VI.D.2 Technology Validation: Fuel Cell Bus Evaluations

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Projected End Date: Projected continuation and direction determined annually by DOE

Objectives

- Determine the status of fuel cell bus (FCB) technologies in transit applications by evaluating them in real-world service.
- Coordinate with the Federal Transit Administration (FTA) and international FCB demonstration programs to harmonize data collection methods and enable the comparison of a wider set of vehicles.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section of the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development, and Demonstration Plan*:*

(A) Lack of fuel cell vehicle performance and durability data

(C) Lack of H_2 fueling infrastructure performance and availability data

(D) Maintenance and training facilities

Contribution to Achievement of DOE Technology Validation Technical Targets

- **Milestone 2: Demonstrate fuel cell vehicles that achieve 50% higher fuel economy than gasoline vehicles**. We are comparing nine heavy-duty fuel cell vehicles of various configurations to baseline diesel or compressed natural gas (CNG) vehicles. Results for these evaluations have shown:
  – Non-hybrid FCBs have a 12% lower fuel economy compared to diesel buses.
  – Hybrid FCBs have a 56% higher fuel economy compared to diesel buses and a 149% higher fuel economy compared to CNG buses.
  – The hybrid hydrogen internal combustion engine (HHICE) bus has a 46% higher fuel economy than CNG buses.
- **Milestone 5: Operate fuel cell vehicle fleets to determine if 1,000-hour fuel cell durability, using fuel cell degradation data, was achieved by industry.** In-service testing on the three non-hybrid fuel cell buses for 17 months resulted in 1,109 hours of operation for the highest mileage bus. Fuel cell degradation data have been obtained from the buses and are being analyzed to determine if the estimated time to a 10% voltage degradation meets the 1,000-hour target in transit applications.
- **Milestone 7: Fuel cell vehicles demonstrate the ability to achieve a 250-mile range without impacting the passenger cargo compartment.** Testing of three 40-foot, non-hybrid demonstration buses has resulted in a range of around 140 miles. Hybrid FCBs have achieved a range over 250 miles. There are no major issues with lost cargo/passenger space on transit buses because the tanks are typically mounted on the roof, however the added weight of the system limits the number of standing passengers allowed on the buses.

Accomplishments

- Collected, analyzed, and reported 17 months of performance and operational data on three full-size, non-hybrid FCBs in revenue service in the United States.
- Collected, analyzed, and reported up to 11 months of performance and operational data on four full-size, hybrid FCBs and one HHICE bus in revenue service in the United States.
- Drafted a list of performance data for data exchange between international FCB demonstration partners.

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Introduction

The transit industry has become an excellent "test-bed" for developing and optimizing advanced transportation technologies. Demonstrations of FCBs are being conducted in transit applications all over the world. Although progress has been made, more work is needed to improve reliability and durability of fuel cell systems to meet the needs of transit agencies.

Demonstration programs are necessary to validate the performance of the current generation of fuel cell systems. Lessons learned will help assess the status of FCB technology and determine issues that require further development. Early prototype FCBs have demonstrated improved performance characteristics–faster acceleration, lower noise, and no tailpipe emissions–over conventional buses in transit applications. Barriers to the use of fuel cells in transportation applications need to be surmounted, however, before these technologies can be commercialized. Future evaluations should help address these issues, which include extending the life of fuel cells, improving reliability and durability of the systems, and lowering vehicle and infrastructure costs.

Coordinating with demonstration programs worldwide is important for comparing data from a larger statistical set of vehicles and leveraging resources without duplicating efforts. The progress made in developing fuel cell propulsion systems for buses can also carry over to other applications, including light-duty passenger vehicles.

Approach

Researchers at the National Renewable Energy Laboratory (NREL) and Battelle have developed an evaluation protocol to provide:

- Comprehensive, unbiased evaluation results of advanced technology vehicle development and operations.
- Evaluations of hydrogen infrastructure development and operation.
- Descriptions of facility modifications required for the safe operation of FCBs.
- Detailed results on fuel cell systems for buses and the requisite hydrogen infrastructure to complement the light-duty demonstrations and further DOE goals.

The evaluation protocol includes two levels of data: operation and maintenance data on the bus and infrastructure, and more detailed data on the fuel cell, system, and components. The first set of data is considered non-sensitive and is obtained mainly from the transit fleet. The analysis, which consists of economic, technical, and safety factors, focuses on performance and use, including progress over time and experience with vehicle systems and supporting infrastructure.

The detailed data are collected with cooperation from the bus/FC system manufacturers and are considered highly sensitive. Results will include aggregate data products that prevent identification of each manufacturer's specific data. NREL has recently begun to collect this data, and will publish aggregate results when enough data is available.

