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Alameda-Contra Costa Transit District (AC Transit) Fuel Cell Transit Buses

Preliminary Evaluation Results

K. Chandler
Battelle

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Technical Report
NREL/TP-560-41041
March 2007

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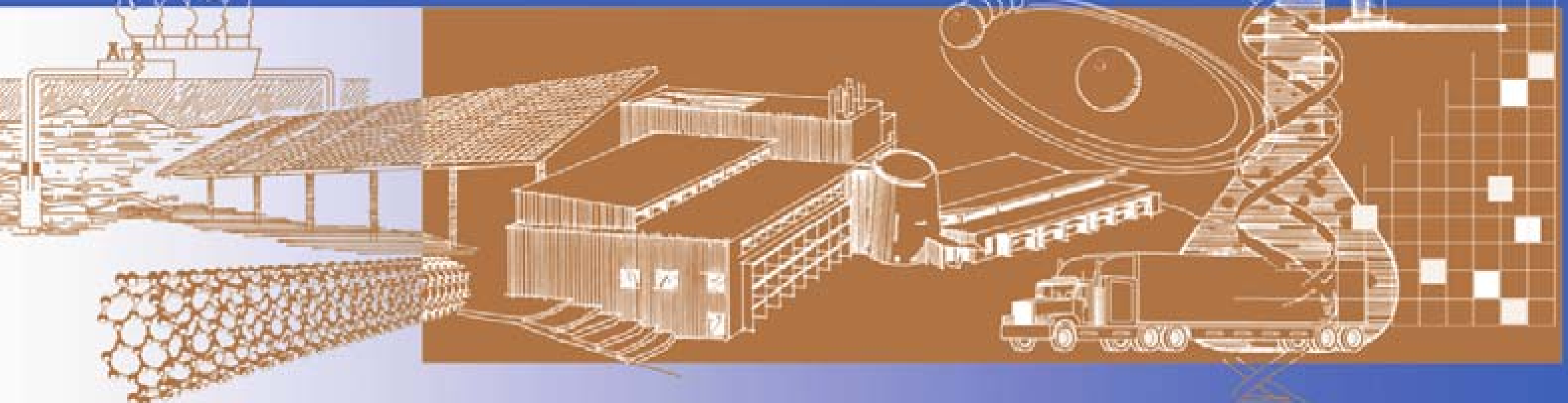

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Executive Summary

This evaluation includes three prototype fuel cell-powered transit buses operating at AC Transit in Oakland, California, since March 20, 2006 and six baseline diesel buses similar in design to the fuel cell buses. This report describes the equipment used (buses and infrastructure) and provides early experience details, lessons learned, and results from the operation of the buses (shown in Figure ES-1) and the supporting hydrogen fueling station through November 30, 2006.

In this evaluation report, the fuel cell buses are considered prototype technology that is in the process of being commercialized. The analysis and comparisons with standard diesel buses were done to help baseline the status and 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).**

Figure ES-1. AC Transit Van Hool buses – diesel (left) and fuel cell (right)

Infrastructure and Facilities

In March 2004, AC Transit joined in partnership with Chevron Technology Ventures to design and build a hydrogen energy station at the East Oakland Division. Construction on the station began in June 2005 and was operational by mid-December the same year. On March 13, 2006, AC Transit and local officials formally inaugurated the Chevron – AC Transit Hydrogen Energy Station, kicking-off the demonstration project. 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 Chevron – AC Transit Hydrogen Energy Station is 366 kg of hydrogen.

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.

Evaluation Results

The evaluation period includes operational results from April 2006 through November 2006. The three $3.2 million Van Hool fuel cell buses use hybrid-electric propulsion systems from ISE Corp. with ZEBRA® sodium/nickel chloride batteries and regenerative braking. The fuel cell system (PureMotion™ 120) was manufactured by UTC Power. The diesel baseline buses are Van Hool buses with Cummins ISL diesel engines equipped with diesel oxidation catalysts.

Route Descriptions – For this program, AC Transit developed two special blocks of work (planned daily bus assignments) on each of two routes (Route 50 and Route 57) for operation of the fuel cell and diesel baseline buses. The two special blocks of work on Route 50 have an average speed of 16 mph, while the special blocks on Route 57 have an average speed of 11.3 mph.

Bus Use and Availability – The fleet 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 three fuel cell buses may be included. During the evaluation period, the fuel cell buses operated 27,065 miles and 2,338 total fuel cell system hours. The usage of the fuel cell buses was approximately 53% of the diesel baseline buses in the same time frame. Overall availability for the fuel cell buses was 77%.

Fuel Economy and Cost

Monthly average fuel economy for the fuel cell buses is shown in Figure ES-2. The fuel cell buses averaged 5.50 miles per kg of hydrogen for the evaluation period, which equates to 6.22 miles per diesel gallon equivalent. The diesel fuel consumption for the evaluation period is not available except for November 2006, because the fuel tracking system was not working properly until late October 2006. AC Transit reports that the diesel bus fleet typically has an average fuel economy of approximately 4.00 mpg, which indicates that the fuel cell buses have an average fuel economy 56% higher than that of the diesel buses.

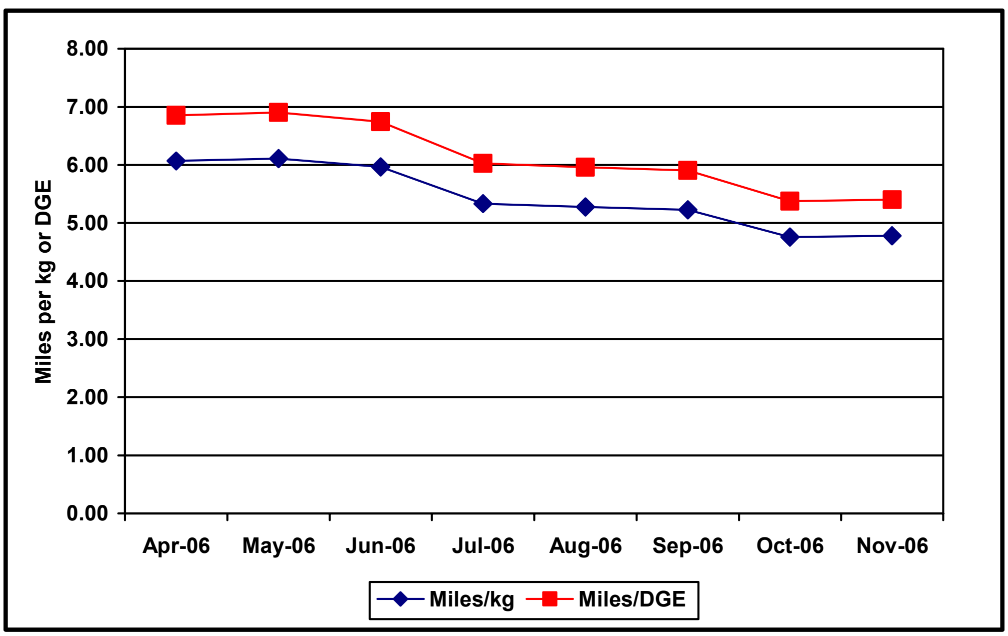

Figure ES-2. Fuel cell bus monthly average fuel economy (evaluation period)

The <u>operating</u> cost for hydrogen production and dispensing for AC Transit is currently estimated at $8 per kg. This excludes capital expenses and has been generated using early data (not optimized operation) and conservative maintenance and operating estimates. This equates to a cost per mile for the fuel cell buses of $1.45. The average diesel fuel cost per gallon during the evaluation period is $2.30 per gallon. If the 4.00 mpg diesel average fuel economy is used, this indicates a $0.58 per mile cost.

Maintenance Analysis – 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 47% lower than the diesel buses
- Parts Costs – The fuel cell buses are 44% lower than the diesel buses
- Labor Hours – The fuel cell buses are 11% higher than the diesel buses
- Cost per Mile (without warranty costs) – The fuel cell buses are 71% higher than the diesel buses

This reflects the fact that the fuel cell buses are prototypes in the development stage for transit bus service.

Specific Experience with Fuel Cell Buses – The first fuel cell bus was delivered in October 2005 and the other two fuel cell buses were delivered in December 2005. Before the buses went into service on March 20, 2006, the mechanics and drivers were trained on the general characteristics of hydrogen, hydrogen safety, and fuel cell bus operation. AC Transit mechanics also received more detailed training on system troubleshooting.

Both ISE and UTC Power have on-site technical support available to AC Transit for warranty support of the fuel cell buses, and AC Transit reports that this support has been excellent. AC Transit is responsible for bus maintenance, and UTC Power and ISE are responsible for the propulsion and drive system. The parts for the fuel cell power system have been provided to AC Transit through the UTC Power technician on an as-needed basis.

There have been a few significant issues with the fuel cell buses:

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 algorithm. A cell failure in this serial string causes a short that decreases the overall voltage of a pack (in the group of three packs). ISE Corp. is working to better optimize the control software to alleviate this issue.

2. **Air conditioning** – This hybrid design is unique because the air conditioning unit is driven electrically instead of mechanically (by belt) like most vehicles. In this application, the system has experienced problems with failed motors. Several changes and upgrades have been attempted and the problem seems to be resolved.

3. **UTC Power PureMotion 120 Fuel Cell Power System** – UTC Power monitors the performance of the fuel cell power system remotely to analyze actual performance vs. predicted performance. In June 2006, UTC Power observed that the Cell Stack Assembly

(CSA) performance was decaying at high current densities at rates that were beyond what was predicted.

With the SunLine bus accumulating the most hours early on, the issue was observed there first. An engineering investigation determined that contaminants were released from a material in the CSAs due to a supplier quality control problem with that material. As part of UTC Power's ongoing development, UTC Power has incorporated corrective action into the CSAs thus eliminating this condition for all builds.

UTC Power has begun the process of retrofitting all three of the AC Transit buses with upgraded units. A spare powerplant is being used to minimize downtime for the buses. As the upgraded fuel cell power systems are installed into the AC Transit buses, there is a desire to maximize/accelerate the use of the fuel cell buses. This accelerated testing is currently limited due to issues with the ZEBRA battery pack failures and charging the batteries up to a nearly full SOC overnight in time for the next day's service. Until the charging regime issue can be resolved, the bus cannot meet the desired 14-16 hours of operation on a regular/daily basis. AC Transit is in the process of upgrading electrical service to the maintenance building at East Oakland so that more battery charging capacity can be added.

The drivers of the fuel cell buses have been excited about and reportedly really like the buses; however, they have expressed some nervousness with potentially "hurting" the new buses. The buses offer smooth, quiet driving and comfortable driver seats with good access to controls.

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. If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a RC.

The diesel study buses had an overall RC rate of 4,468 miles between RCs (MBRC) and the fuel cell buses had 773 MBRC. For propulsion-only RCs, the diesel buses had a rate of 8,563 MBRC and the fuel cell buses had 1,230 MBRC. 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. (Note: AC Transit reports the entire 40-ft Van Hool diesel fleet has a propulsion-related MBRC of 14,000.)

What's Next

This preliminary data report includes an eight-month evaluation period (April 2006 through November 2006) of the prototype fuel cell buses in operation at AC Transit. The next evaluation report, planned for release at the end of 2007, will include at least another 6 months of operations data and experience from AC Transit.

Overview

This report provides preliminary results from an evaluation of three prototype fuel cell transit buses operating at Alameda-Contra Costa Transportation District (AC Transit) in Oakland, California. The three fuel cell transit buses have been operating at AC Transit in passenger service since March 20, 2006. This report describes the equipment used (buses and infrastructure) and provides early experience details, lessons learned, and results from the operation of the buses and supporting hydrogen fueling station through November 30, 2006.

This evaluation is part of DOE's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, which integrates activities in hydrogen production, storage, and delivery with transportation and stationary fuel cell applications. DOE's National Renewable Energy Laboratory (NREL) works with fleets and industry groups to test advanced technology, heavy-duty vehicles in service and provides unbiased information resources for fleet managers considering these technologies. Information collected during vehicle performance and evaluations of vehicle operation are fed back to research programs to help shape future work.

In early 2003, DOE initiated the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, which focuses on light-duty fuel cell vehicles and supporting infrastructure. The purpose of the project is to examine the impact and performance of fuel cell vehicles and supporting hydrogen infrastructure in real-world applications. The data collected and analyzed during this "learning demonstration" is used to verify performance targets and assess technology readiness. To coordinate efforts, the fuel cell bus evaluation team is working closely with the light-duty demonstration project teams. The overall goal of this coordination is to ensure that similar data for heavy-duty fuel cell vehicles are collected to enable a more complete picture of fuel cell performance over a wider range of vehicle applications than just light-duty.

