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National Fuel Cell Bus Program: Proterra Fuel Cell Hybrid Bus Report, Columbia Demonstration

OCTOBER 2011

FTA Report No. 0003
Federal Transit Administration

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U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

L. Eudy, NREL

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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13. ABSTRACT

This report summarizes the experience and early results from a fuel cell bus demonstration funded by the Federal Transit Administration (FTA) under the National Fuel Cell Bus Program. A team led by the Center for Transportation and the Environment and Proterra developed a new concept fuel cell hybrid bus for demonstration. The National Renewable Energy Laboratory has been tasked by FTA to evaluate the bus in service. This report documents the early development and implementation of the bus and includes a summary of the performance results at the first demonstration site—Columbia, South Carolina.

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Introduction and Background

As part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP), a team led by the Center for Transportation and the Environment (CTE) and Proterra developed a new concept fuel cell hybrid bus for demonstration. Designed as a battery-dominant, plug-in hybrid, this bus combines some of the newest technologies into a lightweight bus with zero tailpipe emissions. The National Renewable Energy Laboratory (NREL), one of the Department of Energy's (DOE) national laboratories, is evaluating this technology for FTA as part of the NFCBP. This report documents the early development and implementation of the bus and includes a summary of the performance results at the first demonstration site—Columbia, South Carolina.

National Fuel Cell Bus Program

In 2006, FTA initiated the NFCBP,[1] which supplied $49 million over 4 years in competitive, 50-50 government-industry cost share grants to facilitate the development of commercially-viable fuel cell bus technologies. This FTA program was funded as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU).[2] The objectives of the program include:

- Developing improved components and technologies for fuel cell buses, including fuel cell, energy storage, and power electronics technologies.
- Demonstrating fuel cell buses equipped with these improved components and technologies.
- Understanding the requirements of market introduction, including fuel supply, fueling infrastructure, supplier networks, maintenance, education, safety, and insurance.
- Collaborating in development of design standards for fuel cell bus technologies.

In October 2006, FTA awarded grants to three nonprofit consortia—CALSTART (Pasadena, California), the Center for Transportation and the Environment (CTE, Atlanta, Georgia), and the Northeast Advanced Vehicle Consortium (NAVC, Boston, Massachusetts). These consortia were funded to lead teams to develop and test components, conduct outreach, and demonstrate fuel cell buses in a variety of geographic locations and climates across the United States.

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[1] FTA Bus Research and Testing website, http://www.fta.dot.gov/assistance/technology/research_4578.html.

[2] www.fhwa.dot.gov/safetealu/.

A portfolio of 14 projects (managed by the 3 consortia) was competitively selected by FTA to best advance fuel cell bus commercialization, including eight planned demonstration projects. Bus demonstration projects include both evolutionary and "clean sheet" approaches and incorporate multiple electric-drive technologies and configurations, fuel cell stacks of different sizes, and various energy storage technologies. The buses being demonstrated feature components from four fuel cell power system manufacturers and various implementations of hybrid electric propulsion systems and energy storage, including batteries and ultracapacitors.

For fiscal year 2010 into 2011, an additional $13.5 million in funding was appropriated for the NFCBP. To expand the original effort with this new funding, FTA solicited project proposals from the three selected consortia covering three areas:

1. Extensions or enhancements to existing projects with existing teams
2. New development and demonstration projects
3. Outreach, education, or coordination projects

Eight new projects were selected, including four new development /demonstration projects, two component development projects, one outreach/education project, and one enhancement project for an existing demonstration.

Evaluation Activities

Data collection, analysis, and reporting of the results of the demonstrations all are high priorities for FTA. As such, FTA is collaborating with DOE and funding NREL to ensure that data are collected on all fuel cell bus demonstrations in a complete and consistent manner. FTA tasked NREL as a third-party evaluator for the fuel cell buses developed and demonstrated under the NFCBP.

Under separate funding from DOE, NREL has been evaluating fuel cell buses to help determine the status of hydrogen and fuel cell systems in transit applications. NREL uses a standard data collection and analysis protocol that was established for DOE heavy-duty vehicle evaluations more than 10 years ago. In November 2010, NREL published Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, which outlines the methodology and plans for both the FTA and DOE fuel cell bus evaluations to be performed by NREL.[3]

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[3] Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/TP-5600-49342, Nov 2010, http://www.nrel.gov/hydrogen/pdfs/49342-1.pdf

SECTION

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Project Description

CTE is one of the three non-profit consortia selected by FTA to manage projects within the NFCBP. CTE (http://www.cte.tv/) works with government, industry, and research organizations to develop and demonstrate advanced transportation technologies that are energy efficient and environmentally sustainable. In response to FTA's solicitation for the NFCBP, CTE assembled its development and demonstration team and submitted the proposal "Dual Variable Output Hybrid Fuel Cell Bus Validation Testing and Demonstration Project."

