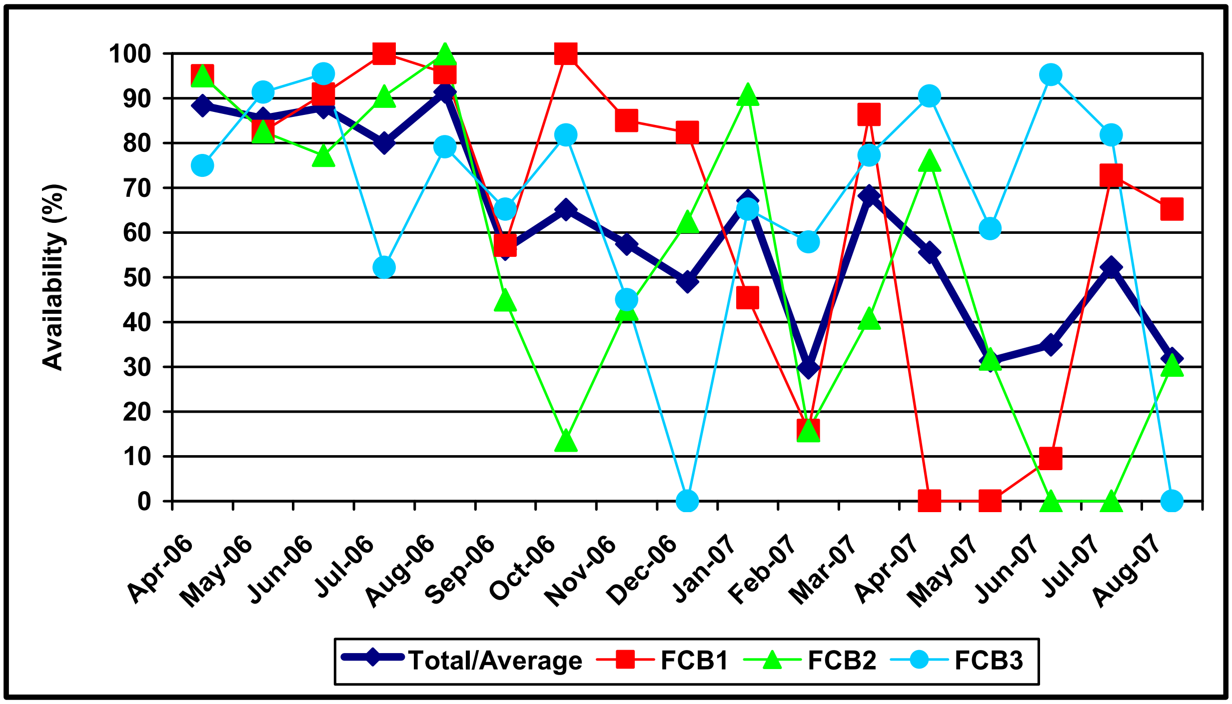

Figure 12. Availability for all three fuel cell buses and overall average

Table 8 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 61%. The overall availability percentage is highlighted in the table for each bus and the average.

Table 8. Summary of Reasons for Availability and Unavailability of Buses for Service

Category	FC1		FC2		FC3		Group Total	
	Days	%	Days	%	Days	%	Days	%
Planned Work Days	361		359		367		1,087	
Days Available	231	64	190	53	244	66	665	61
Available	**231**	**100**	**190**	**100**	**244**	**100**	**665**	**100**
On Route	165	65	162	85	170	70	497	75
Event/Demonstration	14	5	11	6	37	15	62	9
No Driver Available	13	6	7	3	2	1	22	3
Training	13	7	5	3	6	2	24	4
Not Used	26	17	5	3	29	12	60	9
Unavailable	**130**	**100**	**169**	**100**	**123**	**100**	**422**	**100**
Fuel Cell Propulsion	81	62	92	54	52	42	225	53
ISE Propulsion	1	1	4	2	3	2	8	2
ZEBRA Battery	14	11	30	18	25	20	67	16
Air Conditioning	3	2	3	2	2	1	8	2
AC Transit Maintenance	23	18	33	20	29	23	84	20
Event Preparation	3	2	5	3	10	8	18	4
Fueling Unavailable	5	4	2	1	5	4	12	3