Results

Bus Evaluations

During FY 2007, NREL collected data from four FCB demonstrations in the United States:

- Santa Clara Valley Transportation Authority (VTA) in San Jose, CA, and SamTrans in San Carlos, CA.
- Alameda-Contra Costa Transit District (AC Transit) in Oakland, CA.
- SunLine Transit Agency in Thousand Palms, CA.
- Hickam Air Force Base (AFB) in Honolulu, HI.

NREL has published detailed reports on three of these demonstrations, including a final report on VTA and interim reports for both SunLine and AC Transit. Data collection for the remaining project (Hickam AFB) is just getting underway and results will be available in the coming year. A summary of selected results from each project follows.

Santa Clara Valley Transportation Authority

VTA has been operating three FCBs in service since March 2005. The buses were manufactured by Gillig Corporation. They have non-hybrid, fuel cell systems developed by Ballard Power Systems. NREL collected performance and operational data for the three FCBs and five standard diesel buses in the same service (to provide a baseline for comparison). NREL completed the analysis and published the final results, which included 17 months of in-service data (March 2005 through July 2006). Table 1 summarizes a portion of the data results for the buses at VTA.

Bus usage is an indicator of reliability and availability for bus service. During the evaluation

TABLE 1. Summary Data Results on VTA

	FCB	Diesel
Number of buses	3	5
Total fleet miles	40,208	360,447
Average miles per month	809	4,335
Total FC hours	3,219	--
Fuel economy (mi/diesel equivalent gal)	3.52	3.98
Average speed (mph)	12.6	14.5
Availability	58%	85%

period, the FCBs were operated for over 40,000 miles in service, for an average of 809 miles per month. This is still much less than the diesel buses. VTA restricted the FCBs in several ways to allow for potential service interruptions if a bus needed maintenance or was scheduled for an event. These restrictions included weekday peak-hour operation, extra service (placed between regularly scheduled buses on a route), and operation of only two of the buses with one kept as a spare. The diesel buses operate on all routes from a depot, seven days a week. The restrictions on the FCBs contributed to the lower mileage accumulation in comparison to the diesel buses.

Figure 1 shows average monthly energy equivalent fuel economies throughout the evaluation period for the fuel cell and diesel buses. The fuel cell buses averaged 3.12 miles per kg of hydrogen, which translates to 3.52 miles per diesel equivalent gallons (mpg). The diesel buses had a fuel economy of 3.98 mpg. With diesel as the baseline, the fuel cell buses had a fuel economy that was 12% lower on an energy equivalent basis. These results show a need for hybridization in order to maximize the benefits of electric drive technology and to meet the DOE target of a 50% increase in fuel economy.

The average cost of hydrogen during the evaluation period was $9.06 per kg of hydrogen and the average cost of diesel fuel was $2.07 per gallon. These average fuel costs translate to a fuel cost per mile of $2.91 for the fuel cell buses and $0.52 per mile for the diesel buses.

Availability was measured by the number of days a bus might be scheduled for service and the number of days it was unavailable for service due to maintenance issues. During the evaluation period, the diesel buses had an availability rate of 85%. VTA's goal is 80% for diesel buses. During the evaluation period, the fuel cell buses had an average availability rate of 58% for each weekday. Based on VTA's planned usage of the fuel cell buses, the availability goal was 67%.

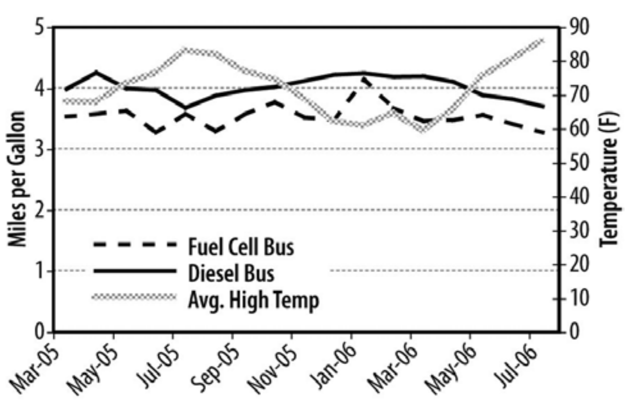

FIGURE 1. Monthly Fuel Economy (Diesel Equivalent), VTA

SunLine Transit Agency

SunLine has been operating one prototype fuel cell bus and one prototype HHICE bus in service. The fuel cell bus was manufactured by Van Hool and ISE Corp. It features an electric-hybrid drive system with a UTC Power fuel cell system and ZEBRA batteries for energy storage. The HHICE bus from New Flyer has essentially the same electric-hybrid drive system from ISE Corp., but with ultracapacitors for energy storage and a Ford V10 Triton engine customized to operate on hydrogen fuel. NREL collected operational and performance data on these two buses in comparison to five new CNG buses in the same operation. A preliminary report outlining the early experience and first 11 months of data (January 2006 through November 2006) was published in early 2007. Table 2 summarizes a selection of the results.