This project was considered one of the higher risk projects in the NFCBP because the manufacturer was a start-up company and the proposed fuel cell hybrid bus design incorporated numerous new technologies that never had been demonstrated in this application. This project provided FTA with an opportunity to support development of a new transit bus manufacturer and a newly-designed electric propulsion transit bus platform for fuel cells as well as all-battery-electric designs. This fuel cell plug-in hybrid bus is Proterra's first bus and a prototype designed specifically for this demonstration project.

Of the original 14 NFCBP projects, CTE was tasked with management of two: one development and demonstration project (the subject of this report) and one analysis and outreach project.[4] In the most recent round of NFCBP funding, CTE was awarded seven additional projects: four development/demonstration projects, one enhancement to the original demonstration project, one component development project, and one analysis, outreach, and coordination project.

Partners and Roles

In addition to CTE as project manager, a number of organizations make up the overall team to develop and demonstrate this bus. These partners and their respective roles are summarized below.

Manufacturer Partners

Proterra—As the primary manufacturer on the team, Proterra (www.proterra.com) leads the design and development of the bus and provides field support for the in-service demonstrations. Headquartered in Golden, Colorado, Proterra (previously known as Mobile Energy Solutions) was founded in 2004 with a goal of producing advanced technology heavy-duty vehicles that emit low or zero emissions and are domestically fueled. The company recently opened a manufacturing facility in Greenville, South Carolina.

Hydrogenics Corporation—Headquartered in Mississauga, Ontario, Hydrogenics Corporation's (www.hydrogenics.com) core business includes

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[4] "A Report on Worldwide Hydrogen Bus Demonstrations," 2002-2007, Federal Transit Administration, FTA-GA-04-7001-2009.01, March 2009, http://www.fta.dot.gov/documents/ReportOnWorldwideHydrogenBusDemonstrations_2002to2007.pdf

developing fuel cell power products such as fully-packaged power modules and electric hybrid systems. Hydrogenics supplied the fuel cell power modules and provided maintenance support during the development and demonstration of the bus.

Altairnano—Headquartered in Reno, Nevada, Altairnano (www.altairnano.com) provides advanced lithium-based energy storage solutions for a variety of applications including transportation. The energy storage system on the bus consists of Altairnano battery cells.

Demonstration Partners

Central Midlands Regional Transit Authority—CMRTA (www.gocmrta.com) provides fixed-route and demand response transportation services in and around the city of Columbia, South Carolina. In addition to operating the bus during the demonstration period, CMRTA provided parking and dedicated space for maintenance and charging of the bus at its facility.

University of South Carolina, Department of Vehicle Management & Parking Services—The University of South Carolina (www.sc.edu) campus is located in the heart of the state's capital city of Columbia. The USC Department of Vehicle Management & Parking Services (VMPS) provides shuttle services around the campus when the university is in session. During the demonstration phase of the project, VMPS operated the bus on its Green Route.

Supporting Partners

Signature Transportation Parts and Service—Established in 1999, Signature Transportation (http://signaturetransportation.net) provides technical and management services to the transit industry. As part of the project team, Signature Transportation provided maintenance and support for bus operation, assisted in planning and conducted operator training, and collected daily operation and fueling logs.

University of South Carolina, College of Engineering and Computing—Researchers from the USC College of Engineering and Computing were involved in data collection and analysis of the bus performance. The university is also part of the USC–City of Columbia Fuel Cell Collaborative that initiated development of the hydrogen fueling station.

City of Columbia—Under the USC–City of Columbia Fuel Cell Collaborative (http://www.fuelcellcollaborative.com) initiative, the City of Columbia provided land for the hydrogen fueling station and staff to operate the station and dispense hydrogen into the bus.

South Carolina Research Authority—SCRA (www.scra.org) builds and leads collaborative teams to develop and commercialize technology solutions for a variety of organizations including federal agencies and private corporations from around the world. SCRA is part of the USC–City of Columbia Fuel Cell Collaborative and led in developing the Columbia hydrogen station.

EngenuitySC—EngenuitySC (www.engenuitySC.com) is a public–private partnership focused on growing a knowledge-based economy in the Columbia area. The organization is also part of the USC–City of Columbia Fuel Cell Collaborative that initiated development of the hydrogen fueling station.