In addition to the light-duty demonstration project, DOE and NREL are also working with the Federal Transit Administration (FTA), an agency of the U.S. Department of Transportation (DOT), and heavy vehicle operators (mostly transit agencies) to demonstrate heavy fuel cell and hydrogen vehicles and to collect operations experience data. This collaboration directly supports FTA's National Fuel Cell Bus Program (NFCBP). This data collection and evaluation follows the DOE/NREL standardized evaluation protocol[1] and detailed data collection templates based on the light-duty demonstration. A customized version of the General Evaluation Plan, created for fuel cell bus evaluations, is described in the draft Fuel Cell Transit Bus Evaluation Protocol of June 2005. Current heavy fuel cell vehicle evaluation sites are shown in Table 1. More information is available at www.eere.energy.gov/hydrogenandfuelcells/tech_validation/ca_transit_agencies.html.

[1] General Evaluation Plan, Fleet Test & Evaluation Projects, July 2002, NREL/BR-540-32392, www.nrel.gov/vehiclesandfuels/fleettest/pdfs/32392.pdf.

Table 1. DOE/NREL Heavy Vehicle Fuel Cell/Hydrogen Evaluations

Fleet	Vehicle/Technology	Evaluation Status
U.S. Air Force/Hickam Air Force Base (Honolulu, Hawaii)	Shuttle bus: Hydrogenics and Enova, battery-dominant fuel cell hybrid (one bus)	Shuttle bus in operation, data collection started
	Delivery van: Hydrogenics and Enova, fuel cell hybrid (one van)	Van in operation, data collection started
Alameda-Contra Costa Transit District (Oakland, California)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp. (three buses)	Evaluation in process, all three buses in operation since March 2006, full service started in April 2006; preliminary evaluation results reported here
SunLine Transit Agency (Thousand Palms, California)	New Flyer ISE Corp. hydrogen internal combustion engine transit bus (one bus-HHICE)	Evaluation in process, preliminary evaluation results reported Feb 2007
	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp. (one bus-FCB)	Evaluation in process, preliminary evaluation results reported Feb 2007
VTA (San Jose, California) and SamTrans (San Carlos, California)	Gillig/Ballard fuel cell transit bus (three buses)	Complete and reported in 2006
SunLine Transit Agency (Thousand Palms, California)	ISE Corp./ UTC Power ThunderPower hybrid fuel cell transit bus (one bus)	Complete and reported in 2003

This preliminary data report examines evaluation results from 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 November 2006 (8 months of operation)
- **Diesel Buses** – April 2006 through November 2006 (8 months of operation)

Project Design and Data Collection

DOE/NREL evaluation projects focus on using a standardized process for data collection and analysis, communicating results clearly, and providing an accurate and complete evaluation. The objectives of the data collection are to validate fuel cell and hydrogen technologies in bus applications to:

- Determine the status of fuel cell systems for buses and corresponding hydrogen infrastructure
- Provide feedback for DOE HFCIT Program research and development
- Provide "lessons learned" on implementing next generation fuel cell systems into bus operations

This evaluation includes three prototype fuel cell-powered transit buses (40-foot) operating at AC Transit in Oakland, California (bus shown in Figure 1). Six diesel buses (bus shown in Figure 2) were selected from AC Transit's newest order of Van Hool diesel buses operating at the same depot (East Oakland Division). Data have been collected in parallel to the three prototype buses for the evaluation period, April 2006 through November 2006. The diesel baseline data were collected and analyzed along side the prototype fuel cell buses to assess the progress of the fuel cell propulsion development for heavy vehicles, specifically in this application at AC Transit.

Figure 1. Fuel cell transit bus at AC Transit

Figure 2. Diesel bus at AC Transit

Data for this evaluation were taken from AC Transit's data system. Data parameters included:

- Diesel fuel consumption by vehicle and fill
- Hydrogen fuel consumption by vehicle and fill
- Mileage data and route assignments from every vehicle in the study
- Preventive maintenance action work orders, parts lists, labor records, and related documents
- Records of unscheduled maintenance, including roadcalls and warranty actions by vendors (when available in the data system)

Additional information has been collected on the maintenance/operation experience, issues at the hydrogen fueling station and at AC Transit facilities, and lessons learned at the start-up and during operation of the study buses.

Host Site Profile

AC Transit (www.actransit.org) was created in 1956, but public transit in Oakland dates as far back as 1869. The district is governed by a seven-member board of directors elected by East Bay voters. Five of these board members represent geographic wards while two are elected at-large. The AC Transit service area of 360 square miles includes 13 cities and adjacent unincorporated areas in Alameda and Contra Costa counties. AC Transit operates 538 transit buses in peak service (717 active buses in the fleet including paratransit) on more than 105 fixed routes and provides school bus service. In fiscal year 2005, annual ridership exceeded 68.9 million. Figure 3 shows the AC Transit and Golden Gate Transit (GGT) operating areas. GGT is a participant in the AC Transit fuel cell bus demonstration and intends to operate the fuel cell buses in its service later in the program.

Golden Gate Transit (www.goldengate.org) 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 as well as the operation of the Golden Gate Bridge and the Golden Gate Ferry operation. GGT, which operates from San Rafael, California, a central location in its operating area, started fixed-route service in 1972 based on transportation planning aimed at reducing traffic congestion on the Golden Gate Bridge. GGT has 260 buses that operated 5.1 million miles in fiscal year 2005.

Figure 3. AC Transit and Golden Gate Transit operating area in California

AC Transit Fuel Cell Bus Program

AC Transit's interest in fuel cell buses started in October 1999, following a successful one-week demonstration of the Ballard P4 ZEbus on scheduled routes in the AC Transit service area. This preceded Ballard operating the bus for a one-year test at SunLine in 2000. Soon after, the California Air Resources Board (CARB) established a new fleet rule in February 2000 to significantly reduce emissions of existing and new transit buses in California. The rule set more stringent emissions standards for new urban bus engines and promoted advancement of the cleanest propulsion technologies – specifically, zero emission buses (ZEBs). This ruling required transit agencies to choose a compliance path – alternative fuel or diesel.

The deadline for choosing one of these compliance paths was later in 2000. AC Transit and GGT chose the diesel path. AC Transit reported that it did not choose the alternative fuel path because it worried about reliability and capital costs for operating an alternative fuel such as compressed natural gas (CNG). Fleets choosing the diesel path were required to reduce the fleet average emissions through methods such as purchasing the cleanest diesel engines and retrofitting existing diesel engines with emissions control devices such as diesel particulate filters (DPFs). All California transit agencies with 200 or more buses (including AC Transit and GGT) choosing the diesel path were subject to demonstrate (by 2003) and eventually procure ZEBs at a rate of 15% of all new bus purchases starting in model year 2008.

AC Transit and GGT agreed in 2001 to partner in the training and operation of the fuel cell buses in order to meet the CARB requirements. AC Transit attempted to purchase fuel cell buses in 2000 and early 2001. The agency received only one bid, which was eventually withdrawn by the vendor. AC Transit set out in 2001 to learn all that it could about fuel cell buses, including operating the Ballard P4/ZEbus for one week for testing, joining the California Fuel Cell Partnership (CaFCP), and operating the ISE/UTC Power ThunderPower 30-foot fuel cell bus during part of 2003 and 2004.

During 2001-2002, AC Transit was looking for a new bus design to purchase for its planned Rapid Bus Rapid Transit (BRT) project. AC Transit's next large purchase of diesel buses (approximately 190 buses) was supplied by Van Hool through its distributor in the U.S., ABC Companies. These new buses featured three doors for quick loading and unloading for the Rapid BRT service, which started in June 2003 with the San Pablo Rapid service.

At the end of 2001, AC Transit started discussions with ISE Corp. about developing a new fuel cell bus design. In April 2002, negotiations were started for a sole source contract with ISE Corp. and UTC Power with plans to use the same Van Hool bus chassis as was used for the diesel buses; however, this project stalled during most of 2002. After a major meeting of the project partners coinciding with an American Public Transportation Association (APTA) meeting in Las Vegas in September 2002, the project was re-energized. The contract for the new fuel cell buses was revised in April 2003, and the project was back on track. This order included three new Van Hool fuel cell buses for AC Transit and one new Van Hool fuel cell bus for SunLine. Rather than using a standard diesel chassis, as was originally planned, Van Hool designed and constructed an entirely new chassis (based on the existing A330 bus design) that could more effectively accommodate fuel cell and hybrid system components.

This new contract had several changes and the delays now required that the CARB deadline for demonstrating fuel cell buses be postponed. The first fuel cell bus was delivered to AC Transit in October 2005, and the other two AC Transit buses arrived in December 2005. The on-site hydrogen fueling station from Chevron was commissioned on March 13, 2006, and the three fuel cell buses went into service on March 20, 2006.

The HyRoad – Once the fuel cell buses were on order and being manufactured, AC Transit got to work putting together its hydrogen future and vision for its hydrogen fuel cell program. This comprehensive fuel cell program (HyRoad) aims to demonstrate the viability of an emission-free transit system and features:

- Three zero-emission hybrid-electric, hydrogen fuel cell buses
- A fleet of fuel cell passenger vehicles (part of DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project)
- On-site hydrogen production and fueling
- On-site fleet maintenance
- Ongoing, outside evaluation (this report and future reports)
- Public education and safety training

The partners for the fuel cell bus program at AC Transit include:

- Van Hool Bus – manufacturer of the bus bodies and chassis
- UTC Power of Connecticut – maker of the fuel cell power systems
- ISE Corporation of San Diego – integrator of the fuel cell power systems and hybrid-electric drive systems
- Chevron Technology Ventures (a division of Chevron USA) – builder of the hydrogen fueling station at AC Transit's East Oakland Division

Funding for this project included more than $21 million from public agencies and private sector companies, as follows:

- State of California – $8 million
- CARB – $2.8 million
- Bay Area Air Quality Management District (BAAQMD) – $1 million
- Federal Transit Administration – $1 million
- California Energy Commission – $1 million
- DOE – $700,000 plus partial funding for the hydrogen station construction and operating expenses
- AC Transit matching funds – $1.2 million
- CALSTART-WestStart – $200,000
- Chevron Technology Ventures – $2 million (matching funds) plus additional funding for capital and operating expenses
- Miscellaneous contributions of more than $3 million

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. As a diesel-path fleet, AC Transit had no prior experience with gaseous fuels. Joining the CaFCP provided an opportunity for the fleet to accelerate the learning curve and gain valuable hydrogen fuel experience before the FCBs were delivered. AC Transit's first hydrogen-related project was in partnership with the CaFCP and Stuart Energy Systems (now Hydrogenics) to install an electrolyzer at the Richmond Division. This station was mainly intended as a satellite station for light-duty fuel cell vehicles (FCVs) being tested by the automotive partners of the CaFCP. This location, between Sacramento and San Francisco, was ideal to enable FCVs to travel between the two cities. In addition to the light-duty FCVs, AC Transit also used this station to fill the ThunderPower FCB during its demonstration.

Richmond Station

The station at the Richmond division produces hydrogen through the electrolysis of water. The electrolyzer is capable of producing up to 24 kg of hydrogen each day. The station was equipped with storage vessels that hold 47 kg. As many as 5 FCVs can be fueled to settled pressures between 3,600 and 5,000 psi in about 8 minutes. The station can be used to fuel buses; however, the storage capacity is not currently large enough for more than one bus to be operated from this site. The electrolyzer and dispenser are pictured in Figure 4.

Figure 4. Electrolyzer (left) and dispenser (right) at Richmond Division

Oakland Energy Station[2]

AC Transit selected the East Oakland Division as the site for demonstrating its fleet of FCBs. This was due to its location in a light industrial area and because space was available for the added fueling infrastructure. AC Transit operates over 200 vehicles from this division, including

[2] Information on the Chevron-AC Transit Hydrogen Energy Station was provided in part by Chevron Technology Ventures, a division of Chevron USA.

the 3 FCBs, 21 40-ft diesel Van Hool buses, 41 paratransit shuttles, and 6 UC Berkeley vans. Of the buses at the site, 138 are required for peak service.

In March 2004, AC Transit joined in partnership with Chevron Technology Ventures to design and build a hydrogen energy station at the East Oakland Division. Plans for a station were already in process as part of the DOE light-duty FCV demonstration. Chevron leads one of the teams that is demonstrating FCVs and hydrogen infrastructure for the DOE project. AC Transit serves as one of the demonstration sites, operating a small fleet of Hyundai/Kia FCVs.

As the FCB demonstration plans began to solidify, the project partners decided it would be cost effective to combine the needs for both demonstrations into one station. Construction on the station began in June 2005 and was completed by November. The station was operational by mid-December. On March 13, 2006, AC Transit and local officials formally inaugurated the Chevron - AC Transit Hydrogen Energy Station, kicking-off the demonstration project. All of the HyRoad project partners participated in the event, which included facility tours and a ribbon-cutting ceremony.

Figure 5 illustrates the overall station layout. The energy station at the East Oakland Division generates hydrogen through steam methane reformation in a 3-step process:

1. **Hydrogen generation** – Natural gas from a utility line is fed to a steam methane reformer that produces a hydrogen-rich output gas. This output gas, called reformate, is typically composed of 75% hydrogen and 20% carbon dioxide and other trace gases.
2. **Reformate compression** – Hydrogen-rich reformate is compressed to approximately 125 psi, as required for the purification step.
3. **Purification** – A pressure swing absorption unit purifies the reformate stream to 99.99% hydrogen, which is acceptable for use in PEM fuel cells. Excess gas is returned to the reformer for combustion.

