

VIII.8 Technology Validation: Fuel Cell Bus Evaluations

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natural gas (CNG) vehicles. Results for these first-generation evaluations have shown:

- Non-hybrid FCBs have a 12% lower fuel economy compared to diesel buses.
- Hybrid FCBs have demonstrated a 71% higher fuel economy compared to diesel buses and a 141% higher fuel economy compared to CNG buses.

- **Milestone 8: Fuel cell vehicles demonstrate the ability to achieve a 250-mile range without impacting the passenger cargo compartment.** Based on in-service fuel economies between 5 and 7 miles per kilogram, hybrid FCBs can achieve a range between 250 and 350 miles per fill. This efficiency depends on duty-cycle. 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.

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) on the data collection for the National Fuel Cell Bus Program and international work groups 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 H₂ 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, first-generation fuel cell vehicles of various configurations to baseline diesel or compressed

Accomplishments

- Collected, analyzed, and reported up to 27 months of performance and operational data on five full-size hybrid FCBs in revenue service in the United States.
- Began data collection on next-generation fuel cell system in revenue service.



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 organizations 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. We need to surmount barriers to the use of fuel cells in transportation applications, however, before these technologies can be commercialized. Future evaluations should help address these barriers,

which include extending the life of fuel cells, improving reliability and durability of the systems, and lowering vehicle and infrastructure costs.

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/fuel cell system manufacturers and are considered highly sensitive. Results will include aggregate data products that protect each manufacturer’s specific data. NREL has begun to collect this data and will publish aggregate results when enough data are available.

Results

Bus Evaluations

During Fiscal Year 2009, NREL collected data from three FCB demonstrations in the United States:

- Alameda-Contra Costa Transit District (AC Transit) in Oakland, CA.
- SunLine Transit Agency in Thousand Palms, CA
- Connecticut Transit (CTTRANSIT) in Hartford, CT

NREL has published detailed reports on all three demonstrations. A summary of selected results from each project follows.

AC Transit

AC Transit has operated its three FCBs since March 2006. The FCBs 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 FCBs at SunLine and CTTRANSIT were included in this procurement and are 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. Three reports outlining the early experience and data results were published in 2007 and 2008. The third report (July 2008) completed the evaluation of the first-generation FCBs at AC Transit planned under DOE funding. NREL has continued to evaluate these buses with new fuel cell systems under FTA funding. The data presented in this report include the more recent data under the FTA program. AC Transit has ordered 12 more next-generation FCBs to be delivered in fall 2009. These buses will be evaluated under DOE funding (if available). Table 1 summarizes a selection of the most recent results.

TABLE 1. Summary Data Results on AC Transit

| | FCB | Diesel |
|--|----------------|---------------|
| Number of buses | 3 | 6 |
| Data period | ~11/07 – 10/08 | 1/07-12/07 |
| Total fleet miles | 49,600 | 266,514 |
| Average miles per month | 1,837 | 3,702 |
| Total fuel cell hours | 4,957 | — |
| Fuel economy (mi./diesel equivalent gal) | 7.33 | 4.2 |
| Average speed (mph) | 10.1 | not available |
| Availability | 61% | 85% |
| Fueling cost (\$/mi.) | 1.23 | 0.55 |

AC Transit began operating its three FCBs in March 2006. At that time, the agency scheduled two buses for weekday service with the third kept as a spare to allow for maintenance, training, and special events. In November 2007, AC Transit began accelerated testing of the buses under the FTA’s National Fuel Cell Bus Program. At that time, UTC Power installed new fuel cell systems in the buses that were expected to perform much better with respect to the number of operating hours than the previous version. To test this, AC Transit began operating each bus for up to 16 hours per day including some weekend service. During the evaluation period, the

FCBs operated more than 49,000 miles and accumulated nearly 5,000 total fuel cell system hours.

The overall availability of the buses has generally been lower than AC Transit's fleet goal of 85%. This lower availability has primarily been because of issues with the traction batteries. The issues include problems with matching the state-of-charge (SOC) among the three traction batteries, the software to manage this SOC, and the interface between the propulsion system software and traction battery software. The manufacturers continue to work on these issues to support maximum operation of the FCBs; however, it continues to be the major obstacle to the accelerated testing activity.