Fuel Economy and Cost

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

Table 9 shows hydrogen and diesel fuel consumption and fuel economy for the study buses during the evaluation period. Overall, the three fuel cell buses averaged 6.17 miles per kg of hydrogen, which equates to 6.97 miles per diesel gallon equivalent. The energy conversion from kg of hydrogen to diesel gallon equivalent is provided in Appendix A. ISE also reported that the fuel cell buses had approximately 1,035 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 10% of the hydrogen dispensed into the fuel cell buses.

Table 9. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (Gallon)	Miles per Gallon
FC1	18,482	2,969.3	6.22	2,627.7	7.03
FC2	15,838	2,609.1	6.07	2,308.9	6.86
FC3	20,084	3,245.2	6.19	2,871.9	6.99
FCB Total	**54,404**	**8,823.5**	**6.17**	**7,808.4**	**6.97**
1043	24,736			6,211.8	3.98
1044	26,328			6,104.5	4.31
1045	26,998			6,421.7	4.20
1046	23,513			6,436.2	3.65
1047	26,547			6,189.6	4.29
1048	21,258			5,748.8	3.70
Diesel Total	**149,380**			**37,112.6**	**4.03**

The diesel fuel consumption for the evaluation period is only available for January through August 2007. For this eight-month period, the six diesel baseline buses averaged 4.03 mpg, which indicates the fuel economy for the fuel cell buses is an overall 73% higher than that of the diesel buses.

Figure 13 shows a two-month rolling average fuel economy in both miles per kg and miles per diesel gallon equivalent 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. After the first change-out of the fuel cell systems, the fuel economy started back up again, but the problems reappeared. In the last four months of the evaluation period, the fuel cell fuel economy was back to the expected level. For those last four months, the fuel cell fuel economy was generally two times higher than the diesel buses on an energy equivalent basis.