Big Fish Advertising and PR—Big Fish Advertising and PR (www.bigfishadpr.com) is a private company that specializes in marketing and public relations. As a member of the team, the company was responsible for organizing public relations events, developing the website, and creating the marketing and education materials for the project.

SECTION

3

Bus Technology Description

The prototype bus (shown in Figure 3-1) was designed from the ground up as an electric drive bus. Instead of integrating the advanced propulsion system into an existing diesel bus chassis, the team took a whole vehicle design approach. The bus features a lightweight, composite bus body with a battery dominant, plug-in hybrid propulsion system.

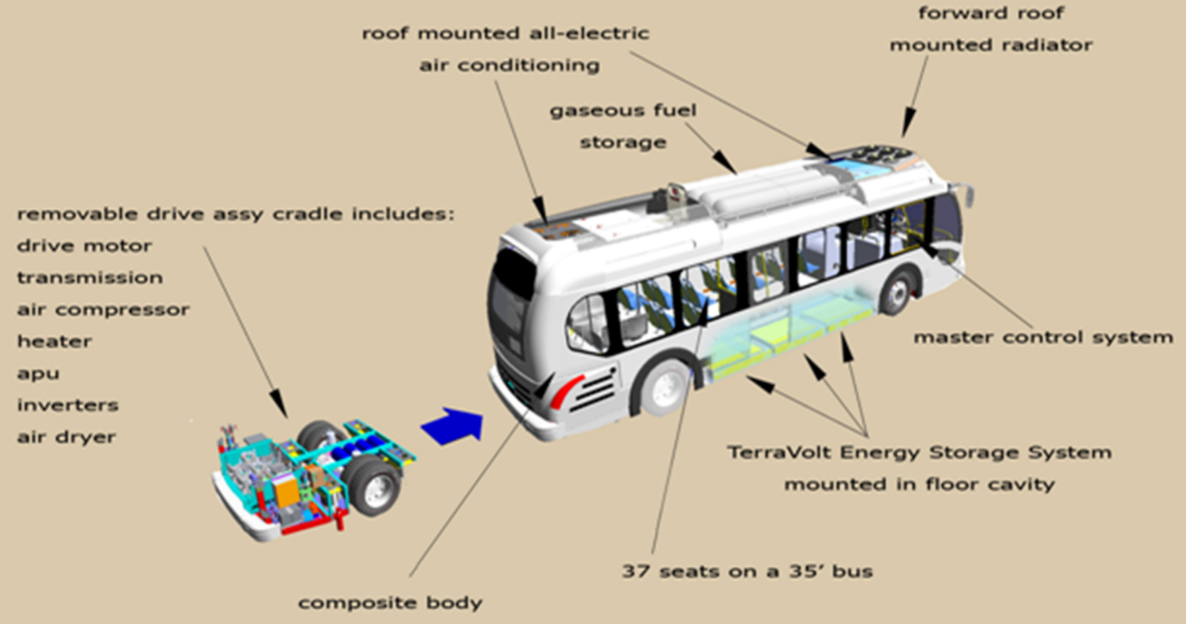
The propulsion system is basically an electric drive system (shown graphically in Figure 3-2 and described technically in Table 3-1). The TerraVolt energy storage system, consisting of advanced lithium-titanate batteries, provides the primary power source for the bus. With fully-charged batteries, the bus has an all-electric range of approximately 24 miles. During driving, regenerative braking provides some power to charge the batteries. The fuel cell system acts as a range extender (auxiliary power unit – APU), providing additional energy to keep the batteries charged. The two fuel cells are connected in parallel and can work separately or in combination to provide energy to the batteries as needed. At the end of the day, the hydrogen tanks are filled and the bus is plugged in to fully charge the batteries from the electric grid (fast charging was not used for this demonstration, but it can be used to fully charge the batteries in less than 10 minutes).

Figure 3-1

Prototype Fuel Cell Plug-in Hybrid Bus Designed for the NFCBP

Figure 3-2

Proterra Electric and Hybrid Electric Bus Propulsion System Layout



(Credit: Proterra)

Table 3-1

Proterra Bus and Propulsion System Description

Design Element	Description
Bus chassis	Proterra, FCBE-35, lightweight composite body
Length/width/height	35 ft/102 in./129 in.
GVWR/curb weight	36,000 lb/26,680 lb
Passenger capacity	37 seated (or 33 seated with two wheelchairs), 18 standees
Hybrid system	Proterra: battery-dominant plug-in hybrid (series, charge depleting)
Fuel cell	Hydrogenics: HyPM HD16, - two 16-kW PEM stacks
Energy storage	Proterra TerraVolt, Altairnano lithium-titanate, 48 23-V modules
Traction motor	UQM: PowerPhase 150, 150-kW peak power
Transmission	Klune-V
Accessories	Electrically driven
Fuel/storage	Compressed hydrogen @ 5,000 psi, 29 kg in four SCI Type III tanks

This design includes many aspects that make the bus unique. The development team saw potential advantages to these design choices.