Monthly average fuel economy for the FCBs is shown in Figure 1. The FCBs averaged 6.49 miles per kg of hydrogen for the evaluation period, which equates to 7.33 miles per diesel gallon equivalent. The average fuel consumption for the diesel buses was 4.2 mpg, which indicates that the FCBs have an average fuel economy 75% 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. This equates to a cost for the FCBs of \$1.23 per mile. The average diesel fuel cost per gallon during the evaluation period was \$2.29 per gallon, which equates to a cost of \$0.55 per mile.

SunLine Transit Agency

SunLine has been operating one prototype FCB in service since January 2006. The FCB is essentially the same as the buses at AC Transit. NREL collected operational and performance data on the bus in comparison to five new CNG buses in the same operation. Three reports have been published outlining the early experience and data results from the first

generation fuel cell system. In April 2008, a new version fuel cell system was installed. A fourth report was published in early 2009 that outlined the data results on the new fuel cell system. Table 2 summarizes a selection of the results.

TABLE 2. Summary Data Results on SunLine

| | FCB | CNG |
|--|--------------|---------|
| Number of buses | 1 | 5 |
| Data period | 4/08 – 10/08 | |
| Total fleet miles | 11,461 | 159,150 |
| Average miles per month | 1,694 | 4,547 |
| Total fuel cell hours | 885 | -- |
| Fuel economy (mi./diesel equivalent gal) | 8.19 | 3.16 |
| Average speed (mph) | 13 | 13.2 |
| Availability | 76% | 86% |
| Fueling cost (\$/mi.) | 1.10 | 0.61 |

Since the installation of the new fuel cell system through October 2008, SunLine operated the FCB more than 11,000 miles. Using the CNG buses as the baseline, the FCB's average monthly mileage was about one third that of the CNG operation.

Figure 2 shows the average monthly fuel economies for each of the study groups of buses. The average fuel economy for the FCB was fairly constant during this time frame. Using the CNG buses as the baseline, the FCBs had a fuel economy more than 2.5 times higher than the CNG buses. SunLine estimates that the best steady-state operating point for its reformer would result in an average hydrogen cost of around \$8 per kilogram. (Actual cost varies based on current natural gas cost and station load.) SunLine paid \$1.72 per gasoline gallon equivalent for CNG during the data-collection period.

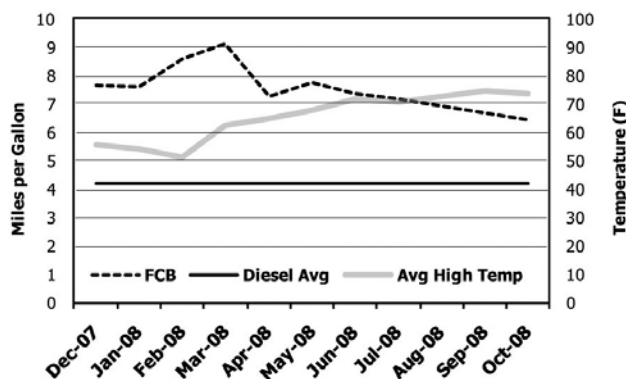


FIGURE 1. Monthly Fuel Economy (diesel equivalent), AC Transit

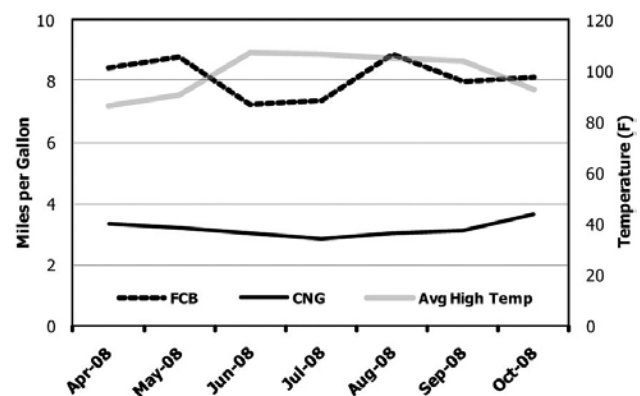


FIGURE 2. Monthly Fuel Economy (diesel equivalent), SunLine

The fuel costs per mile were \$1.10 for the FCB and \$0.61 for the CNG buses.