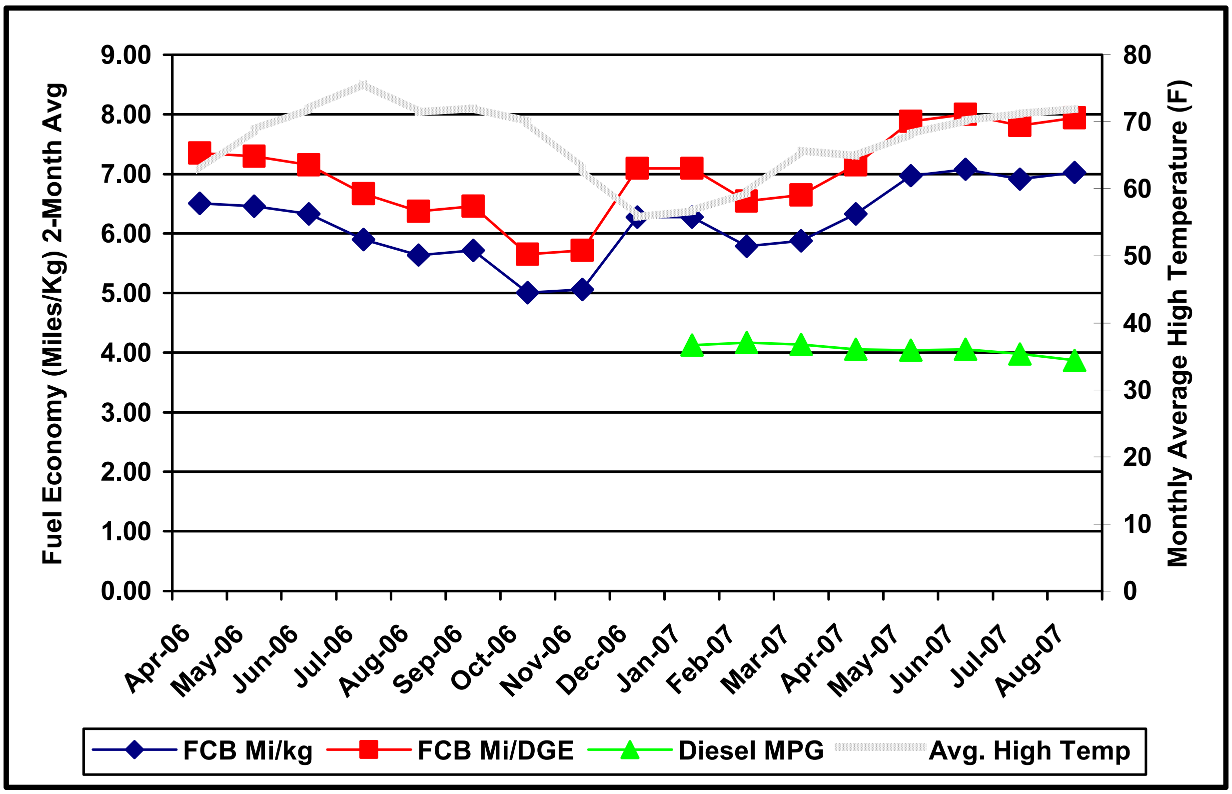

Figure 13. Two-month average fuel economy (evaluation period)

The operating cost for hydrogen production and dispensing for AC Transit is currently estimated at $8 per kg. This amount, which excludes capital expenses, was generated using early data (not optimized operation) and conservative maintenance and operating estimates. Using this cost estimate for hydrogen fuel indicates a cost per mile for the fuel cell buses of $1.30. The average diesel fuel cost per gallon during the evaluation period is $2.20 per gallon. This indicates a $0.55 per mile cost. The diesel cost per mile is about 42% of the fuel cell bus fuel cost per mile.

In addition to overall fuel economy analysis, the study buses had fuel economy calculations by route as shown in Table 10. As the specific routes and blocks were operated by the two study bus groups, the fuel consumption and economy were tracked. As shown in the table and depending on the route, the fuel economy for the fuel cell buses ranged from 60% up to nearly 90% higher than the diesel buses on the same route blocks during the evaluation period. The fuel cell bus fuel economy for the Route 57 was lower than expected due to the problems with the fuel cell systems during that period.

Table 10. Route-specific fuel economy analysis (evaluation period)

Route	Average Speed	Fuel Cell			Diesel		FC/Diesel (%)
		Period	Mi/kg	Mi/DGE	Period	MPG	
50	16.0	3-6/06; 3-6/07	6.64	7.50	6/06-3/07	4.39	71
57	11.3	6/06-3/07	5.69	6.43	3-6/06; 3-6/07	3.95	63
18	19.2	6/07-8/07	6.83	7.72	6/07-8/07	4.09	89
51	9.5	6/07-8/07	5.87	6.63	6/07-8/07	3.68	80

Maintenance Analysis

The maintenance cost analysis in this section is only for the evaluation period (April 2006 through August 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 11 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 all unscheduled and scheduled maintenance on the fuel cell buses for the fuel cell power systems and hybrid drive systems up until the end of the evaluation period. The AC Transit mechanics have done mostly cleaning and maintenance on the bus body (inside and outside) and doors. Some support has been provided for responding to roadcalls and that effort is reflected in the maintenance discussion that follows.

AC Transit has expressed a strong desire to have its mechanics get more involved in all maintenance activities for these buses so that they get the experience. AC Transit has assigned one project manager/supervisor, one bus mechanic, one body mechanic, and two service workers 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 toward the end of this evaluation period and with the future plans for more fuel cell buses.

Maintenance issues for the fuel cell buses centered around problems with the traction batteries and the fuel cell system CSAs being replaced twice for FC1, FC2, and FC3 (and awaiting the next replacement). 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.