The station design includes two reformers that are capable of producing a total of 150 kg hydrogen per day. One of the reformers is a standard design (Figure 6) and produces hydrogen through the 3-step process outlined above. This reformer is intended to be the primary production reformer for hydrogen at the station.

Chevron is using the second reformer, which is an advanced technology design, to investigate ways to further refine production methods and increase efficiency. For that second reformer, steps 1 and 2 are reversed: the natural gas is compressed to about 150 psi, and the reformer then generates hydrogen at the higher pressure. An advantage of this is that compressing natural gas takes less energy than compressing the hydrogen-rich reformate stream. Producing a reformer capable of operating at the higher pressure, however, will potentially increase the cost of that equipment. This may be offset by the reduced cost for the natural gas vs. reformate compressor. The demonstration will help Chevron determine the trade-offs between the increased efficiency of compressing natural gas and the change in equipment cost.

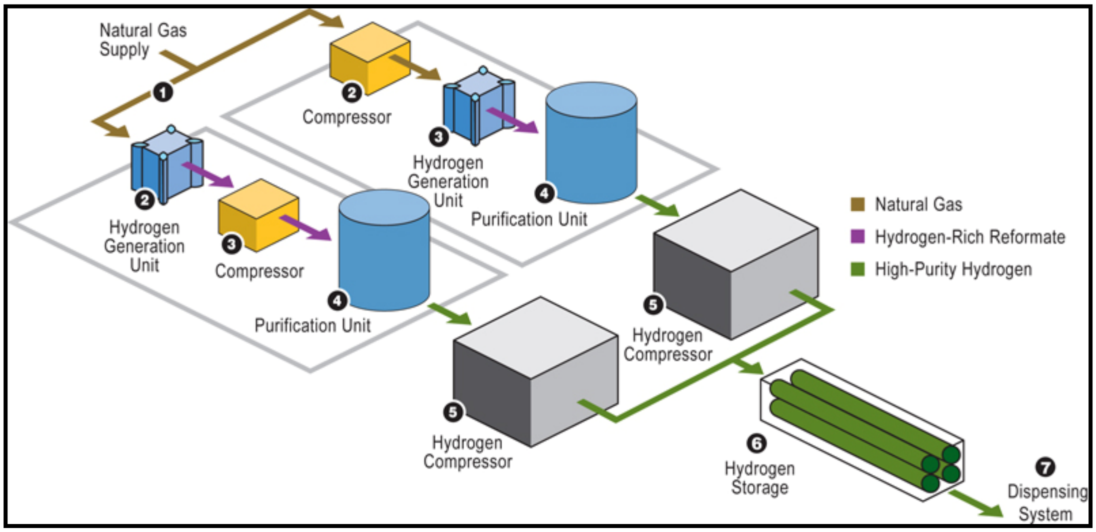

Figure 5. Chevron – AC Transit (Oakland) Hydrogen Energy Station overall layout

Figure 6. Reformer train #1 at Chevron – AC Transit Hydrogen Energy Station (75 kg/day)

The purified hydrogen is then compressed to 6,250 psi and stored in a series of cascade pressure vessels (Figure 7). Total storage capacity at the station is 366 kg of hydrogen. The station is equipped with two dispensers that supply the compressed hydrogen to the buses and light-duty vehicles. The system connections monitor the tank-fill status and provide an appropriate fill at 5,000 psi. The dispensing system is designed to enable simultaneous fills for two buses (or light-duty fuel cell vehicles). Figure 8 shows the hydrogen fueling dispensers at the station. AC Transit's agreement with Chevron includes all operation and maintenance of the station for two years. Chevron technicians are also responsible for fueling the buses. AC Transit will assume fueling responsibility by mid-2007.

Photo courtesy of Chevron Technology Ventures

Figure 7. Cascade hydrogen storage vessels at AC Transit station

Photo courtesy of Chevron Technology Ventures

Figure 8. One of two dispensers at the Chevron – AC Transit Hydrogen Energy Station

The design of the station includes various safety devices to alert AC Transit and Chevron of any potential problems. These devices include hydrogen detectors, flame sensors, emergency stop buttons, and alarm indicator lights (Figure 9). The alarm indicators reflect the condition of the station as follows:

- **Green light** – normal operating conditions
- **Yellow light** – a problem is occurring or has occurred
- **Red light** – hazardous condition exists, evacuation from area required
- **Strobe and siren** – fire condition, fire department notified

Early Experience with Hydrogen Fueling – AC Transit reports a relatively smooth process for permitting the hydrogen station in Oakland. The experience gained from the Richmond station gave them a good knowledge base of what was needed. The agency took a proactive approach to the process for permitting the new station in Oakland; this process began in early 2003. Agency representatives held an initial meeting with the local fire marshal to give an overview of the HyRoad program. They also prepared a flyer describing the project and hydrogen station plans, which was shared with the local community as a direct mail piece sent to more than 8,500 residences and businesses within a quarter mile of the station. Several town hall meetings were held and AC Transit staff gave numerous presentations to community and civic groups. Because of the considerable work accomplished to educate the public and local officials early in the process, AC Transit reported no opposition to the station. This was considered an early success for the program, especially since this process has proven to be a major challenge for some other fuel cell and hydrogen demonstrations around the world.

Even with the relative ease of permitting, the buses began to arrive before the station was operational. During the two-month lag time, the fleet used an on-site tube trailer to fuel the buses. The station was fully operational on December 2, 2005. During the initial period of use, Chevron held the fueling rate to that recommended for the light-duty FCVs. Because of this, bus fuelings sometimes took more than 2 hours. As Chevron developed data on the temperature rise during fueling of the buses, which have approximately ten times the on-board hydrogen volume compared to a light-duty FCV, the rate was increased. The buses can now be fueled in under 15 minutes.

As can be expected with any high pressure system that contains a small molecule such as hydrogen, there have been a small number of leaks in piping and process systems, but no safety incidents. The integrated safety system was designed to detect leaks and take the appropriate action. The safety systems have been functioning as designed.

Figure 9. Condition indicator lights (left) and hydrogen flame sensor (right) at the Chevron – AC Transit Hydrogen Energy Station

Maintenance Facility Modifications

AC Transit chose to modify an existing facility to enable staff to safely maintain the hydrogen-fueled buses. The required modifications (~$1.5 million) were completed and the bay was cleared for use in January 2006. The selected maintenance bay was isolated from the rest of the facility by a firewall. There is space for maintaining two buses simultaneously. Figure 10 shows the modified maintenance bay. Safety features include:

- Hydrogen leak and fire detection (thermal) systems
- Two-hour firewall
- Ignition-free space heating system
- Anti-static, non-skid, grounded floor covering
- High Speed roll-up doors
- Magnetic door release
- Audiovisual strobe alarms
- Three-fan ventilation system capable of providing up to four to six air exchanges per hour
- Class 1 Division 2 electrical classification

Figure 10. Modified maintenance bay at AC Transit

The detection system in the maintenance bay is configured to trigger specific actions if a leak or fire is detected. At 20% lower flammability limit (LFL), the garage doors automatically open, ventilation fans are turned on, the heating system is shut down, and the magnetic doors release. If a leak is detected at 40% LFL or a fire is detected, the fire department is automatically notified, all electrical power to the bay is disconnected (except for ventilation and emergency equipment), and a fire alarm is activated to signal evacuation of the building. These safety measures are all in place to ensure maximum protection for staff and facilities in case of a hydrogen-related incident. None have been recorded to date.

Because the specially equipped maintenance bay is co-located with the rest of the maintenance building, maintenance staff are 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. This decision to lower the fuel pressure in the vehicle was made early in the design process to reduce the overall cost of the facility modifications. The safety requirements for a facility capable of maintaining buses with full hydrogen tanks are more costly. Although capturing the vented hydrogen for future use is possible, early investigation showed it was not cost-effective using available methods. For a fleet of only three buses, the amount of hydrogen vented was deemed not significant enough to warrant the cost of the equipment to capture and reuse the fuel.

Early Experience with Maintenance Facility – AC Transit reports that modifications and start-up of the maintenance bay for the FCBs went relatively smoothly, with only a few challenges. The biggest issue was timing for the bay to be completed and certified by inspectors for fleet use. As with the infrastructure, the maintenance bay was not cleared for use by the time the FCBs began to arrive. The first bus was delivered in October 2005, but the bay did not get approval for use until January 2006. During this gap, maintenance workers had to do repairs or service prep on the buses outside. This resulted in some discomfort for the workers from winter weather conditions.

AC Transit experienced some early issues in operation of the new bus lift system in the maintenance facility. At one point, one of the fuel cell buses was stuck up on the lift system and missed pull out. This problem has been corrected through documented operating procedures and experience.

Hydrogen Fuel Dispensing Analysis – The buses were officially put into service in late March 2006. Figure 11 shows the monthly amounts of fuel consumed by the three buses since the station was opened. During the early months, the buses were used on a limited basis for testing and training. Once service began, the hydrogen use increased, as expected. From April through November 2006, the station dispensed over 4,500 kg of hydrogen into the three buses. Figure 12 shows the average daily hydrogen consumed by the buses. The overall average for the evaluation period is 33.3 kg per day (for days that hydrogen was dispensed into buses).

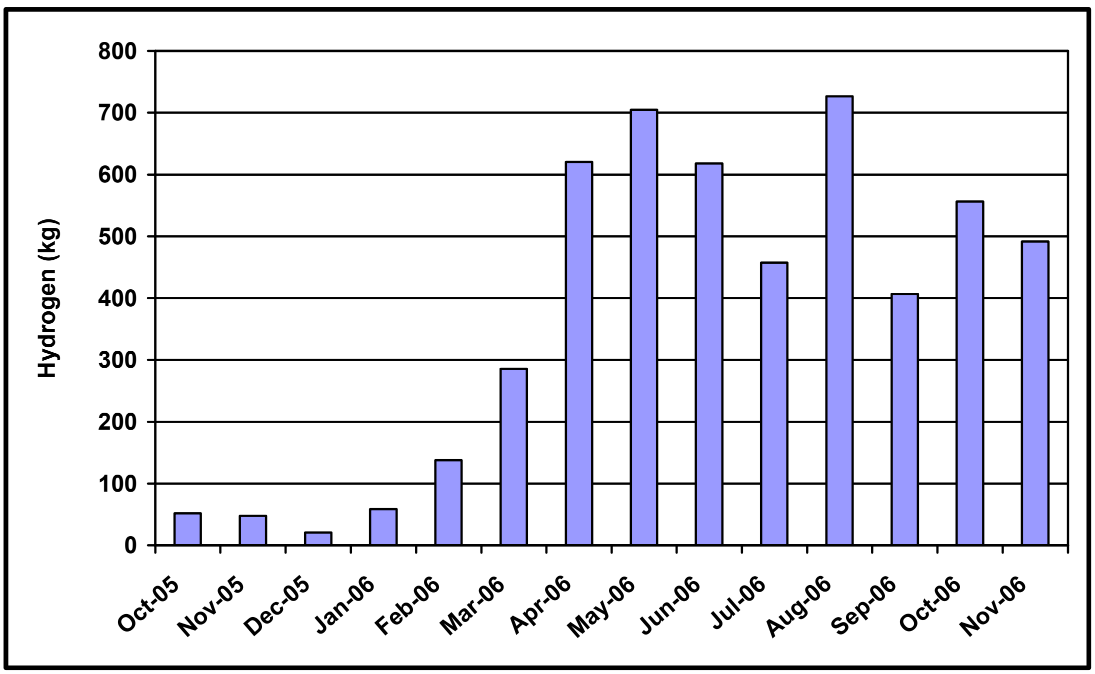

Figure 11. Total hydrogen consumption for the FCBs by month

Figure 13 shows a histogram of the fueling rates during the evaluation period (April – November 2006). Since the buses went into service, the hydrogen station provided 215 bus fueling events, with an overall average fill of 21.8 kg. The fueling rate has ranged between 0.08 and 3.01 kg per minute with an average of 1.35 kg per minute. On average, it takes approximately 16 minutes to fuel a bus.