SunLine has an availability goal of 85% for all buses. The CNG buses exceeded this goal at 86% availability. The FCB achieved an availability of 76% during this time period. The FCB was available at or near the target six out of the seven months including two months at 100% availability. This is an improvement over what was previously reported (66%).

CTTRANSIT

CTTRANSIT began operating its FCB in revenue service beginning in March 2007. The FCB is essentially the same system as the buses at AC Transit and SunLine. This demonstration site is the first cold-weather location for the bus.

NREL collected operational and performance data on the bus in comparison to three of CTTRANSIT's newest diesel buses, which are 40-foot New Flyer buses. The FCB is currently being operated on a downtown circulator route, which involves low-speed, stop-and-go driving. The diesel buses are operated on all of CTTRANSIT's routes, which results in a faster average speed. Table 3 summarizes a selection of the results.

TABLE 3. Summary Data Results on CTTRANSIT

| | FCB | Diesel |
|--|-------------|---------|
| Number of buses | 1 | 3 |
| Data period | 1/08 – 2/09 | |
| Total fleet miles | 24,127 | 137,127 |
| Average miles per month | 1,723 | 3,265 |
| Total fuel cell hours | 3,544 | — |
| Fuel economy (mi./diesel equivalent gal) | 5.34 | 3.66 |
| Average speed (mph) | 6.8 | 12 |
| Availability | 77% | 85% |
| Fueling cost (\$/mi.) | 1.12 | 0.74 |

CTTRANSIT has operated its FCB since April 2007. In January 2008 the bus had a new version fuel cell system installed, similar to that of the other two agencies. At that time, CTTRANSIT began accelerated operation of the bus, scheduling service for two shifts per day and some weekend service. During the evaluation period, the FCB operated 24,127 miles and accumulated 3,544 fuel cell system hours. Overall availability for the FCB was 77%, which is an improvement from what was previously reported (53%). CTTRANSIT's goal for availability for their fleet is 85%.

Monthly average fuel economy for the FCBs and diesel buses is shown in Figure 3. The FCB averaged

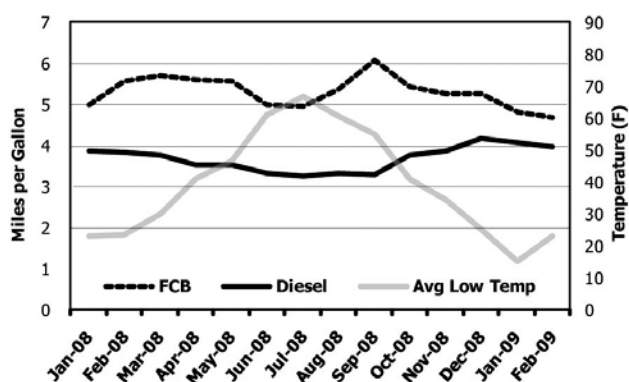


FIGURE 3. Monthly Fuel Economy (diesel equivalent), CTTRANSIT

4.7 miles per kg of hydrogen for the evaluation period, which equates to 5.3 miles per diesel gallon equivalent. The diesel buses averaged 3.66 mpg. Using the diesel buses as a baseline, the FCB has an average fuel economy 46% higher.

CTTRANSIT fuels its FCB at the UTC Power hydrogen station. The cost for hydrogen for CTTRANSIT is currently \$5.29 per kg. This equates to a cost for the FCBs of \$1.12 per mile. The average diesel fuel cost per gallon during the evaluation period was \$2.70 per gallon, which equates to a fueling cost of \$0.74 per mile.

The fuel economy for transit buses is highly dependent on the duty-cycle. Figure 4 illustrates this by comparing each fleet result side-by-side. The same design FCB achieves different results under varied conditions. This bus gets the lowest fuel economy in the low speed (6.8 mph average speed), high idle time, and stop-and-go duty cycle at CTTRANSIT. The bus in service at SunLine achieves the highest fuel economy, where the duty cycle includes high speed (14 mph average speed) with long distances between stops and little idle time.

FTA Data Collection/International Coordination

FTA has funded NREL to evaluate each of the demonstrations under its National Fuel Cell Bus Program. The evaluations follow the same protocol as the DOE-funded evaluations. This will provide similar data and analysis on a wider array of fuel cell systems in buses, which will aid in determining the progress of the technology toward market readiness. Through the FTA funding NREL also continues to work with international groups to collaborate among FCB demonstrations worldwide. A core group of agencies – NREL, FTA, the Electric Drive Transportation Association, and the Northeast Advanced Vehicle Consortium – coordinated the 6th International Fuel Cell Bus Workshop in Vancouver, Canada, in June 2009.