During the evaluation period, SunLine operated the FCB over 19,000 miles and the HHICE bus over 23,000 miles. Using the CNG buses as the baseline, the fuel cell bus had average monthly mileage 40% of CNG operation and the HHICE bus had average monthly mileage 50% of CNG operation.

Figure 2 shows the average monthly fuel economies for each of the three study groups of buses. The average fuel economy for the fuel cell bus fluctuated during May through September because of the low number of fuelings and limited bus usage during those months. Using the CNG buses as the baseline, the fuel cell bus had a fuel economy 2.5 times higher than the CNG buses and the HHICE bus had a fuel economy 46% higher than the CNG buses. The fuel cell bus had a fuel economy 71% higher than the HHICE bus.

SunLine has an availability goal of 85% for all buses. The CNG buses essentially met this goal; however, it should be noted that one CNG bus had availability at 63% and the other CNG buses were above the availability target. The HHICE bus was at or above the availability target except for July through August 2006.

TABLE 2. Summary Data Results on SunLine

	FCB	HHICE	CNG
Number of buses	1	1	5
Total fleet miles	19,208	23,661	108,540
Average miles per month	1,746	2,162	4,342
Total FC hours	1,345	—	—
Fuel economy (mi/diesel equivalent gal)	8.23	4.85	3.32
Average speed (mph)	13	13	13.2
Availability	61%	80%	86%

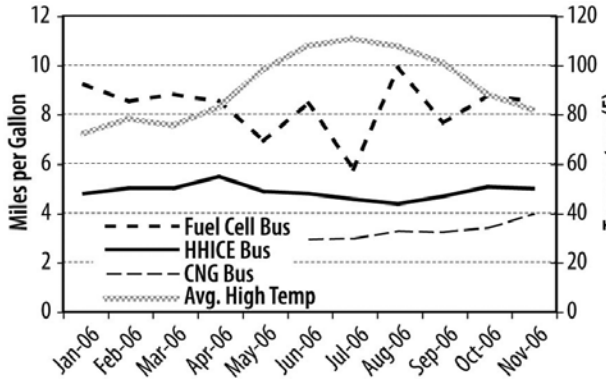

FIGURE 2. Monthly Fuel Economy (Diesel Equivalent), SunLine

During this time, the HHICE bus was out of service because of a lack of hydrogen availability due to the installation of a new reformer unit. The fuel cell bus was much lower than the availability target during May through September 2006 because of problems with the air conditioning and the fuel cell systems. When the air conditioning and fuel cell systems were operating properly, the availability was generally close to the target.

AC Transit

AC Transit has been operating three fuel cell buses since March 2006. The fuel cell buses were manufactured by Van Hool and ISE Corp. They feature electric-hybrid drive systems with UTC Power fuel cell power systems and ZEBRA batteries for energy storage. The agency procured the buses to meet the demonstration requirements under the California Air Resources Board Transit Bus Fleet Rules. (Note: the FCB at SunLine was included in this procurement and is essentially identical to the buses at AC Transit.)

NREL collected operational and performance data on these buses in comparison to six similar Van Hool diesel buses in the same operation. A preliminary report outlining the early experience and first eight months data (April 2006 through November 2006) was published in early 2007. Table 3 summarizes a selection of the results.

AC Transit decided to place only two of the three fuel cell buses into service on any given weekday to allow for maintenance, training, and special events. 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 timeframe. Overall availability for the fuel cell buses was 77%.

TABLE 3. Summary Data Results on AC Transit

	FCB	Diesel
Number of buses	3	6
Total fleet miles	27,065	102,755
Average miles per month	1,128	2,141
Total FC hours	2,338	--
Fuel economy (mi/diesel equivalent gal)	6.22	4.46
Average speed (mph)	11.6	N/A
Availability	77%	85%

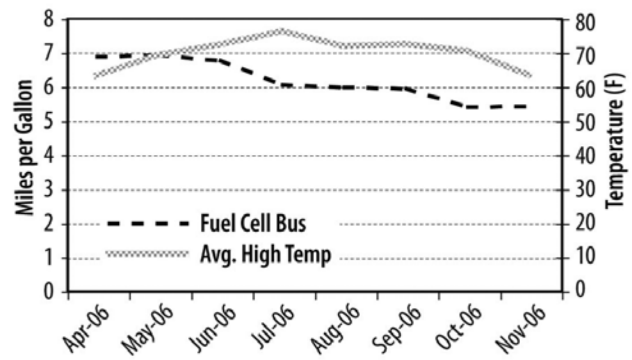

FIGURE 3. Monthly Fuel Economy (Diesel Equivalent), AC Transit

Monthly average fuel economy for the fuel cell buses is shown in Figure 3. 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 was 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 the diesel buses.