- **Composite body:** To gain efficiency without sacrificing passenger space the team developed a lightweight bus body. At 35 ft in length, the bus is shorter than the standard 40-ft transit bus, but it is still considered a heavy-duty design and fits a similar number of passengers. By designing the body along with the propulsion system, the developers could also optimize placement of components and hardware. The composite body is described as 20 to 40 percent lighter than typical transit bus bodies.

- **Plug-in hybrid electric system:** The basic system design can be produced as a battery-only version or combined with the fuel cell system as a range extender. This gives the manufacturer more than one product that can meet zero emission requirements. Proterra has designed the hybrid control system and software using UQM's PowerPhase 150-kW traction motor (customized for Proterra). Accessories are electrically driven for both all-electric and hybrid electric configurations.
- **Dual fuel cell system:** Combining two 16-kW Hydrogenics proton exchange membrane (PEM) fuel cells (model HyPM HD16) in parallel allows the system to operate each one separately or both in combination to provide battery charge. This strategy has the potential to lengthen fuel cell system life.
- **Advanced energy storage system:** Based on tests conducted by researchers at the University of California at Davis, the project team selected lithium-titanate batteries produced by Altairnano for the energy storage system. Test results showed these batteries had better energy and power density, a wider temperature range, and an ability to take a fast charge, and they can handle more charge cycles than competing technologies. Proterra designed the traction battery strategy and battery management system for this bus design using Altairnano's battery modules.

SECTION

4

Facilities for Columbia Demonstration

This project required the use of a hydrogen fueling station located in Columbia and maintenance and charging equipment located at CMRTA.

Hydrogen Fueling Station

The bus was fueled at a hydrogen station located near downtown Columbia. The station was developed as part of an initiative to foster the growth of hydrogen and fuel-cell-related research and business opportunities in the area. The USC–City of Columbia Fuel Cell Collaborative was established in 2006 to coordinate this initiative. The Fuel Cell Collaborative comprises the University of South Carolina, the City of Columbia, SCRA, and EngenuitySC.

The station development team, led by CTE, included the Gas Technology Institute (GTI) as technical lead and Greenfield Compression as supplier of the major equipment and components. The station is designed for hydrogen delivery, compression, storage, and dispensing. Hydrogen is supplied by tube trailers that are replaced and refilled as needed. Hydrogen gas from the tube trailer is compressed and stored in three ASME tubes at up to 7,000 psi for dispensing into the bus at 5,000 psi. Total high pressure storage is 66 kg. The station was designed to be expandable, should the local need for hydrogen increase, and could incorporate renewable generation methods. Figure 4-1 shows the hydrogen dispenser, high pressure storage vessels, and tube trailer at the Columbia station. Construction began in December of 2008 and was completed on February 20, 2009.

Airgas was awarded the contract to supply hydrogen to the station. The hydrogen is produced from landfill gas in Quebec, Canada, where it is liquefied and trucked to Charlotte, North Carolina. Airgas regasifies the hydrogen and delivers it in a tube trailer to the station in Columbia. The hydrogen cost to the team is $9.93 per kg. Airgas charges a monthly equipment lease of $2,000 plus a delivery charge for replacing the tube trailer when it needs to be filled.

Figure 4-1

Aspects of Columbia Hydrogen Station, including Dispenser (left), High-pressure Storage (top right), and Tube Trailer (bottom right)

Maintenance and Charging Facilities

CMRTA provided space for maintenance, charging, and storing the bus during the demonstration. For most fuel cell bus demonstrations, permanent facilities are modified to provide a safe maintenance area for working on a hydrogen-fueled bus. Because this was a short-term demonstration, the team developed a temporary solution. The CMRTA bus wash area (pictured in Figure 4-2) was set up with a lift to facilitate staff in maintaining the bus. The area is covered but has three open sides with sufficient airflow to allow safe maintenance of the bus without special air handling and combustible gas sensing equipment. This avoided the costs of building retrofits that can be extensive depending on local code official requirements. The solution works well for southern U.S. locations such as Columbia, where the temperature rarely gets below freezing.