Table 11. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Cost per Mile ($)
FC1	18,482	1,995.75	136.9	0.48
FC2	15,848	3,100.01	138.8	0.63
FC3	20,084	5,243.21	162.9	0.67
Total Fuel Cell	**54,404**	**10,338.97**	**438.6**	**0.59**
Avg. per Bus	**18,135**	**3,446.32**	**146.2**	**--**
1043	45,349	7,069.91	155.4	0.33
1044	50,534	8,531.68	162.9	0.33
1045	44,321	16,304.30	176.0	0.57
1046	49,587	11,872.98	184.4	0.45
1047	47,166	14,406.51	184.6	0.50
1048	43,451	12,585.31	186.6	0.50
Total Diesel	**277,408**	**70,770.69**	**1,049.8**	**0.44**
Avg. per Bus	**46,235**	**11,795.12**	**175.0**	**--**

Maintenance issues for the diesel buses were mostly related to engine problems with the turbocharger (three buses) and ECM (three buses). The diesel buses also had significant brake repair costs for standard relining (five times). The other major maintenance cost issues were for accident repair and replacing seats and windows (three 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 61% lower than the diesel buses
- Parts Costs – The fuel cell buses are 71% lower than the diesel buses
- Labor Hours – The fuel cell buses are 16% lower than the diesel buses
- Cost per Mile (without warranty costs) – The fuel cell buses are 34% higher than the diesel buses

Maintenance Costs Broken Down by System—Table 12 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**

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.

Table 12. 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	0.30	51	0.18	41
Propulsion-Related	0.08	13	0.10	23
PMI	0.11	19	0.07	16
Brakes	0.08	13	0.06	14
Frame, Steering, and Suspension	0.00	0	0.02	4
HVAC	0.01	2	0.00	0
Lighting	0.01	2	0.00	0
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	**0.59**	**100**	**0.44**	**100**

* Excludes warranty work costs

Propulsion-Related Maintenance Costs—The propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. Table 13 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 13. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	54,404	277,408
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	644.25	15,394.42
Labor hours	72.3	238.0
Total cost ($)	4,278.25	27,293.42
Total cost ($) per mile	**0.08**	**0.10**
Exhaust System Repairs		
Parts cost ($)	0.00	625.82
Labor hours	0.0	17.6
Total cost ($)	0.00	1,503.32
Total cost ($) per mile	**0.00**	**0.01**
Fuel System Repairs		
Parts cost ($)	0.00	1,942.50
Labor hours	11.4	44.8
Total cost ($)	570.50	4,182.50
Total cost ($) per mile	**0.01**	**0.02**
Powerplant System Repairs		
Parts cost ($)	126.00	7,235.65
Labor hours	15.0	80.8
Total cost ($)	874.68	11,276.15
Total cost ($) per mile	**0.02**	**0.04**
Electric Motor and Propulsion Repairs		
Parts cost ($)	235.32	0.00
Labor hours	41.9	0.0
Total cost ($)	2,330.82	0.00
Total cost ($) per mile	**0.04**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	0.00	1,072.38
Labor hours	2.0	30.6
Total cost ($)	100.00	2,600.88
Total cost ($) per mile	**0.00**	**0.01**
Air Intake System Repairs		
Parts cost ($)	294.45	1,048.51
Labor hours	0.0	0.0
Total cost ($)	294.45	1,048.51
Total cost ($) per mile	**0.01**	**0.00**
Cooling System Repairs		
Parts cost ($)	7.80	2,992.15
Labor hours	0.0	55.5
Total cost ($)	7.80	5,767.15
Total cost ($) per mile	**0.00**	**0.02**
Transmission Repairs		
Parts cost ($)	0.00	342.65
Labor hours	2.0	2.8
Total cost ($)	100.00	480.15
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 14 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 14. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC	Fuel Cell only MBRC
FC1	18,482	15	1,232	13	1,422	4,621
FC2	15,838	14	1,131	11	1,440	3,960
FC3	20,084	10	2,008	9	2,232	10,042
Total FCB	**54,404**	**39**	**1,395**	**33**	**1,649**	**5,440**
1043 Diesel	45,349	7	6,478	2	22,675	
1044 Diesel	50,534	13	3,887	6	8,422	
1045 Diesel	44,321	12	3,693	4	11,080	
1046 Diesel	46,587	8	5,823	2	23,294	
1047 Diesel	47,166	11	4,288	8	5,896	
1048 Diesel	43,451	10	4,345	4	10,863	
Total Diesel	**277,408**	**62**	**4,474**	**26**	**10,670**	

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

What's Next for This Demonstration?