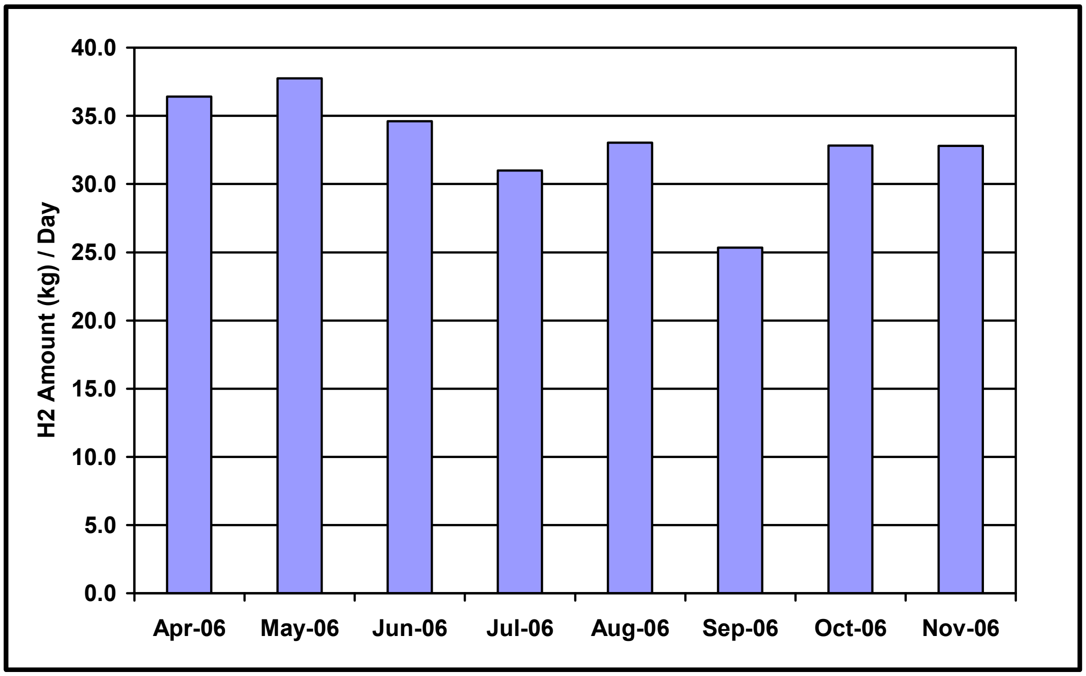

Figure 12. Average hydrogen use per day for the FCBs

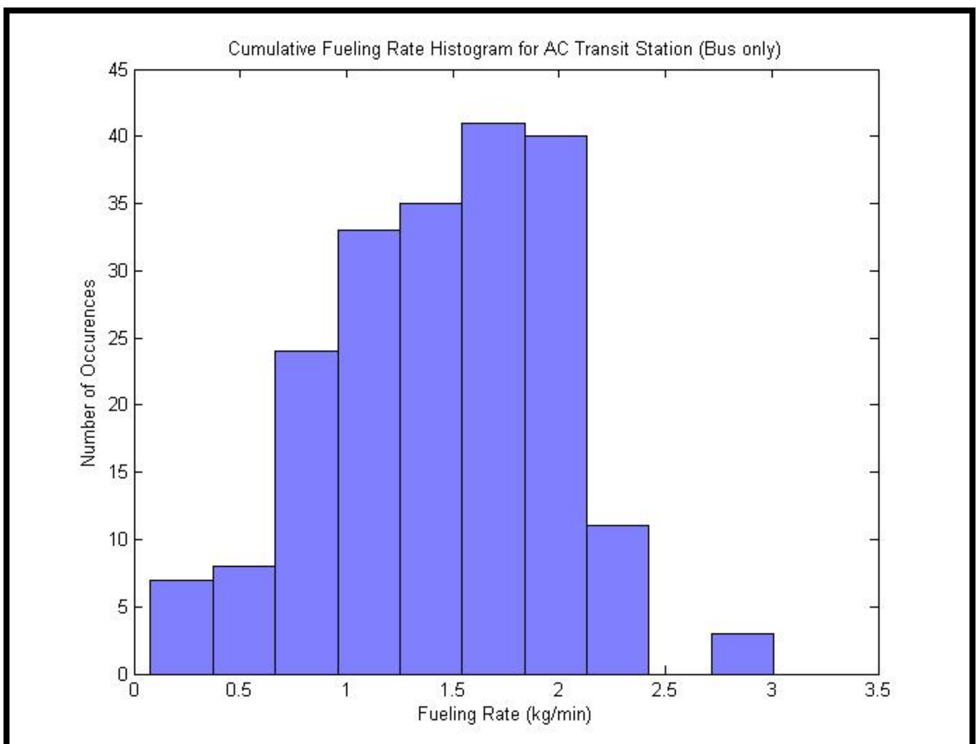

Figure 13. Fueling rate histogram for the AC Transit Hydrogen Energy Station

Fuel Cell and Diesel Buses

Table 2 provides bus system descriptions for the fuel cell and diesel buses that were studied in this evaluation. AC Transit unveiled its hydrogen fuel station and hydrogen fuel cell buses on March 13, 2006. The buses started in passenger service on March 20, 2006. The purchase, manufacturing, and packaging of the Van Hool fuel cell buses took about two years and cost approximately $3.2 million each.

The Van Hool diesel buses were ordered in 2002, with delivery in 2003 and 2004. For this evaluation, six of the diesel Van Hool buses were selected from the 21 buses of that type operating from the East Oakland Division. These six diesel buses are operated along side the fuel cell buses. The diesel buses cost $323,000 each.

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 2. 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
Rated Torque	220 Nm	860 lb-ft @ 1600 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 3 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 3. 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

Fuel Cell Bus Propulsion System Description

The prototype fuel cell buses in service at AC Transit are the result of a collaboration between ISE Corporation (www.isecorp.com), UTC Power (www.utcpower.com), and Van Hool (www.abc-companies.com/sales_vh.htm). The buses use the PureMotion 120 Fuel Cell Power System manufactured by UTC Power in a hybrid electric drive system designed by ISE. Van Hool redesigned the A330 transit bus chassis to integrate the fuel cell and hybrid systems. The buses have a low floor from front to back and three doors for easy passenger boarding.

ISE's hybrid system (shown in Figure 14) is a series configuration, meaning the fuel cell power system is not mechanically coupled to the drive axle. The fuel cell power system and energy storage system work together to provide power to two electric drive motors, which are coupled to the driveline through a combining gearbox. When the bus needs extra power, the fuel cell power system and energy storage provide power to the drive motors. When the power requirements of the bus are low, the fuel cell power system provides power and recharges the energy storage system.

The hybrid system is also capable of regenerative braking, which captures the energy typically expended during braking and uses it to recharge the energy storage system. Each component of the propulsion system is carefully controlled through an ISE-developed operating system.

ISE designed the system to be flexible. Depending on a client's needs, a variety of powerplants and energy storage options can be integrated into the system. The buses at AC Transit have a fuel cell power system and three ZEBRA (sodium/nickel chloride) batteries (www.betard.co.uk/) as the energy storage system.

The powerplant, which is the primary power source for the hybrid system is UTC Power's PureMotion 120 Fuel Cell Power System, which produces 120 kW from its proton exchange membrane (PEM) fuel cell stacks. UTC Power's fuel cells operate at near-ambient pressure, which eliminates the need for a compressor. This not only increases the efficiency of the system, but results in very quiet operation as well.

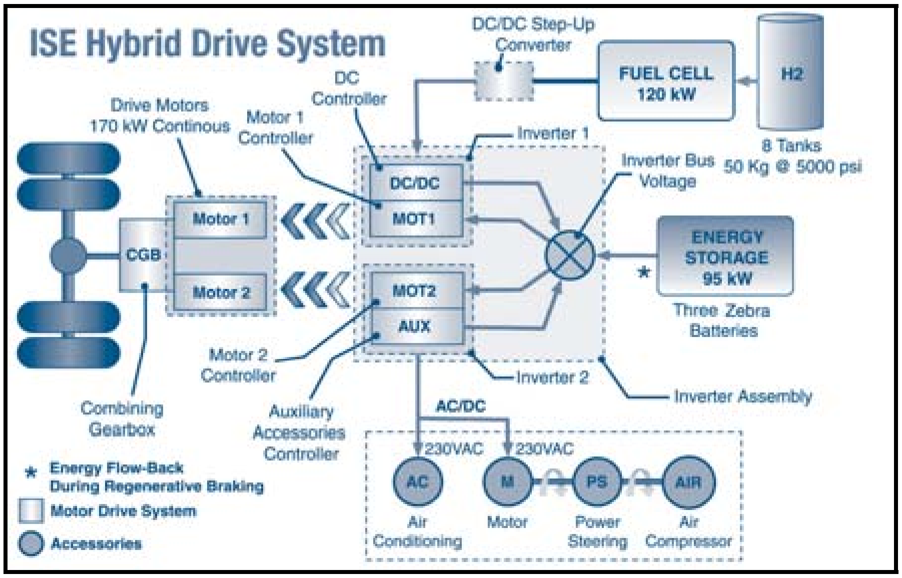

Figure 14. ISE's hybrid propulsion system

Early Bus Experience

The diesel Van Hool 40-foot buses were delivered to AC Transit during 2003 and 2004. There have been a few issues and campaigns so far:

1. Steering tie rod sleeve and steering defect
2. Seat retrofit
3. Wheelchair control cabinet change

The buses have a shorter wheelbase compared to the older, existing bus fleet at AC Transit. This has proved to be the biggest issue with the diesel Van Hool buses. Drivers not used to the short wheelbase have damaged the rear corner of the bus body by hitting things close to the curb on the street and in the parking lots. As the drivers gained experience with the buses, this problem has essentially been eliminated.

The first fuel cell bus was delivered in October 2005 and the other two fuel cell buses were delivered in December 2005. AC Transit had to add specific equipment to the buses, such as the Satcom system, fareboxes, and radios. Before the buses went into service on March 20, 2006, the mechanics and drivers were trained on the general characteristics of hydrogen, hydrogen safety, and fuel cell bus operation. AC Transit mechanics received more detailed training on system troubleshooting. The fleet also trained several groups of emergency and first responders during this time.

Both ISE and UTC Power have on-site technical support available to AC Transit for warranty support of the fuel cell buses, and AC Transit reports that this support has been excellent. AC Transit is responsible for bus maintenance and UTC Power and ISE are responsible for the propulsion and drive system. The parts for the fuel cell power systems have been provided to

AC Transit through the UTC Power technician on an as-needed basis. This has not caused any significant delays in maintaining the buses. UTC Power has converted its fuel cell power system operating-hour based preventive maintenance schedule to miles, and in the AC Transit operation, this has translated into 3,000-mile intervals. The fuel cell power systems reportedly use significant amounts of de-ionized water. The main issues with the ISE drive system have been with belts; parts have been readily available.

Some minor operational issues have arisen with the fuel cell buses:

1. The fuel cell buses are significantly taller than the diesel bus fleet. This has caused a need to keep up with tree trimming on routes where the fuel cell buses are operated.
2. Several roadcalls have been reported due to the fuel cell buses stalling on the road. These issues were the result of the driver not starting the fuel cell power system before operating the bus, mainly a factor of the quiet nature of UTC Power's fuel cell power system and the fact that there are no audible indicators that the fuel cell is powered on. This would eventually cause the onboard traction batteries to run down, followed by bus shut down. A software change has addressed this issue. Now, when the bus senses the traction battery pack at 30% state of charge (SOC), it automatically starts up the fuel cell power system on its own.
3. Non-propulsion-related issues on the fuel cell buses included securing wiring clamps and changing cable routing, and making some minor changes to the operation of the bus heating system.

There have been a few significant issues with the fuel cell buses:

1. **ZEBRA batteries** – These batteries have had significant problems in this application. The main challenges have been accommodating cell failures and optimizing the SOC algorithm. A cell failure in this serial string causes a short that decreases the overall voltage of a pack (in the group of three packs). The battery failures have been caused by several issues; including internal short circuits, internal isolation faults, and thermal isolation faults. Because these batteries operate at about 260° C, it has also been difficult to make sure that a spare battery is available and up to operating temperature for efficient replacement of another battery in the set of three batteries. This issue has led to significant down-time for the bus. ISE Corp. is working to better optimize the control software to alleviate this issue.

2. **Air conditioning** – This hybrid design is unique because the air conditioning unit is driven electrically instead of mechanically (by belt) like most vehicles. In this application, the system has experienced problems with failed evaporator and condenser motors. Several changes and upgrades have been attempted, and the problem seems to be resolved.

3. **UTC Power PureMotion 120 Fuel Cell Power System** – UTC Power monitors the performance of the fuel cell power system remotely to analyze actual performance vs. predicted performance. In June 2006, UTC Power observed that the cell stack assembly

(CSA) performance was decaying at high current densities at rates that were beyond what was predicted and required for a minimum 4,000-hour fuel cell life.

This problem was first observed in the SunLine fuel cell bus, because it had the highest number of miles and hours accumulated. On June 30, 2006, the fuel cell power system in the SunLine bus (the unit had approximately 1,140 hours) was removed from the bus and sent to UTC Power in Connecticut for advanced testing that could not be accomplished in the field. To minimize down time, the SunLine bus was retrofitted with a spare, developmental UTC Power fuel cell power system on July 6, 2006.

During testing, it became apparent to UTC Power that the problem was with the CSAs and not a boundary condition issue (such as bad fuel). An engineering investigation determined that contaminants were released from a CSA material due to a supplier quality control problem with that material, which resulted in decayed performance. It should be noted that the issue was performance-related only and did not pose any safety issues, nor was there a failure of the CSAs.