The operating cost for hydrogen production and dispensing for AC Transit is currently estimated at $8 per kg. This excludes capital expenses and was generated using early data (not optimized operation) and conservative maintenance and operating estimates. Full analysis using the H2A tool would be necessary to generate a hydrogen cost estimate comparable to research program production targets. This equates to a cost for the fuel cell buses of $1.45 per mile. The average diesel fuel cost per gallon during the evaluation period was $2.30 per gallon. If the 4.00 mpg diesel average fuel economy is used, this indicates a $0.58 per mile cost.

International FCB Coordination

NREL continues to work with international groups to collaborate among FCB demonstrations worldwide. A core group of agencies–NREL, FTA, the Electric Drive Transportation Association, the European Commission, and the Flemish Institute for Technological Studies–coordinated the 4th International Fuel Cell Bus Workshop in Yokohama, Japan, in October 2006.

The goals of the workshop were to

- Enhance information sharing on FCB demonstrations worldwide.
- Develop a standard set of data elements on the performance of FCBs and hydrogen infrastructure to collect and share.
- Investigate the potential for further collaboration and coordination of future FCB demonstrations.

The attendees were split into two groups for the breakout discussion on data sharing. Progress made during the discussion included:

- Determined which data items are collected by all represented projects and could be shared.
- Established who from each demo would see any shared data and how these data would be used.
- Agreed that a 'membership' may be necessary for participation. The group will establish a set of rules for use of the data and an agreement (memorandum of understanding or something similar) that will need to be signed by all participants prior to becoming a member.
- Set a tentative date and location for the next workshop: June 2008 in Reykjavik, Iceland (in conjunction with a HyFLEET CUTE meeting).

Conclusions and Future Directions

Fuel cell propulsion systems, such as those used in the demonstration buses, are prototypes in the early stages of technological development. These evaluations are helping to build a base of vehicle and infrastructure data that will facilitate understanding and determine future resource needs. Results from these demonstrations show that there are many challenges to overcome and more data are needed to determine the status. Remaining challenges include:

- Costs of purchasing, operating, and maintaining buses and infrastructure.
- Standardized hydrogen building codes.
- Durability/reliability of the fuel cell systems and other components.
- Fully trained transit personnel to maintain all aspects of the buses.

Future work includes:

- Collect, analyze, and report on performance data of hydrogen-fueled vehicles in service at the following sites:
  - Hickam Air Force Base
  - AC Transit District
  - SunLine
  - Connecticut Transit
  - Additional sites as funding allows
- Investigate reliability, durability, and life cycle of FCBs as a part of ongoing evaluations; these efforts complement the DOE light-duty FCV demonstrations.
- Coordinate with FTA to ensure harmonized data collection efforts for the National Fuel Cell Bus Program.
- Coordinate with FTA to plan the 5th International Fuel Cell Bus Workshop in 2008.

FY 2007 Publications/Presentations

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

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

3. Eudy, L., Quinn, T. (2006). *Fuel Cell Bus Evaluation at Hickam AFB: Status Report*. Internal report to DOE, Sept.

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

5. Eudy, L. (2006). International FCB Working Group: Historical Overview; U.S. FCB Update; DOE Technology Validation Data Collection and Analysis Methodology. All presented at the 4th International Fuel Cell Bus Workshop, Yokohama, Japan, Oct.

6. Eudy, L. (2006). Harmonization and Sharing of Data from International Fuel Cell Bus Demonstrations. Presented at the 2006 Fuel Cell Seminar, Honolulu, HI, Oct.

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

8. Eudy, L. DOE/NREL (2007). Fuel Cell Bus Evaluation. Presented at the 86th Annual Transportation Research Board Meeting, Washington, DC, Jan.

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

10. Chandler, K., Eudy, L. (2007). *Alameda-Contra Costa Transit District, Fuel Cell Transit Buses: Preliminary Evaluation Results*, NREL/TP-540-41041, NREL, Golden, CO, March.

11. Eudy, L. (2007). Preliminary Results from FCB Evaluations. Presented at American Public Transportation Association Bus and Paratransit Conference, Nashville, TN, May.

12. Eudy, L. (2007). Technology Validation: Fuel Cell Bus Evaluations. Presented at the 2007 Annual Merit Review, Arlington, VA, May.