Figure 4-2

CMRTA Bus Wash Area Used for Maintenance Work on Hydrogen Hybrid Bus

For optimal range, the bus needs to be plugged into a charger on a routine basis. The project team installed an AeroVironment EV30-FS charger at CMRTA for this purpose. The unit has a power rating of 30 kW and is capable of providing a fast charge. Once connected to the bus, the unit establishes communication with the on-board battery management system (BMS), which then controls the power output to charge the battery system. A separate electric meter was set up at the site to measure the energy used to charge the bus. The time and total kilowatts were recorded for each charging event. Figure 4-3 includes photos of the charger, the electric meter, and the connector.

Figure 4-3

AeroVironment EV30-FS Charger Installed at CMRTA (left), Close-up View of Electric Meter (top right), and Charger Connection (bottom right)

SECTION

5

Implementation and Operations Experience

At the outset of the NFCBP, FTA created a balanced overall research portfolio by selecting projects of differing risk levels, technical approaches, applications, and project sizes. The agency felt this strategy would provide the most effective approach to advance fuel cell bus technologies. The CTE/Proterra project was considered one of the higher-risk projects in the NFCBP portfolio. Since the project began, the team has had its share of successes and difficulties in carrying out the first portion of the demonstration. This section summarizes the achievements and challenges encountered during the demonstration implementation and operations in Columbia.

Proterra – A New Transit Bus Manufacturer

Although collectively Proterra's staff had many years of experience developing hybrid electric drivetrains, the company was a newly-formed original equipment manufacturer (OEM) that had not yet produced a product. For FTA, selecting a company with no proven track record added a level of uncertainty to the project. So far, the investment has shown promise toward helping meet FTA's goals of advancing zero-emission bus technology. The funds from the NFCBP have enabled this start-up company to begin growth into an OEM that provides only clean bus technologies to the transit industry.

After building the prototype for the NFCBP, Proterra secured a contract to produce a second fuel cell hybrid bus for the City of Burbank, California. A third bus was ordered as part of a Department of Defense project in Washington State. In addition to the fuel cell hybrid bus, Proterra has further developed a battery-only bus that now is being tested in real-world service. The company has secured several additional grants from FTA to produce the quick-charge battery bus for fleets around the United States. To handle the increased production, the company recently opened a manufacturing plant in Greenville, South Carolina. This rapid growth of a new bus manufacturer specializing in clean technologies was spurred by the initial NFCBP funding.

Another high-risk aspect of the project was that it involved a brand new, ground-up bus design incorporating various advanced technologies that had never been combined into one bus. Introducing each of the new technology systems posed a challenge separately—integrating them all into one platform significantly increased the level of difficulty. Throughout the project, Proterra has experienced the usual growing pains of a new manufacturer during product development. Selecting specific components, configuring the system and software controls for communication between components, and dealing with changing parts suppliers taxed the team's capabilities and frequently resulted in schedule delays. Despite the difficulties, the team was the first of the NFCBP project teams to complete and deliver a new-design bus for demonstration.

Prototype Bus Development

Typically, new vehicle propulsion technologies for transit buses are developed and introduced in six phases:

1. **Concept development**—the process of determining concepts, market needs and strategy, and technology requirements.
2. **Technology research and development**—research into the specific needs of the propulsion and vehicle powertrain as well as integration needs.
3. **Vehicle development, design, and integration**—actual test vehicle integration and laboratory testing.
4. **Manufacturing and assembly integration**—study of component suppliers and needs for manufacturing a small number of vehicles.
5. Vehicle demonstration, testing, and preproduction—a phase typically executed in three steps:
    a. Field testing and design shakedown (1 to 2 vehicles)
    b. Full-scale demonstration and reliability testing (5 to 10 vehicles at several locations)
    c. Limited production (50 to 100 vehicles at a small number of locations)
6. **Deployment, marketing, and support**—the first fully commercially-available products.

This project takes a new design from stage 1 through stage 5a: field testing and design shakedown. Moving through these stages is an iterative process that can take a significant amount of time and resources. The manufacturer designs, develops, tests, and reconfigures the design based on the test results. Technical difficulties and setbacks are expected during these stages. For this project, the team minimized the early development into a very short timeframe (FTA NFCBP funding received in early 2007, testing at Columbia completed in 2010, and upgrades at Proterra to be completed by mid-2011).

The team experienced a number of technical problems in the design and development stage. From developing the composite bus body to combining various advanced components into one cohesive system, the team encountered various issues that had to be solved. This section summarizes some of the obstacles that the team faced during the early prototype development stage.