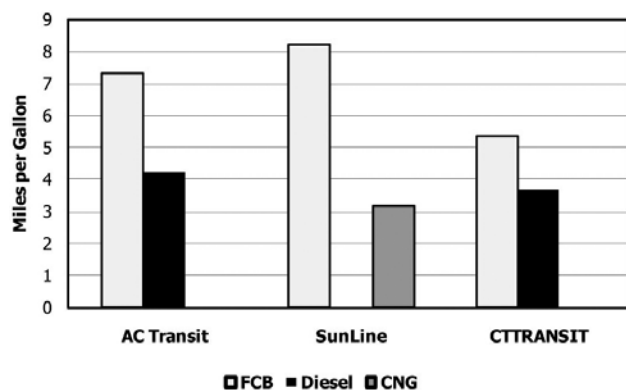


FIGURE 4. Fuel Economy Comparison by Fleet (diesel equivalent)

Conclusions and Future Directions

First-generation fuel cell propulsion systems in buses are showing progress, although they are considered prototypes in the early stages of technological development. Manufacturers have learned from the results of these first-generation demonstrations and are incorporating design improvements into the next-generation systems. There are still challenges to overcome, and more data are needed on these new systems just being introduced. Remaining challenges include:

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

Future work includes:

- Collecting, analyzing, and reporting on performance data for next-generation hydrogen-fueled vehicles in service at the following sites:
 - Bay Area FCB Demonstration led by AC Transit
 - Connecticut Transit
 - City of Burbank
 - Additional sites as funding allows
- Investigating reliability, durability, and life cycle of FCBs as a part of ongoing evaluations; these efforts complement the DOE light-duty fuel cell vehicle demonstrations.
- Coordinate with FTA to ensure harmonized data-collection efforts for the National Fuel Cell Bus Program.
- Coordinate with FTA to plan the 7th International Fuel Cell Bus Workshop in 2010.

FY 2009 Publications/Presentations

1. Chandler, K., Eudy, L. (2008). *Alameda-Contra Costa Transit District, Fuel Cell Transit Buses: Third Evaluation Report and Appendices*, NREL/TP-540-43545-1 & NREL/TP-540-43545-2, NREL, Golden, CO, July.
2. Eudy, L., Chandler, K. (2008). *NREL Technology Validation: Results for FCB Evaluations*. Presentation for the APTA Bus Technical, Maintenance, & Procurement Workshop and EXPO, San Diego, CA, Oct.
3. Eudy, L. (2008). *Fuel Cell Bus Evaluation Results*. Presentation for the 2008 Fuel Cell Seminar, Phoenix, AZ, Oct.
4. Eudy, L. (2008). *CTTRANSIT, Fuel Cell Transit Bus: Preliminary Evaluation Results*. NREL/TP-560-43847, NREL, Golden, CO, Oct.
5. Eudy, L. (2008). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008*. Presentation for the 2008 California Transit Association Conference, Monterey, CA, Nov.
6. Eudy, L., Chandler, K., Gikakis, C. (2008). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008*. NREL/TP-560-44133, NREL, Golden, CO, Dec.
7. Eudy, L. DOE/NREL (2009). *Fuel Cell Bus Evaluation Results*. Presented at the 88th Annual Transportation Research Board Meeting, Washington, D.C., Jan.
8. Chandler, K., Eudy, L. (2009). *SunLine Transit Agency, Fuel Cell Transit Bus: Fourth Evaluation Report and Appendices*. NREL/TP-560-44646-1, and NREL/TP-560-44646-2, NREL, Golden, CO, Jan.
9. Eudy, L. (2009). *CTTRANSIT, Fuel Cell Transit Bus: Second Evaluation Report and Appendices*. NREL/TP-560-45670-1 & NREL/TP-560-46570-2, NREL, Golden, CO, May.
10. Eudy, L. (2009). *Technology Validation: Fuel Cell Bus Evaluations*. Presented at the 2009 Annual Merit Review, Arlington, VA, May.