As part of UTC Power's ongoing development, UTC Power has incorporated corrective action into the CSAs, thus eliminating this condition for all builds. On September 25, 2006, the spare fuel cell power system was removed from the SunLine bus and replaced with a new fuel cell power system that incorporated the new CSA design.

On September 21, 2006, the fuel cell power system in AC Transit FCB2 was removed and sent back to Connecticut for refurbishing and upgrading. The developmental UTC Power fuel cell power system was brought from SunLine to AC Transit and installed into FCB2. The installation of the fuel cell power system was completed in approximately 10 hours and FCB2 went back into service on October 19, 2006.

On November 27, 2006, the fuel cell power system in AC Transit FCB3 was removed and returned to UTC Power in Connecticut. The first refurbished and upgraded fuel cell power system was received at AC Transit and installed into FCB3 on January 2, 2007. The entire upgrade process should be completed by the end of the first quarter of 2007.

As the upgraded fuel cell power systems are installed into the AC Transit buses, there is a desire to maximize/accelerate the use of the fuel cell buses. This accelerated testing is currently limited due to issues with the ZEBRA battery pack failures and charging the batteries up to a nearly full SOC overnight in time for the next day's service. Until the charging regime issue can be resolved, the bus cannot meet the desired 14-16 hours of operation on a regular/daily basis. AC Transit is in the process of upgrading electrical service to the maintenance building at East Oakland so that more battery charging capacity can be added.

The drivers of the fuel cell buses have been excited about and reportedly really like the buses; however, they have expressed some nervousness with potentially "hurting" the new buses. The buses offer smooth, quiet driving and comfortable driver seats with good access to controls. There have also been some concerns about hydrogen safety.

Training and Public Awareness

AC Transit is taking a proactive stance in its training program. Since the start of the program, the fleet has provided hydrogen familiarization training to approximately 1,500 of its 2,300 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 Golden Gate Transit has been learning light diagnostics and preventative maintenance for the FCB powertrain. 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. A quick reference card was produced for emergency responders showing the locations of specific equipment and places where it would be dangerous to cut into the bus.

AC Transit has produced several training videos for its staff, emergency responders, and the general public. Videos produced include:

- **Employee Training Video**: In this short video (< 5 minutes), employees are provided with basic information on the characteristics and safety aspects of hydrogen gas as well as the benefits of using the fuel for transit.
- **First-Responder Safety**: To facilitate training for a large number of first responders, AC Transit filmed an initial training session for Oakland firefighters. The video includes a classroom portion that outlines the general characteristics of hydrogen and related safety concerns and provides instruction for emergency responders should an incident occur with a fuel cell bus or the hydrogen facility. This portion also includes a question and answer period. The second part of the video provides a walk-through of the hydrogen fuel production and dispensing facility, the maintenance bay, and the fuel cell bus. Representatives from Chevron, ISE Corp., and Schatz Energy Research Center describe all safety devices, including locations and instructions on how to safely shut-down and disable electric power and fuel lines in case of emergency.
- **AC Transit Grand Opening, March 13, 2006**: The video of the grand opening ceremony for the Chevron – AC Transit Energy Station at AC Transit's Seminary Division provides a comprehensive outline of the HyRoad program.

Raising public awareness for hydrogen and fuel cell technology is extremely important to AC Transit. Thousands of transit riders have been introduced to the fuel cell buses in daily service since March 2006 when the buses began service. The buses serve as mobile learning centers through on-board exhibits describing various aspects of the technology, such as the buses' systems and how fuel cells work. 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 over the next two years 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.

AC Transit receives frequent requests for tours from various individuals and groups. Staff accommodates these requests and brings the buses to outside events as time and resources allow. From January through November 2006, AC Transit estimates it reached a potential of over 220,000 people through various events and tours. Table 4 summarizes those events by category.

Table 4. Public Awareness Events by Category

Event Category	Number of Events	Number of People
Academic	6	2,284
General Public	26	224,536
Industry	4	7
International	9	41
Government	6	109
Partner Event	3	360
Total	**54**	**227,337**

Such events, tours, and presentations include:

- **September 2005**: AC Transit participated in the APTA Annual Meeting and Expo in Dallas, Texas. The fuel cell bus was officially unveiled to the transit industry at a press conference on the floor of the Dallas Convention Center. Other activities during the event included a fuel cell bus for static display as well as a fully functional bus for demonstration rides. The bus carried approximately 100 to 200 people over the course of three days on short trips around the Dallas Convention Center.
- **November 2005:** AC Transit held training sessions for various fire battalions.
- **February 2006:** AC Transit provided tours of the bus and facilities to the president of Protium Energy Technologies; French parliamentarians; and representatives from PG&E, the U.S. Fuel Cell Council, and the Science Club from St. Elizabeth School.
- **March 2006:** AC Transit and Chevron held a grand opening event for the hydrogen station. Approximately 300 attendees participated in the event, which included presentations and remarks from all the demonstration project partners. Also during the month, AC Transit hosted tours of the hydrogen facility and fuel cell bus to six representatives from Tsinghua University (China), representatives from the Oakland Mayor's office, an FTA representative, and about 50 science students from Martin Luther King Middle School in Berkeley.
- **April 2006:** AC Transit participated in several off-site events including the Transportation and Land Use Choices Annual Summit, the City of Oakland's Earth Day Celebration, Lawrence Hall of Science's Earth Week Celebration, the El Cerrito Earth Week Celebration, a press event for the Transportation and Land Use Coalition, and an

event for UTC Power at the San Francisco Ritz Carlton Hotel. Also during the month, AC Transit provided tours of the fuel cell bus and facilities to representatives from DOE and the Korea Automotive Technology Institute.

- **May 2006:** AC Transit provided a fuel cell bus for Oakland's Bike to Work Day, the Capitol Bike Fest and Cal/EPA Transportation Fair at State Capitol Park, and a Spare the Air Kick-off Media Event at Great Lawn, Treasure Island. Tours of the AC Transit facility and fuel cell bus were provided for delegations from Japan and the China Academy of Urban Planning and Design.
- **June 2006:** A fuel cell bus was provided for two Get on the Bus events, sponsored by City Space, the Juneteenth Parade in Richmond, California, and the Water Keepers Conference at San Francisco State. Tours of the fuel cell bus and facility were provided to a Chinese delegation from the China Academy of Urban Planning and Design and a group of visitors from Evobus.
- **July 2006:** AC Transit provided a fuel cell bus for several area events including the Fremont City 4th of July Parade, the Piedmont City 4th of July Parade, the Alameda Mayor's 4th of July Parade, and the AAA Greenlight Rally from Santa Clara to Concord to Sacramento. The combined attendance at these events was estimated at over 42,000.
- **August 2006:** AC Transit provided tours of the hydrogen station and fuel cell bus to several professors from Kent State University, Ohio, and a representative from the California Air Resources Board. A fuel cell bus participated in several events including the Alameda County's Road to Sustainability Event and the Festival of India Parade. AC Transit also operated a fuel cell mini bus in the Sistahs Steppin in the Oakland Gay Pride Parade.
- **September 2006:** AC Transit provided a fuel cell bus and car for a meeting of the Newark Optimist Club, the Solano Stroll Parade, the Newark City Parade, and the Bay Area Healthy Neighborhood event. AC Transit hosted tours of the hydrogen station and fuel cell bus to representatives from the Oakland Tribune, the East Bay Business Times, and a representative from the Japanese Automotive Research Institute.
- **October 2006:** AC Transit provided a fuel cell bus and car for the UC Berkeley Lawrence Hall of Science October Fair, a Columbus Club event, a Central County Policy Advisory Committee event at Hayward City Hall, and an event in San Francisco with State Senator Don Perata, U.S. Senator Diane Feinstein, and local Bay Area officials. AC Transit also provided a road demonstration of the fuel cell bus for Chevron's Environmental Awards Program.
- **November 2006:** AC Transit hosted tours of the facility and fuel cell bus to two representatives from the Beijing Non-Ferrous Metal Research Institute and a group from the South Carolina Hydrogen and Fuel Cell Alliance. AC Transit also hosted a visit by representatives of Weekend Weather TV, a local adolescent-run, Web-based news program. Off-site events included the Get on the Bus!-ES 24 Freshman Seminar at UC Berkeley on Transportation and Sustainability. Approximately 25 students participated in the seminar, which was held on the bus.

Evaluation Results

The evaluation period for the fuel cell and diesel baseline buses for this report includes eight months of operation from April 2006 through November 2006. The fuel cell buses started in revenue service on March 20, 2006, but the March 2006 data has 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.

In this evaluation report, the fuel cell buses are considered prototype technology that is in the process of being commercialized. The analysis and comparison discussions with standard diesel buses were done to 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).

Route Descriptions

Overall, AC Transit operates 105 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 for two eight-hour blocks on two routes 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 fleet 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.

As mentioned above, 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. During this same timeframe, 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 the end of the evaluation period (November 30, 2006), 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.

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

Originally, the fuel cell and diesel baseline buses should have switched to the next set of test blocks of work around the end of September 2006. This was delayed because of delays in overall route changes at AC Transit. Currently, the next major service change at AC Transit has most likely been delayed until at least March 2007, and maybe as late as May 2007.

In the meantime, there are plans to switch the diesel buses back to the two blocks of work on Route 57 starting in January 2007. This has been planned so that fuel economy data can be collected. During the three months that the diesel baseline buses were originally on the Route 57 blocks, the diesel fuel data collection system at the depot was not operating properly and the fuel economy data was lost.

At the same time, there is a desire to increase the amount of work that the fuel cell buses are assigned to accomplish, as discussed above in the Early Bus Experience section. AC Transit intends to create three 13- to 14-hour blocks of work for each of the three fuel cell buses. Starting in late January 2007, current planning involves having all three fuel cell buses on several existing routes operating out of its division, including Route 50. Although there is a desire to maximize the operation of the fuel cell buses, they need to be back at the division so that the batteries can be properly charged before starting service the next day.

When AC Transit makes its next service change (sometime between March and May 2007), there are plans for six special blocks of work on two new routes (the newly created Route 18 and Route 51). There will be two blocks of work per weekday for each of the three fuel cell buses and for three of the six diesel baseline buses. There are also plans to try a new regime of switching the diesel and fuel cell buses each week instead of every three months.

Bus Use and Availability

Bus use and availability are indicators of reliability. The lack of bus usage may be an indication of 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 15 shows mileage and fuel cell power system operating hour accumulation from the start of testing at AC Transit in October 2005 through November 2006. 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. Other limiting factors included maintenance issues, availability of trained drivers, and availability of hydrogen fueling.

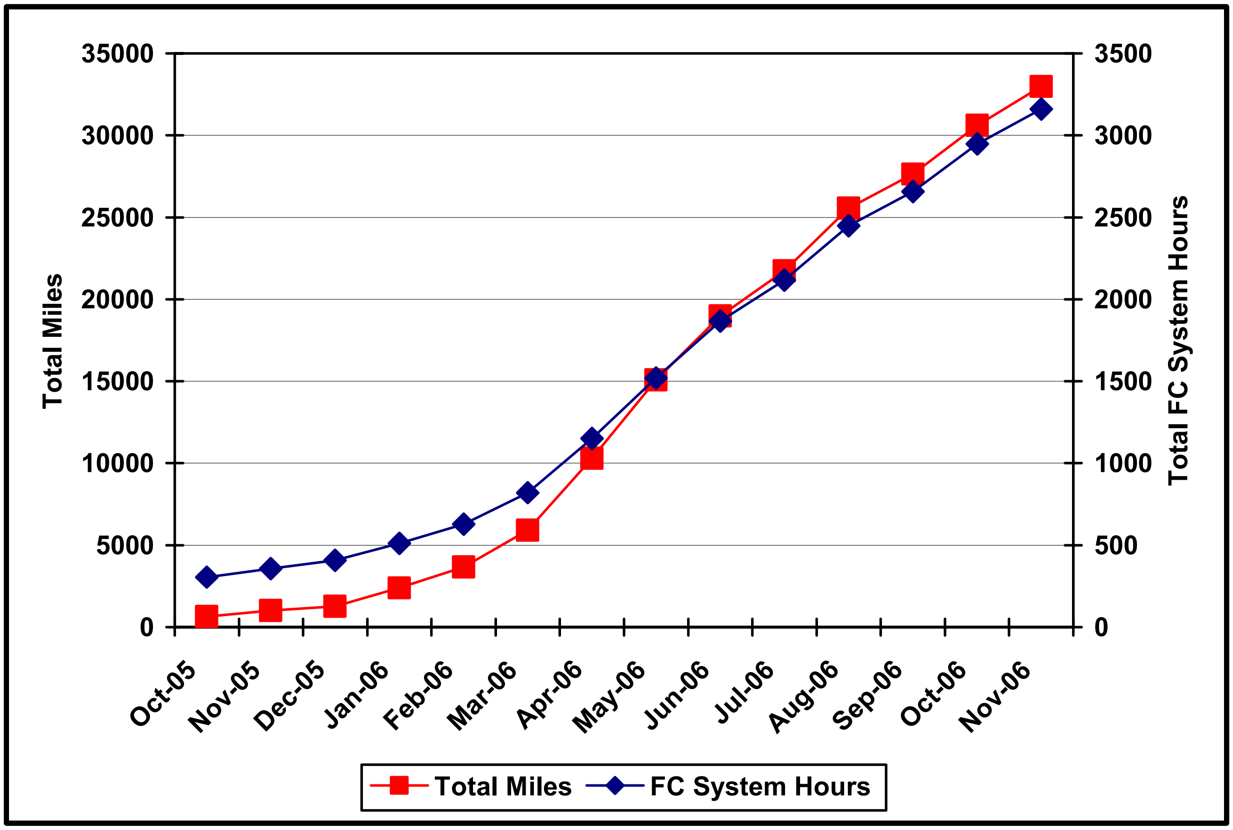

Figure 15. Cumulative mileage and fuel cell system hours for all three fuel cell buses

Table 6 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 33,000 miles. For the evaluation period (eight months), the fuel cell buses have accumulated 27,065 miles and 2,338 fuel cell power system hours. The diesel buses operated a monthly average of 2,141 miles each as compared to the fuel cell buses, which operated a monthly average of 1,128 miles each. This indicates that the fuel cell buses operated just over half (53%) the miles that the diesel buses did in the same period. The fuel cell buses were controlled to only weekdays and one eight-hour shift per weekday. The diesel buses were used in typical service up to seven days per week and 16-20 hours per day. There is some indication that the study diesel buses were not used as much as typical diesel buses at the division. This will be investigated further in the next evaluation report.