This report covers AC Transit operation of the fuel cell and diesel buses through August 2007. The next evaluation report for this site will include operational data through February 2008 and is planned for release around May 2008. The future evaluation report will include experiences from the operation of one of these fuel cell buses at GGT with planned operation starting in late October 2007 through November 2007.

The Federal Transit Administration (FTA) announced the projects for its National Fuel Cell Bus Program on October 12, 2006. AC Transit received a grant for $3.575 million for "testing to failure" of the existing fuel cell buses. This grant project is just getting under way, and the implications will be discussed in the next evaluation report.

In response to the updated California Air Resources Board (CARB) zero-emission bus regulations, AC Transit continues to work with regional transit agency partners and potential funding partners for an expanded fuel cell bus demonstration. This future demonstration should result in the addition of 12 new zero-emission buses with partner transit agencies. Details for this activity are still being developed.

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Acronyms and Abbreviations

AC	alternating current
AC Transit	Alameda-Contra Costa Transit District
APTA	American Public Transportation Association
BAAQMD	Bay Area Air Quality Management District
BRT	Bus rapid transit
C	Celsius
CaFCP	California Fuel Cell Partnership
CARB	California Air Resources Board
CNG	compressed natural gas
CSA	cell stack assembly
DC	direct current
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
DPF	diesel particulate filter
FC	fuel cell
FCB	fuel cell bus
FCV	fuel cell vehicle
ft	feet
FTA	Federal Transit Administration
GGBHTD	Golden Gate Bridge, Highway, and Transportation District
GGT	Golden Gate Transit
HFCIT	Hydrogen, Fuel Cells, and Infrastructure Technology
HHICE	hydrogen hybrid internal combustion engine
hp	horsepower
HVAC	heating, ventilation, and air conditioning
HyTEC	Hydrogen Technology and Education Curriculum
in	inches
kg	kilogram
kW	kilowatts
kWh	kilowatt hour
lb	pounds
LFL	lower flammability limit
MBRC	miles between roadcalls
mpg	miles per gallon
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
Nm	Newton meters
NREL	National Renewable Energy Laboratory
PEM	proton exchange membrane
PMI	preventive maintenance inspection
psi	pounds per square inch
RC	roadcall
rpm	revolutions per minute
SOC	state of charge
VAC	volts alternating current
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

Appendix A: Fleet Summary Statistics

Fleet Summary Statistics: Alameda-Contra Costa Transit District (AC Transit) Diesel and FCB Study Groups

Fleet Operations and Economics

	Fuel Cell	Diesel
Number of Vehicles	3	6
Period Used for Fuel and Oil Op Analysis	4/06-8/07	1/07-8/07
Total Number of Months in Period	17	8
Fuel and Oil Analysis Base Fleet Mileage	54,404	149,380
Period Used for Maintenance Op Analysis	4/06-8/07	4/06-8/07
Total Number of Months in Period	17	17
Maintenance Analysis Base Fleet Mileage	54,404	277,408
Average Monthly Mileage per Vehicle	1,067	2,720
Availability	61%	N/A
Fleet Fuel Usage in Diesel Gal/H2 kg	8,824	37,113
Roadcalls	39	62
RCs MBRC	1,395	4,474
Propulsion Roadcalls	33	26
Propulsion MBRC	1,649	10,670
Fleet Miles/kg Hydrogen	6.17	
(1.13 kg H2/gal Diesel Fuel)		
Representative Fleet MPG (energy equiv.)	6.97	4.03
Hydrogen Cost per kg	8.00	
Diesel Cost per Gallon		2.20
Fuel Cost per Mile	**1.30**	**0.55**
Total Scheduled Repair Cost per Mile	0.21	0.10
Total Unscheduled Repair Cost per Mile	0.38	0.55
Total Maintenance Cost per Mile	**0.59**	**0.44**
Total Operating Cost per Mile	**1.88**	**0.99**