Composite body development—The team's first challenge was the design and build of a fully composite body to reduce the overall weight of the bus. Adding battery packs and a hydrogen fuel storage and delivery system to a bus increases weight and therefore reduces passenger capacity. The team had a goal of reducing the bus weight and size without sacrificing this capacity. The first problem arose when the original composite body manufacturer withdrew from the project. At that time, only a portion of the tooling necessary to produce the main body of the bus had been completed. To move forward with the project, the team had to scramble to find alternative solutions. Proterra had to secure additional funds to purchase the completed tooling. The remaining work was either brought in-house or moved to new partners. Through a concentrated effort, the team was able to complete the bus body; however, this delayed the project schedule.

Hybrid system development—Knowing that the design and construction of the bus body would take time, the team needed a way to configure and test the propulsion system components. A mobile development laboratory (MDL) was created using an old school bus as a temporary platform for testing the system. Proterra acquired the school bus, removed the majority of the interior seats and some of the drive system, and installed the primary hybrid system components, including the traction motor, the battery system, and the vehicle control system. The MDL allowed the manufacturer to accelerate development of the system while the bus body was being built. The goal of the testing was to identify operational issues, validate the integration, and optimize the control strategy. The testing also allowed Proterra to evaluate the efficiency and performance of the system and separate components.

The team considers the MDL an extremely valuable step that facilitated the development and resulted in important design changes for better operation and improved safety. One specific incident during testing identified a serious safety issue with the battery system. An electrolyte leak in a battery cell caused a short and then ignited. Because the battery pack design did not contain the cells, this fire spread and caused significant damage to the MDL. Investigation of the incident uncovered design flaws and resulted in a redesign of the battery management system to prevent further issues. In the new design, a BMS monitors and controls the individual batteries. Each battery module is completely enclosed to minimize damage from vibration and is insulated to prevent the possibility of shorting.

Component selection and integration—At the onset of the project, the team wanted to produce an advanced technology bus at a reasonable price. To minimize cost, Proterra selected off-the-shelf parts whenever possible. The team learned that while this strategy works for some components, it poses a problem for others. This is not unusual in the early design and development of a prototype bus—all manufacturers have encountered the challenge of combining separate components and making them work together in a system. Off-the-shelf components may be cost effective, but sometimes they cannot be made to fit into a system because of limitations such as size, power requirements, software control, or lack of adequate cooling. By the end of the first phase of development and demonstration, the team had dealt with several component integration issues involving the DC-DC converters, transmission, software controls, and fuel cells.

DC-DC converter issues—The biggest component challenge for the team has been with the DC-DC converters for the fuel cell systems. The propulsion system requires two DC-DC converters—one for each fuel cell system. The first converters shipped to Proterra were not capable of reliably supplying the required power conversion. The fuel cells supplied 16 kW, but the converters would provide only 9 kW of power to the batteries. The bus was operational with the reduced power converters, but the range was much lower than expected. The team was forced to wait while the supplier redesigned the part to meet power requirements. Throughout the development and demonstration stage, the team continued to address converter-related problems. The issues were not fully solved during the Columbia demonstration, resulting in limited bus performance and operation. Because of the dual stack configuration, the bus still is able to operate with only one fuel cell. Resolution of this converter issue is critical to getting this prototype bus back on the road in the next phase of the demonstration in Austin, Texas. FTA also has provided additional funding to support developing a replacement converter for this bus application.

Fuel cell issues—The Hydrogenics fuel cells were ordered and shipped to Proterra early in the design/development stage of the project. Hydrogenics reports that their approach for this project was to participate as a traditional supplier providing the fuel cell systems and technical support to Proterra as requested. This relationship has worked well, as reported by Hydrogenics and Proterra. The major challenge has been the DC-DC convertors and the lack of full range operation of the bus, as reported above. The next-generation HyPM HD30 product is expected to be a single 30 kW product so that only one fuel cell system would be needed for a Proterra-type bus application. As with all fuel cell power system manufacturers, Hydrogenics continues to develop and optimize its products.

Vehicle compliance/certification—The manufacturer was required to conduct a variety of tests to comply with Federal Motor Vehicle Safety Standards (FMVSS) and other regulations before this prototype bus could be operated on the road. This can be a lengthy process involving transportation of the bus to testing locations around the country. The team set an aggressive schedule for this testing to meet its obligations to FTA and the demonstration partners. This schedule left little time to deal with any unforeseen issues during the testing. Any problems with the bus could delay the process. The team also had to consider that any delays with one test could put them out of the schedule window for the next set of tests.