For the fuel cell buses, the average operating speed during the evaluation period was 11.6 mph. Figure 16 shows the average monthly operating speed for the fuel cell buses during the evaluation period. At the beginning of the evaluation period, the average speed was around 12-13 mph, which is slightly lower than the average operating speed (shown above, 16 mph) for the special route blocks on Route 50. During the rest of the evaluation period, the fuel cell buses operated on Route 57 with a planned average speed of 11.3 mph. The actual average speed data from July through November 2006 was slightly lower at 10.7 mph. In both cases, the actual operating speeds were slightly lower than the planned operation average speed. This was caused by additional operation of the fuel cell buses during start-up inspection; events where the fuel cell system is operating, but the bus does not move (or moves very little for demonstrations); and operation for testing and troubleshooting.

Table 6. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage	Fuel Cell System Hours
FC1	5,164	15,032	9,868	8	1,234	N/A
FC2	778	9,666	8,888	8	1,111	N/A
FC3	3,153	11,192	8,309	8	1,039	N/A
Fuel Cell			**27,065**	**24**	**1,128**	**2,338**
1043	91,534	108,222	16,688	8	2,086	N/A
1044	108,346	127,965	19,619	8	2,452	N/A
1045	125,972	139,105	13,133	8	1,642	N/A
1046	125,685	144,583	18,898	8	2,362	N/A
1047	108,336	125,361	17,025	8	2,128	N/A
1048	94,092	111,484	17,392	8	2,172	N/A
Diesel			**102,755**	**48**	**2,141**	**N/A**

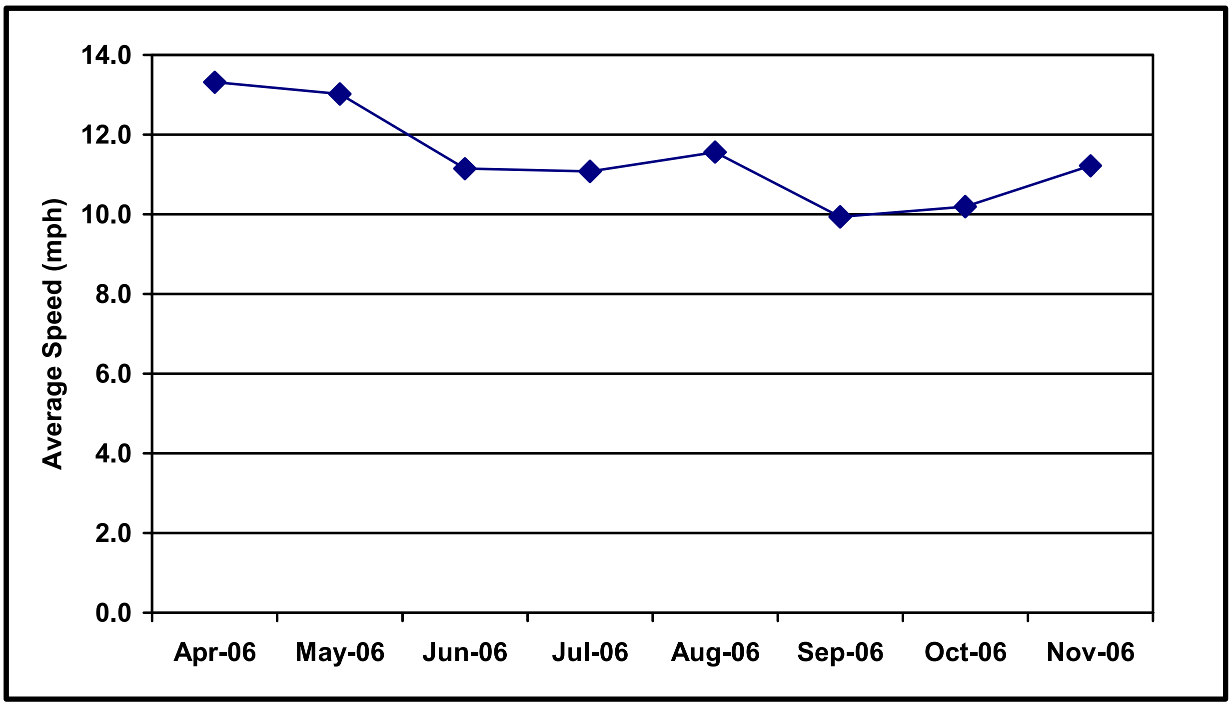

Figure 16. Fuel cell bus monthly average speed (evaluation period)

Figure 17 shows the planned monthly mileage for the fuel cell buses and the actual monthly mileage accumulation. The fuel cell buses operated at a mileage level within 80% of the planned mileage except for September and November 2006. Fuel cell bus usage was low in September 2006 due to ZEBRA battery issues and the lack of hydrogen fuel at the end of the month. FCB2 had the fuel cell stack assemblies changed in October 2006, and had issues with the ZEBRA batteries in September and November 2006. FCB3 had issues with the ZEBRA batteries and had the fuel cell stack assemblies removed in November 2006, causing a significant reduction in bus usage.

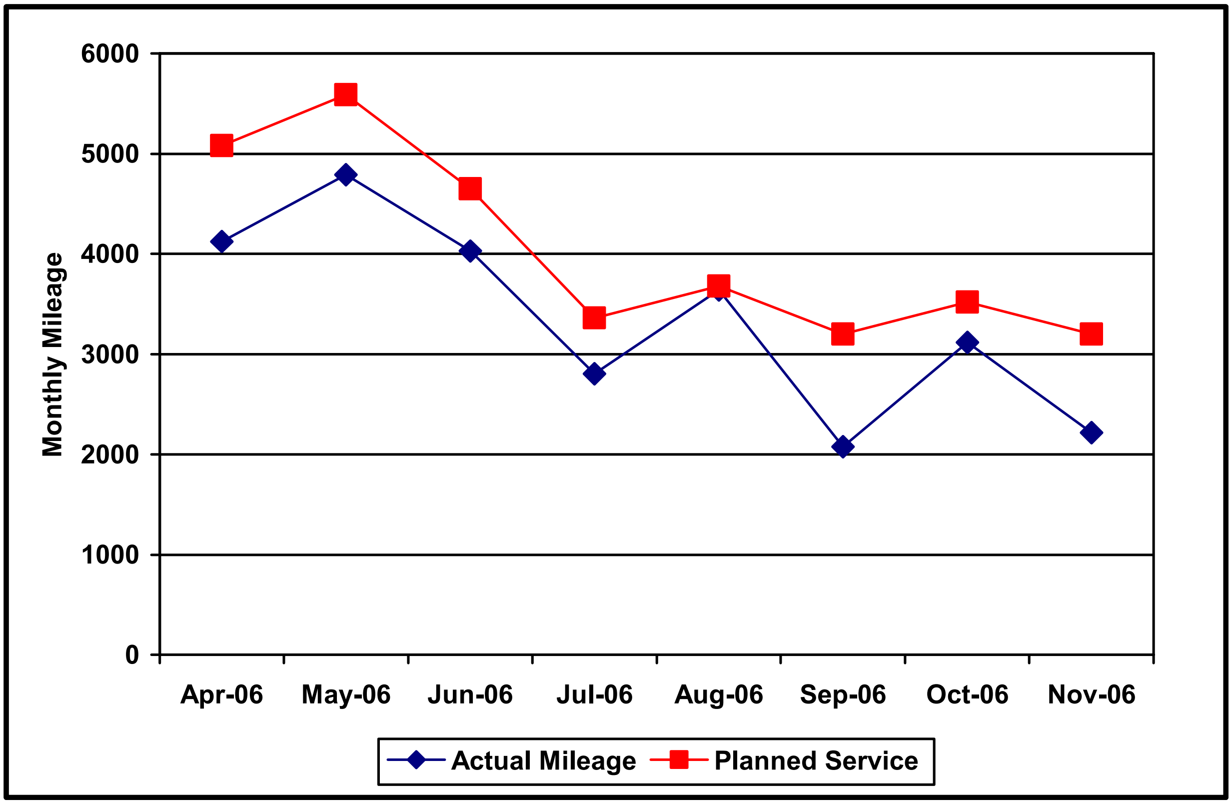

Figure 17. Planned versus actual mileage for fuel cell buses

Figure 18 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, as described above. Problems with the air conditioning on the three fuel cell buses were also worked on during September 2006.

Table 7 provides a summary of the availability and unavailability reasons for each of the three fuel cell buses. During the evaluation period, the average availability for the fuel cell buses was 77%. Issues that kept the fuel cell buses out of service included the fuel cell power system (26%), ZEBRA batteries (37%), air conditioning (3%), AC Transit maintenance (14%), event preparation (11%), and hydrogen fuel unavailability (9%). Note that FCB1 had the best availability and that FCB2 and FCB3 had significant unavailability due to the fuel cell stack assemblies being removed and replaced during the evaluation period. FCB3 was the designated event bus during most of the evaluation period, and the availability for events accounted for 18% and related cleaning accounted for 17% of unavailable days.

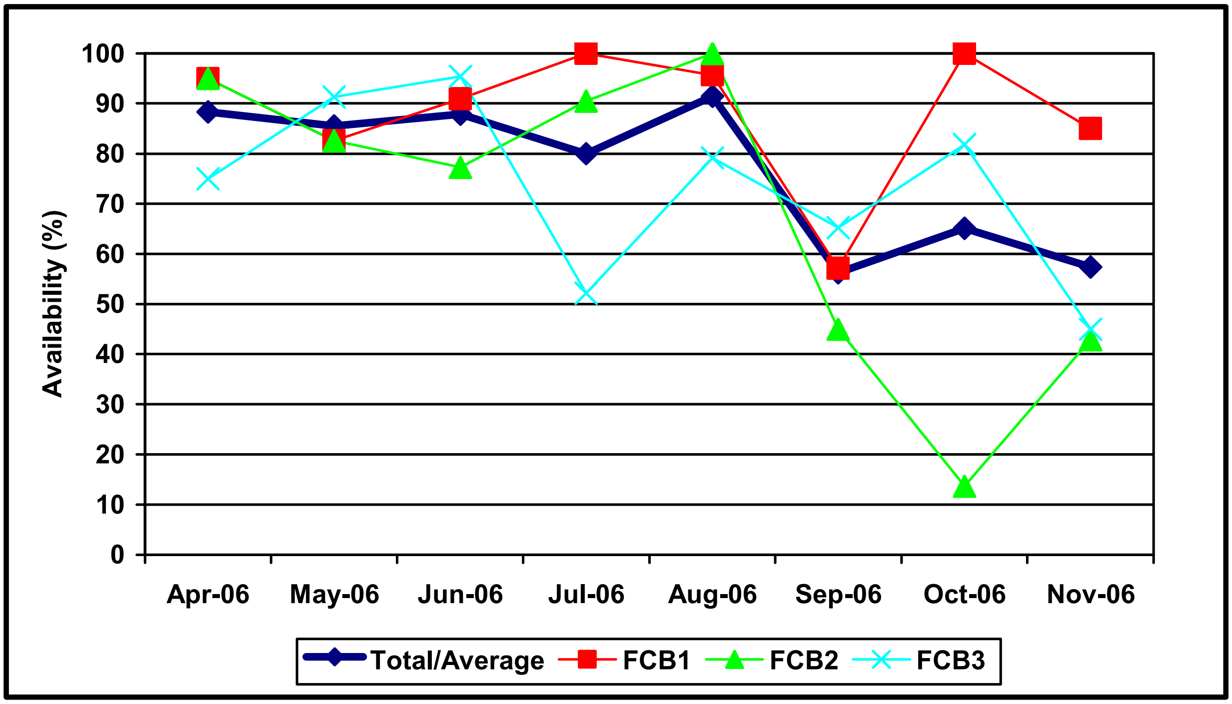

Figure 18. Availability for all three fuel cell buses and overall average

Table 7. Summary of Reasons for Availability and Unavailability of Buses for Service