Maintenance Costs

	Fuel Cell	Diesel
Fleet Mileage	54,404	277,408
Total Parts Cost	10,036.14	70,770.71
Total Labor Hours	436.6	1049.8
Average Labor Cost (@ $50.00 per hour)	21,831.00	52,489.00
Total Maintenance Cost	31,867.14	123,259.71
Total Maintenance Cost per Bus	10,622.38	20,543.29
Total Maintenance Cost per Mile	**0.59**	**0.44**

Breakdown of Maintenance Costs by Vehicle System

	Fuel Cell	Diesel
Fleet Mileage	54,404	277,408
Total Propulsion-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)		
Parts Cost	664.25	15,394.42
Labor Hours	72.3	238.0
Average Labor Cost	3,614.00	11,899.00
Total Cost (for system)	4,278.25	27,293.42
Total Cost (for system) per Bus	1,426.08	4,548.90
Total Cost (for system) per Mile	**0.08**	**0.10**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost	0.00	625.82
Labor Hours	0.0	17.6
Average Labor Cost	0.00	877.50
Total Cost (for system)	0.00	1,503.32
Total Cost (for system) per Bus	0.00	250.55
Total Cost (for system) per Mile	**0.00**	**0.01**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost	0.00	1,942.50
Labor Hours	11.4	44.8
Average Labor Cost	575.50	2,240.00
Total Cost (for system)	575.50	4,182.50
Total Cost (for system) per Bus	190.17	697.08
Total Cost (for system) per Mile	**0.01**	**0.02**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost	126.68	7,235.65
Labor Hours	15.0	80.8
Average Labor Cost	748.00	4,040.50
Total Cost (for system)	874.68	11,276.15
Total Cost (for system) per Bus	291.56	1,879.36
Total Cost (for system) per Mile	**0.02**	**0.04**
Electric Propulsion Repairs (ATA VMRS 46)		
Parts Cost	235.32	0.00
Labor Hours	41.9	0.0
Average Labor Cost	2,095.50	0.00
Total Cost (for system)	2,330.82	0.00
Total Cost (for system) per Bus	776.94	0.00
Total Cost (for system) per Mile	**0.04**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	Diesel
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost	0.00	1,072.38
Labor Hours	2.0	30.6
Average Labor Cost	100.00	1,528.50
Total Cost (for system)	100.00	2,600.88
Total Cost (for system) per Bus	33.33	433.48
Total Cost (for system) per Mile	**0.00**	**0.01**
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost	294.45	1,048.51
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	294.45	1,048.51
Total Cost (for system) per Bus	98.15	174.51
Total Cost (for system) per Mile	**0.01**	**0.00**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost	7.80	2,992.15
Labor Hours	0.0	55.5
Average Labor Cost	0.00	2,775.00
Total Cost (for system)	7.80	5,767.15
Total Cost (for system) per Bus	2.60	961.19
Total Cost (for system) per Mile	**0.00**	**0.02**
Hydraulic System Repairs (ATA VMRS 65)		
Parts Cost	0.00	134.76
Labor Hours	0.0	6.0
Average Labor Cost	0.00	300.00
Total Cost (for system)	0.00	434.76
Total Cost (for system) per Bus	0.00	72.46
Total Cost (for system) per Mile	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)		
Parts Cost	12.34	284.80
Labor Hours	0.0	13.6
Average Labor Cost	0.00	677.50
Total Cost (for system)	12.34	962.30
Total Cost (for system) per Bus	4.11	160.38
Total Cost (for system) per Mile	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	Diesel
Brake System Repairs (ATA VMRS 13)		
Parts Cost	4,098.95	11,813.82
Labor Hours	2.0	90.7
Average Labor Cost	100.00	4,535.00
Total Cost (for system)	4,198.95	16,348.82
Total Cost (for system) per Bus	1,399.65	2,724.80
Total Cost (for system) per Mile	**0.08**	**0.06**
Transmission Repairs (ATA VMRS 27)		
Parts Cost	0.00	342.65
Labor Hours	2.0	2.8
Average Labor Cost	100.00	137.50
Total Cost (for system)	100.00	480.15
Total Cost (for system) per Bus	33.33	80.03
Total Cost (for system) per Mile	**0.00**	**0.00**
Inspections Only – No Parts Replacements (101)		
Parts Cost	0.00	0.00
Labor Hours	123.8	405.0
Average Labor Cost	6,187.50	20,249.00
Total Cost (for system)	6,187.50	20,249.00
Total Cost (for system) per Bus	2,062.50	3,374.83
Total Cost (for system) per Mile	**0.11**	**0.07**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost	4,754.85	38,808.54
Labor Hours	227.9	197.3
Average Labor Cost	11,394.00	9,866.00
Total Cost (for system)	16,148.85	48,674.54
Total Cost (for system) per Bus	5,382.95	8,112.42
Total Cost (for system) per Mile	**0.30**	**0.18**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost	0.00	267.96
Labor Hours	7.6	3.4
Average Labor Cost	380.00	169.00
Total Cost (for system)	380.00	436.96
Total Cost (for system) per Bus	126.67	72.83
Total Cost (for system) per Mile	**0.01**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	Diesel
Lighting System Repairs (ATA VMRS 34)		
Parts Cost	178.24	336.96
Labor Hours	1.6	16.4
Average Labor Cost	80.50	822.00
Total Cost (for system)	258.74	1,158.96
Total Cost (for system) per Bus	86.25	193.16
Total Cost (for system) per Mile	**0.00**	**0.00**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost	138.88	2,866.60
Labor Hours	1.5	86.5
Average Labor Cost	75.00	3,424.00
Total Cost (for system)	213.88	6,290.60
Total Cost (for system) per Bus	71.29	1,048.43
Total Cost (for system) per Mile	**0.00**	**0.02**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost	188.62	188.62
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	188.62	188.62
Total Cost (for system) per Bus	62.87	62.87
Total Cost (for system) per Mile	**0.00**	**0.00**
Tire Repairs (ATA VMRS 17)		
Parts Cost	0.00	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00
Total Cost (for system) per Mile	**0.00**	**0.00**