Demonstration Experience

Once the prototype bus was completed, the team was ready to begin the field service/design shakedown stage of development. For that step, the bus needed to be placed in the hands of a potential operator. In-service demonstrations are essential for commercializing new technologies by allowing the manufacturer to evaluate how the systems and components perform and to verify lab testing and modeling results. For these demonstrations, the transit agency becomes an active partner in the development process. The agency needs to understand this role and be prepared to aid the manufacturer as it further optimizes and improves the systems. Downtime for the test bus is expected, as the manufacturer identifies potential performance issues and continues to improve specific components as well as the overall system. For new bus designs, this phase is critical for measuring progress and determining the next steps toward commercialization.

Demonstration partner expectations—During this phase of prototype bus testing, selection of demonstration partners is important. An operator must be willing to aid the manufacturer in the development process, which is not something they are used to. It is helpful if the agency has past experience with new technology introductions and understands the nature of prototype bus development. At this point, the bus is not expected to replace a conventional bus that operates every day for up to 20 hours. As a smaller-size transit agency, CMRTA has not had the opportunity to gain experience with advanced bus technologies. The agency was excited to be part of the project but found the uncertain nature of the demonstration to be a big challenge. USC reported a good experience with the bus operation. Shuttle service drivers and passengers responded that the performance of the bus was very good. The students expressed interest in the technology and its environmental impact.

Hydrogen fueling—Providing hydrogen for fuel cell buses remains one of the biggest challenges for demonstration projects. The CTE/Proterra project was no exception. The primary difficulty was securing funding for the station. The initial design was a multi-phase effort that included on-site hydrogen production from renewable sources, storage, and dispensing. Although the team had support from the USC–City of Columbia Fuel Cell Collaborative to build the fueling station, a portion of the funding was to come from a State grant to SCRA. Due to lower-than-expected revenues in 2007, the State was forced to cut more than $80 million in planned spending, including the funding planned for the hydrogen station. This caused a delay while other funding sources were explored. Also contributing to the funding issue was that the initial bids for the station came in higher than expected. Because of these issues, the team had to reduce the scope of the station to the minimum necessary to provide hydrogen for the bus. The team secured additional funds through the SC Hydrogen Infrastructure Development Fund in late 2008, and the station was completed in early 2009.

Insurance issues—The fuel cell bus is a prototype demonstration vehicle that is titled to the team lead, CTE. To allow CMTRA and USC to operate the bus, CTE developed a leasing agreement. Because the bus did not belong to the operator, there were issues with finding a company that would insure the bus at a reasonable cost. CMRTA's current insurer was not comfortable with the prototype nature and the high replacement cost of the bus. The team had to explore other options that fit within the established budget. Another issue was that an insurer did not want to cover both operators at the same time. All these difficulties led to more delays in getting the bus in service.

Funding—There were two primary funding challenges for the teams participating in the NFCBP. One was that the program required a 50-50 cost share. Securing high quality cost share for demonstrations remains a big challenge, especially for transit partners that typically do not have a budget for research and development projects. The team originally planned to operate the bus in three locations but was forced to seek out new partners when two of the sites were not able to secure the required cost share. The second funding challenge for the NFCBP participants was that the total program budget was spread out over a four-year time period. The awarded project teams received their federal share in increments, which limited the tasks that could be accomplished. Any work conducted outside this process and timeframe was at risk of not being paid by the government to the project partners.

Public outreach

Educating the public and increasing awareness of the technology was a major goal of the project team. Prior to the bus going into service, the team developed outreach materials (examples shown in Figure 5-1) to aid in teaching the public about the potential benefits of the technology and introducing the use of hydrogen as a fuel. Materials included fact sheets, videos, and even a coloring book for the younger audience. The team also developed a website (www.hydrogenhybridbus.com) that provided information on the project, the bus, and the technology.

The bus was showcased at numerous events and conferences and was used for shuttling attendees at several USC football games. Major events included the following:

- American Public Transportation Association EXPO, San Diego, California, October 2008
- National Hydrogen Association Annual Conference, Columbia, South Carolina, March 2009
- 2010 Olympic and Paralympic Winter Games, Vancouver, Canada, February–March 2010

Figure 5-1

Outreach Materials for Project included a Coloring Book, Fact Sheet, and Website

In response to the DOT/FTA National Fuel Cell Bus Program (NFCBP), a team of creative, best-in-class private companies and transit agencies are collaborating to integrate into a single vehicle all of the appropriate technologies for a reliable, durable, environmentally-friendly, high-performance, moderately-priced, easy-to-operate fuel cell bus. The program will consist of three primary tasks:

1. Development and manufacture of the fuel cell bus
2. Demonstration and robust testing of the fuel cell bus in three states beginning in South Carolina in 2009
3. Evaluation and reporting

First Demonstration in Columbia, South Carolina

SC Demonstration Operators Team

Purpose -Built Hybrid-Electric
Composite Body, 35-ft. low-floor bu
passengers. Designed to capture m
drive technology, the composite bod
with capacity for 37 seated passeng

Smaller Fuel Cells
Reduces capital and replacement c
efficiency of fuel cell buses that prov
emission transit operations.