Category	FCB1		FCB2		FCB3		Group Total	
	Days	%	Days	%	Days	%	Days	%
Planned Work Days	172		172		177		521	
Days Available	152	88	118	69	130	73	400	77
Available	**152**	**100**	**118**	**100**	**130**	**100**	**400**	**100**
On Route	99	65	100	85	74	57	273	68
Event/Demonstration	7	5	4	3	24	18	35	9
No Driver Available	9	6	7	6	1	1	17	4
Training	11	7	3	3	5	4	19	5
Not Used	26	17	4	3	26	20	56	14
Unavailable	**20**	**100**	**54**	**100**	**47**	**100**	**121**	**100**
Fuel Cell Propulsion	0	0	23	43	8	17	31	26
ISE Propulsion	0	0	0	0	0	0	0	0
ZEBRA Battery	4	20	23	42	17	36	44	37
Air Conditioning	2	10	1	2	1	2	4	3
AC Transit Maintenance	7	35	2	4	8	17	17	14
Event Preparation	2	10	4	7	8	17	14	11
Fueling Unavailable	5	25	1	2	5	11	11	9

Fuel Economy and Cost

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

Table 8 shows hydrogen fuel consumption and fuel economy for the three fuel cell buses during the evaluation period. Overall, the three fuel cell buses averaged 5.50 miles per kg of hydrogen, which equates to 6.22 miles per diesel gallon equivalent. The energy conversion from kg of hydrogen to diesel gallon equivalent is provided in the appendix. ISE also reported that the fuel cell buses had approximately 313 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 6% of the hydrogen dispensed into the fuel cell buses. If that fuel were removed from the fuel economy calculation, the result would be 5.88 miles per kg and 6.64 miles per diesel gallon equivalent (DGE).

Table 8. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (Gallon)	Miles per Gallon
FCB1	9,868	1,726.0	5.72	1,527.4	6.46
FCB2	8,888	1,700.1	5.23	1,504.5	5.91
FCB3	8,309	1.492.7	5.57	1,321.01	6.29
FCB Total	**27,065**	**4,918.7**	**5.50**	**4,352.9**	**6.22**

The diesel fuel consumption for the evaluation period is not available except for November 2006, because the fuel tracking system was not working properly until late October 2006. For the month of November 2006, the six diesel baseline buses averaged 4.46 mpg, which indicates the fuel economy for the fuel cell buses is 39% higher than that of the diesel buses. AC Transit reports that the diesel bus fleet typically has an average fuel economy of approximately 4.00 mpg. Using this number in the calculation, the fuel cell buses have a fuel economy 56% higher than the diesel buses.

As mentioned earlier, there have been some key issues with the fuel cell buses that are in the process of being resolved. Figure 19 shows the average monthly fuel economy in both miles per kg and miles per diesel gallon equivalent. The chart shows a progression downward for the average fuel economy. Some of the fuel economy decrease, starting in June-July 2006, was caused by the fuel cell buses changing operating routes from an average speed around 16 mph down to 11.3 mph. The average fuel economy also decreased during summer operation because of increased air conditioning loading. However, the fuel economy continued down in the fall months as well. Once the UTC Power fuel cell power systems have been replaced and the buses are back in service, the fuel economy is expected to come back up.

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. This cost for hydrogen fuel indicates a cost per mile for the fuel cell buses of $1.45. The average diesel fuel cost per gallon during the evaluation period is $2.30 per gallon. If the 4.00 mpg diesel average fuel economy is used, this indicates a $0.58 per mile cost. If the 4.46 mpg diesel average fuel economy is used, this indicates a $0.52 per mile cost. In either case, the diesel cost per mile is about one-third of the fuel cell bus fuel cost per mile.

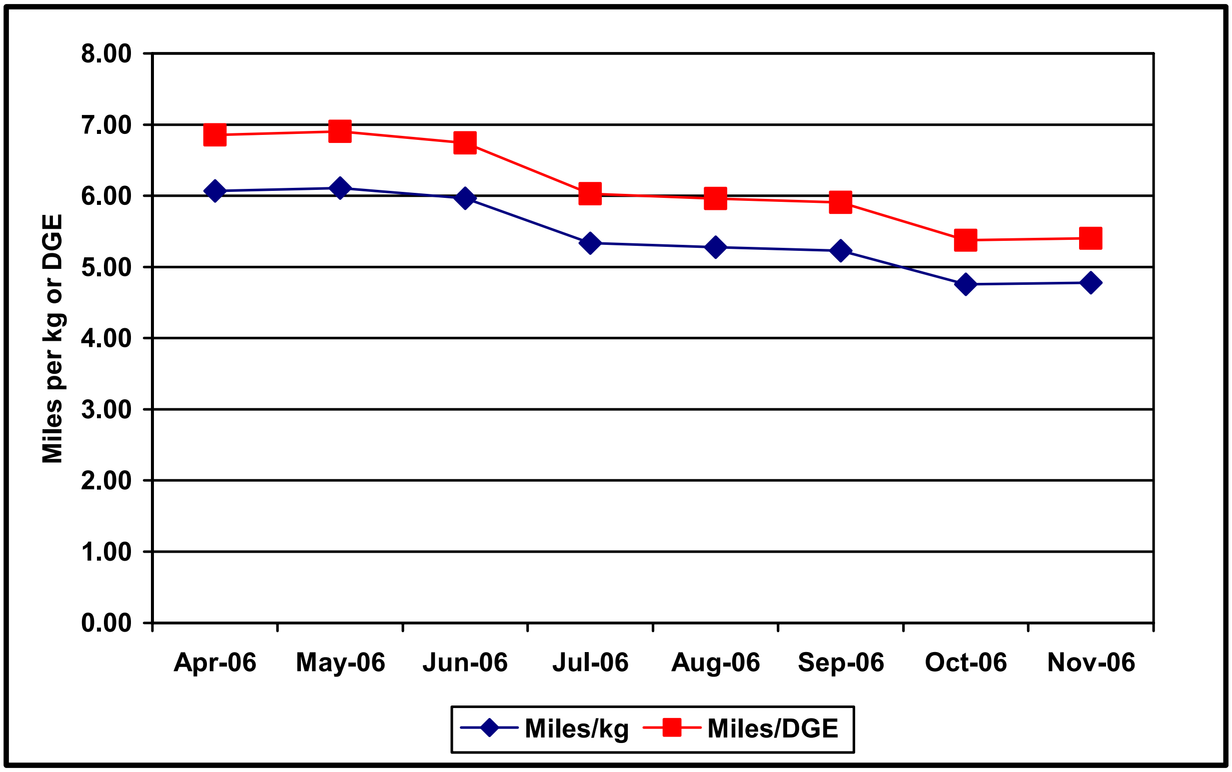

Figure 19. Fuel cell bus monthly average fuel economy (evaluation period)

Maintenance Analysis

The maintenance cost analysis in this section is only for the evaluation period (April 2006 through November 2006). 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 is not reflective of 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 9 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 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. The AC Transit mechanics have only done 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. This will also be necessary based on the desired increase in operation of the fuel cell buses.

For the fuel cell buses, FCB2 has the lowest cost per mile and the other two have similar costs per mile. The AC Transit mechanics did start to participate on one of the preventive maintenance actions for FCB1 in September, with 48 hours of mechanic time charged, and for FCB3 in July, with 6 hours of mechanic time charged. FCB3 had some body damage repaired in August 2006, which significantly increased maintenance costs. The diesel buses had a few significant maintenance repairs, including two buses with turbocharger replacements and window replacements/repairs.

Table 9. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Cost per Mile ($)
FCB1	9,868	1,837.01	98.8	0.69
FCB2	8,888	98.64	69.4	0.40
FCB3	8,309	2,192.00	72.2	0.70
Total Fuel Cell	**27,065**	**4,127.65**	**240.4**	**0.60**
Avg. per Bus	**9,022**	**1,375.88**	**80.1**	**--**
1043	16,688	3,137.64	89.2	0.46
1044	19,619	2,911.93	55.9	0.29
1045	13,133	1,729.76	66.9	0.39
1046	18,898	3,564.22	64.2	0.36
1047	17,025	2,470.96	84.2	0.39
1048	17,392	831.93	70.9	0.25
Total Diesel	**102,755**	**14,646.47**	**431.3**	**0.35**
Avg. per Bus	**17,126**	**2,441.08**	**71.9**	**--**

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 47% lower than the diesel buses
- Parts Costs – The fuel cell buses are 44% lower than the diesel buses
- Labor Hours – The fuel cell buses are 11% higher than the diesel buses
- Cost per Mile (without warranty costs) – The fuel cell buses are 71% higher than the diesel buses

This reflects the fact that the fuel cell buses are in the prototype development stage for transit bus service.

Maintenance Costs Broken Down by System—Table 10 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; and cab, body, and accessories. These three systems, along with the frame, steering, and suspension system, were also the highest maintenance cost systems for the diesel buses. The additional category of frame, steering, and suspension reflects the higher use of the older diesel buses compared to the fuel cell buses.

Table 10. 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	0.38	63	0.11	31
Propulsion-Related	0.06	10	0.12	34
PMI	0.15	25	0.08	23
Brakes	0.00	0	0.01	3
Frame, Steering, and Suspension	0.00	0	0.02	6
HVAC	0.00	0	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	3
Tires	0.00	0	0.00	0
Total	**0.60**	**100**	**0.35**	**100**

* Excludes warranty work costs

The maintenance cost reported in the AC Transit system for the fuel cell buses was low because the warranty work was done by on-site manufacturer technicians. For maintenance work that has been done by the AC Transit mechanics, the reported costs appear large because of the low mileage of the fuel cell buses. The cab, body, and accessories category for the fuel cell buses is higher than the diesel buses in both cost per mile and percent of total maintenance. The propulsion-related maintenance for the fuel cell buses is significantly lower than for the diesel buses because nearly all of the work was done by the manufacturers. The PMI labor started to increase for the fuel cell buses during the evaluation period as the AC Transit mechanics participated more. However, all of the parts used during preventive maintenance and unscheduled maintenance for the fuel cell power systems and drive systems have been covered under warranty.

Preventive maintenance activities for the fuel cell bus power system involve daily inspection of the bus including download of electronic data and diagnosis of any warnings provided by the on-board computer. On an as-needed basis, de-ionized water is added based on inspections at start-up, after any shutdown or warning from the fuel cell power system, after movement by trailer or towing, and after loss of water from maintenance or leaks. UTC Power created a preventive maintenance schedule based on 6,000 miles, which is an equivalent of 500 fuel cell system hours. The 6,000-mile work is planned at 2.5 hours, the 12,000-mile work is planned at 5 hours, and the 24,000-mile work is planned at 7.5 hours.

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 11 shows a breakdown of the propulsion-related system repairs for the two study groups during the evaluation period (no warranty costs). The fuel cell buses had significantly higher maintenance costs for all of the systems shown in the table except for the exhaust and transmission systems.

Table 11. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	27,065	102,755
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	235.32	6,355.53
Labor hours	27.2	127.5
Total cost ($)	1,592.82	12,730.53
Total cost ($) per mile	**0.06**	**0.12**
Exhaust System Repairs		
Parts cost ($)	0.00	172.39
Labor hours	0.0	4.6
Total cost ($)	0.00	399.89
Total cost ($) per mile	**0.00**	**0.00**
Fuel System Repairs		
Parts cost ($)	0.00	661.50
Labor hours	1.2	32.0
Total cost ($)	61.00	2,261.50
Total cost ($) per mile	**0.00**	**0.02**
Powerplant System Repairs		
Parts cost ($)	0.00	4,109.26
Labor hours	0.0	38.8
Total cost ($)	0.00	6,049.26
Total cost ($) per mile	**0.00**	**0.06**
Electric Motor and Propulsion Repairs		
Parts cost ($)	0.00	0.00
Labor hours	20.9	0.0
Total cost ($)	1,046.50	0.00
Total cost ($) per mile	**0.04**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	235.32	79.04
Labor hours	3.0	11.4
Total cost ($)	385.32	649.04
Total cost ($) per mile	**0.01**	**0.01**
Air Intake System Repairs		
Parts cost ($)	0.00	448.42
Labor hours	0.0	0.0
Total cost ($)	0.00	448.42
Total cost ($) per mile	**0.00**	**0.00**
Cooling System Repairs		
Parts cost ($)	0.00	803.23
Labor hours	0.0	40.5
Total cost ($)	0.00	2,828.23
Total cost ($) per mile	**0.00**	**0.03**
Transmission Repairs		
Parts cost ($)	0.00	81.69
Labor hours	2.0	0.3
Total cost ($)	100.00	94.19
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. 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 12 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. (Note: AC Transit reports the entire 40-ft Van Hool diesel fleet has a propulsion-related MBRC of 14,000.)