Notes

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

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

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

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

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

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

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

7. Warranty costs are not included.

Appendix B: Fleet Summary Statistics – SI Units

Fleet Summary Statistics: Alameda-Contra Costa Transit District (AC Transit) Diesel and FCB Study Groups

Fleet Operations and Economics

	Fuel Cell	Diesel
Number of Vehicles	3	6
Period Used for Fuel and Oil Op Analysis	4/06-8/07	1/07-8/07
Total Number of Months in Period	17	8
Fuel and Oil Analysis Base Fleet Kilometers	87,552	240,397
Period Used for Maintenance Op Analysis	4/06-8/07	4/06-8/07
Total Number of Months in Period	17	17
Maintenance Analysis Base Fleet Kilometers	87,552	446,433
Average Monthly Kilometers per Vehicle	1,717	4,377
Availability	61%	N/A
Fleet Fuel Usage in Diesel L/H2 kg	8,824	140,473
Roadcalls	39	62
Kilometers between roadcalls (KBRC)	2,245	7,201
Propulsion Roadcalls	33	26
Propulsion KBRC	2,653	17,170
Fleet kg Hydrogen/100 km	10.08	
Representative Fleet MPG (L/100 km)	33.76	58.43
Hydrogen Cost per kg	8.00	
Diesel Cost per Liter		0.58
Fuel Cost per Kilometer	**0.81**	**0.34**
Total Scheduled Repair Cost per Kilometer	0.13	0.06
Total Unscheduled Repair Cost per Kilometer	0.23	0.22
Total Maintenance Cost per Kilometer	**0.36**	**0.28**
Total Operating Cost per Kilometer	**1.17**	**0.62**

Maintenance Costs

	Fuel Cell	Diesel
Fleet Kilometers	87,552	446,433
Total Parts Cost	10,036.14	70,770.71
Total Labor Hours	436.6	1049.8
Average Labor Cost (@ $50.00 per hour)	21,830.00	52,490.00
Total Maintenance Cost	31,866.14	123,260.71
Total Maintenance Cost per Bus	10,622.05	20,543.45
Total Maintenance Cost per Kilometer	**0.36**	**0.28**

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