Table 12. Roadcalls and MBRC (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC
FCB1	9,868	10	987	7	1,410
FCB2	8,888	15	593	9	988
FCB3	8,309	10	831	6	1,385
Total FCB	**27,065**	**35**	**773**	**22**	**1,230**
1043 Diesel	16,688	4	4,172	2	8,344
1044 Diesel	19,619	2	9,810	2	9,810
1045 Diesel	13,133	5	2,627	3	4,378
1046 Diesel	18,898	4	4,725	0	
1047 Diesel	17,025	5	3,405	5	3,405
1048 Diesel	17,392	3	5,797	0	
Total Diesel	**102,755**	**23**	**4,468**	**12**	**8,563**

What's Next

This preliminary data report includes an eight-month evaluation period (April 2006 through November 2006) of the prototype fuel cell buses in operation at AC Transit. The next evaluation report, planned for release at the end of 2007, will include at least another 6 months of operations data and experience from AC Transit.

For the next evaluation report, additional data collection will focus on the following existing and new topics:

- Gain more experience with the new/upgraded/refurbished fuel cell power systems, specifically looking for fuel economy improvements from this preliminary evaluation report.
- Track and document AC Transit's efforts to maximize the use of the fuel cell buses, the use of the study buses on the next routes and special route blocks on Route 18 and Route 51, and the planned weekly switching of the fuel cell and diesel buses between the two new routes.
- Collect more information regarding standard diesel bus usage at AC Transit. One question that needs to be answered is what is typical diesel bus usage from the East Oakland Division? The next issue has to do with getting comparable fuel economy information from the diesel baseline buses. AC Transit has committed to fueling the diesel study buses before and after operation on one of the special route blocks. This is done to allow fuel economy comparisons between the diesel and fuel cell buses on the same route blocks. It also allows AC Transit to maximize the use of its diesel buses (AC Transit started this fuel procedure in December 2006).
- Collect more information about fuel cell bus maintenance for the fuel cell power system and the hybrid drive system. Track and document increases in AC Transit mechanic inclusion in the maintenance of these fuel cell buses.
- Attempt to collect more detailed information about the on-site hydrogen production and cost/price of hydrogen fuel from the Oakland Energy Station as cost estimates become available.
- Track and document any fuel cell bus operation activities with GGT.

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 accelerated "testing to failure" of the existing fuel cell buses.

The California Air Resources Board has been working on updating its zero emission bus regulations. The current proposed program includes an advanced fuel cell bus demonstration for transit agencies on the diesel path by 2009. In this proposed regulation, a single transit agency would need to demonstrate six new zero emission buses or work within a multi-transit agency group to demonstrate at least 12 new zero emission buses. CARB has also required that existing fuel cell buses qualify as new zero emission buses as long as the fuel cell power systems are upgraded with newer design units.

Several transit agencies in the San Francisco Bay area have started working together as the Bay Area Working Group to put a plan together for implementing a multi-transit agency advanced demonstration to meet this proposed CARB regulation. The transit agencies included are AC Transit, Santa Clara VTA, Golden Gate Transit, SamTrans, and San Francisco MUNI. One of the major barriers to responding to CARB's regulation is the amount of funding required to establish and operate this advanced demonstration.

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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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Reports from DOE/NREL evaluations can be downloaded via the following Web sites:
Hydrogen and fuel cell related: www.nrel.gov/hydrogen/proj_fc_bus_eval.html
Hybrid and other technologies: www.nrel.gov/vehiclesandfuels/fleettest/publications_bus.html

Appendix: Fleet Summary Statistics

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

Fleet Operations and Economics

	Diesel Buses	Fuel Cell Buses
Number of Vehicles	6	3
Period Used for Fuel and Oil Op Analysis	4/06-11/06	4/06-11/06
Total Number of Months in Period	8	8
Fuel and Oil Analysis Base Fleet Mileage	N/A	27,065
Period Used for Maintenance Op Analysis	4/06-11/06	4/06-11/06
Total Number of Months in Period	8	8
Maintenance Analysis Base Fleet Mileage	102,755	27,065
Average Monthly Mileage per Vehicle	2,141	809
Availability	N/A	77%
Fleet Fuel Usage in Diesel Gal/H2 kg	N/A	4,919
Roadcalls	23	35
RCs MBRC	4,468	773
Propulsion Roadcalls	12	22
Propulsion MBRC	8,563	1,230
Fleet Miles/kg Hydrogen		5.50
(1.13 kg H2/gal Diesel Fuel)		
Representative Fleet MPG (energy equiv.)	4.66	6.22
Hydrogen Cost per kg		8.00
Diesel Cost per Gallon	2.30	
Fuel Cost per Mile	**0.52**	**1.45**
Total Scheduled Repair Cost per Mile	0.12	0.37
Total Unscheduled Repair Cost per Mile	0.23	2.23
Total Maintenance Cost per Mile	**0.35**	**0.60**
Total Operating Cost per Mile	**0.87**	**2.05**

Maintenance Costs

	Diesel Buses	Fuel Cell Buses
Fleet Mileage	102,755	27,065
Total Parts Cost	14,646.48	4,127.65
Total Labor Hours	431.3	240.4
Average Labor Cost (@ $50.00 per hour)	21,565.00	12,020.00
Total Maintenance Cost	36,211.48	16,147.65
Total Maintenance Cost per Bus	6,035.25	5,382.55
Total Maintenance Cost per Mile	**0.35**	**0.60**

Breakdown of Maintenance Costs by Vehicle System

	Diesel Buses	Fuel Cell Buses
Fleet Mileage	102,755	27,065
Total Propulsion-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 65)		
Parts Cost	6,355.53	235.32
Labor Hours	127.5	27.2
Average Labor Cost	6,375.00	1,357.50
Total Cost (for system)	12,730.53	1,592.82
Total Cost (for system) per Bus	2,121.76	530.94
Total Cost (for system) per Mile	**0.12**	**0.06**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost	172.39	0.00
Labor Hours	4.6	0.0
Average Labor Cost	225.50	0.00
Total Cost (for system)	399.89	0.00
Total Cost (for system) per Bus	66.65	0.00
Total Cost (for system) per Mile	**0.00**	**0.00**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost	661.50	0.00
Labor Hours	32.0	1.2
Average Labor Cost	1,600.00	61.00
Total Cost (for system)	2,261.50	61.00
Total Cost (for system) per Bus	376.92	20.33
Total Cost (for system) per Mile	**0.02**	**0.00**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost	4,109.26	0.00
Labor Hours	38.8	0.0
Average Labor Cost	1,940.00	0.00
Total Cost (for system)	6,049.26	0.00
Total Cost (for system) per Bus	1,008.21	0.00
Total Cost (for system) per Mile	**0.06**	**0.00**
Electric Propulsion Repairs (ATA VMRS 46)		
Parts Cost	0.00	0.00
Labor Hours	0.0	20.9
Average Labor Cost	0.00	1,046.50
Total Cost (for system)	0.00	1,046.50
Total Cost (for system) per Bus	0.00	348.83
Total Cost (for system) per Mile	**0.00**	**0.04**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Buses	Fuel Cell Buses
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost	79.04	235.32
Labor Hours	11.4	3.0
Average Labor Cost	570.00	150.00
Total Cost (for system)	649.04	385.32
Total Cost (for system) per Bus	108.17	128.44
Total Cost (for system) per Mile	**0.01**	**0.01**
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost	448.42	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	448.42	0.00
Total Cost (for system) per Bus	74.74	0.00
Total Cost (for system) per Mile	**0.00**	**0.00**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost	803.23	0.00
Labor Hours	40.5	0.0
Average Labor Cost	2,025.00	0.00
Total Cost (for system)	2,828.23	0.00
Total Cost (for system) per Bus	471.37	0.00
Total Cost (for system) per Mile	**0.03**	**0.00**
Hydraulic System Repairs (ATA VMRS 65)		
Parts Cost	0.00	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00
Total Cost (for system) per Mile	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)		
Parts Cost	44.87	0.00
Labor Hours	1.6	0.0
Average Labor Cost	77.50	0.00
Total Cost (for system)	122.37	0.00
Total Cost (for system) per Bus	20.40	0.00
Total Cost (for system) per Mile	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Buses	Fuel Cell Buses
Brake System Repairs (ATA VMRS 13)		
Parts Cost	670.69	0.00
Labor Hours	5.0	0.0
Average Labor Cost	250.00	0.00
Total Cost (for system)	920.69	0.00
Total Cost (for system) per Bus	153.45	0.00
Total Cost (for system) per Mile	**0.01**	**0.00**
Transmission Repairs (ATA VMRS 27)		
Parts Cost	81.69	0.00
Labor Hours	0.3	2.0
Average Labor Cost	12.50	100.00
Total Cost (for system)	94.19	100.00
Total Cost (for system) per Bus	15.70	33.33
Total Cost (for system) per Mile	**0.00**	**0.00**
Inspections Only – No Parts Replacements (101)		
Parts Cost	0.00	0.00
Labor Hours	160.7	79.5
Average Labor Cost	8,032.50	3,975.00
Total Cost (for system)	8,032.50	3,975.00
Total Cost (for system) per Bus	1,338.75	1,325.00
Total Cost (for system) per Mile	**0.08**	**0.15**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost	6,626.72	3,777.83
Labor Hours	93.1	132.0
Average Labor Cost	4,656.00	6,600.50
Total Cost (for system)	11,282.72	10,378.33
Total Cost (for system) per Bus	1,880.45	3,459.44
Total Cost (for system) per Mile	**0.11**	**0.38**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost	88.77	0.00
Labor Hours	2.4	0.1
Average Labor Cost	119.00	5.00
Total Cost (for system)	207.77	5.00
Total Cost (for system) per Bus	34.63	1.67
Total Cost (for system) per Mile	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Buses	Fuel Cell Buses
Lighting System Repairs (ATA VMRS 34)		
Parts Cost	117.33	114.50
Labor Hours	3.3	1.6
Average Labor Cost	162.50	80.50
Total Cost (for system)	279.83	195.00
Total Cost (for system) per Bus	46.64	65.00
Total Cost (for system) per Mile	**0.00**	**0.01**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost	742.56	0.00
Labor Hours	30.9	0.0
Average Labor Cost	1,544.00	0.00
Total Cost (for system)	2,286.56	0.00
Total Cost (for system) per Bus	381.09	0.00
Total Cost (for system) per Mile	**0.02**	**0.00**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost	0.00	0.00
Labor Hours	7.0	0.0
Average Labor Cost	347.50	0.00
Total Cost (for system)	347.50	0.00
Total Cost (for system) per Bus	57.92	0.00
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: Fleet Summary Statistics – SI Units

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

Fleet Operations and Economics

	Diesel Buses	Fuel Cell Buses
Number of Vehicles	6	3
Period Used for Fuel and Oil Op Analysis	4/06-11/06	4/06-11/06
Total Number of Months in Period	8	8
Fuel and Oil Analysis Base Fleet Kilometers	N/A	43,548
Period Used for Maintenance Op Analysis	4/06-11/06	4/06-11/06
Total Number of Months in Period	8	8
Maintenance Analysis Base Fleet Kilometers	165,333	43,548
Average Monthly Kilometers per Vehicle	3,444	1,815
Availability	N/A	77%
Fleet Fuel Usage in Diesel L/H2 kg	N/A	4,919
Roadcalls	23	35
Kilometers between roadcalls (KBRC)	7,188	1,244
Propulsion Roadcalls	12	22
Propulsion KBRC	13,778	1,979
Fleet kg Hydrogen/100 km		11.30
Representative Fleet MPG (L/100 km)	N/A	
Hydrogen Cost per kg		8.00
Diesel Cost per Liter	0.61	
Fuel Cost per Kilometer	**0.32**	**0.90**
Total Scheduled Repair Cost per Kilometer	0.08	0.23
Total Unscheduled Repair Cost per Kilometer	0.14	0.14
Total Maintenance Cost per Kilometer	**0.22**	**0.37**
Total Operating Cost per Kilometer	**0.54**	**1.27**

Maintenance Costs

	Diesel Buses	Fuel Cell Buses
Fleet Kilometers	165,333	43,548
Total Parts Cost	14,646.48	4,127.65
Total Labor Hours	431.3	240.4
Average Labor Cost (@ $50.00 per hour)	21,565.00	12,020.00
Total Maintenance Cost	36,211.48	16,147.65
Total Maintenance Cost per Bus	6,035.25	5,382.55
Total Maintenance Cost per Kilometer	**0.22**	**0.37**

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

This evaluation includes three prototype fuel cell-powered transit buses operating at AC Transit in Oakland, California, and six baseline diesel buses similar in design to the fuel cell buses. This report describes the equipment used and provides early experience details, lessons learned, and results for the operation of the buses and supporting hydrogen fueling station.

15. SUBJECT TERMS

hydrogen infrastructure; AC Transit; fuel cell bus; fuel cell transit bus; hydrogen technology validation

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