Advanced Drive System
Improves the overall function of tran

Proximity Advertising
Allows transit operators to maximize
the service route to assist in offsetti

Manuals and Training Program
User friendly manuals allow technic
the advanced technologies now bei

Touch Screen Monitors
Touch screen monitors allow drivers
efficiency and monitor bus operatio

American Built
American Designed and Built, using
materials that surpass Buy America

BC Transit 2010 Olympics Demonstration

In June 2009, members of the project team participated in the 6th International Fuel Cell Bus Workshop, which was held in Vancouver, Canada. This event, funded by FTA as part of the NFCBP, brought together representatives of fuel cell bus demonstrations from around the world to share information and performance results. Discussions with the representative from BC Transit led to a unique opportunity for direct collaboration and data sharing. At that time, BC Transit was in the process of implementing a fleet of 20 fuel cell buses to be operated in Whistler, Canada, beginning with the 2010 Olympic Winter Games. The agency requested that the CTE/Proterra team allow them to showcase this fuel cell bus during the event. This would provide BC Transit the opportunity to test the new bus for feasibility of a potential longer-term demonstration. In turn, the agency would provide the CTE/Proterra team with data on the bus in a cold climate and significantly increase the public exposure to the new technology. The demonstration would be funded jointly by Canada, the U.S., and Proterra. FTA agreed to the request, and the team began preparation for the demonstration.

The team had to overcome a number of challenges to prepare the bus for service in Canada, including meeting differing Canadian standards for safety, vehicle compliance, fuel tank certification, testing for electromagnetic interference, and obtaining insurance. For most of these, actual tests were performed to meet certification standards. In the case of the fuel tank certification, the team negotiated a variance to allow routine inspections of the tanks. The bus was not allowed to operate in actual revenue service with passengers but was able to operate in simulated service with added weight to account for load.

The fuel cell bus completed a 30-day demonstration in Victoria, British Columbia. The team and BC Transit considered it a success, with the bus accumulating more than 900 miles in mixed suburban-urban routes. Table 5-1provides a summary of the data with the bus operating on hydrogen only; no charging was available.

Table 5-1

Fuel Economy Data Summary from BC Transit Demonstration

Data Item	FCB
Total mileage	922
Total fuel (kg)	101.9
Fuel economy (mi/kg)	9.04
Number of fueling events	8

SECTION

6

Fuel Cell Bus Operations-Evaluation Results in Columbia

This fuel cell bus is a prototype vehicle in the early stage of development. The demonstration and evaluation results reported here reflect the prototype status of the bus.

The team's demonstration plan for the fuel cell bus included in-service operation with CMRTA and USC Shuttle Service. Early issues with the DC-DC converter and other components resulted in a shorter-than-planned demonstration period. This is typical of any newly-developed technology. Because of this, the data presented in this section are not sufficient to make any long-term performance assessment of the technology. The bus was first placed in service with CMRTA in early June 2010 and was switched to USC Shuttle service in mid-August 2010 when the college began its fall session. The data presented include service from June 2010 through November 2010.

In-use Demonstration Summary

On June 2, 2010, the bus was placed in service on CMRTA's Route 8 – Rose Hill, which is approximately 12 miles in length and takes about 1 hour per loop. The route has an average speed of 14.7 mph. The bus was operated on this route for eight days before the DC-DC converter failure caused the bus to be temporarily removed from service. The bus was out of service from June 14 through August 16 while Proterra addressed the issue.

During the downtime, the bus was repaired and prepped for service as a USC campus shuttle. On August 17, the fuel cell bus was placed into service on USC's Green Route. This route is a loop through campus that is approximately 2 miles in length and takes about 10 minutes per circuit. The bus was operated on the campus through the end of November 2010. During that time, the bus accumulated 2,947 miles and averaged 5.4 hours per in-service day.

Availability—the percentage of time that a bus is planned for operation compared with the time the bus is actually available for that planned operation is a measure of reliability for transit buses. Availability is calculated by dividing the number of days in operation by the number of planned service days, which is typically every weekday. Weekends and holidays are included in the calculation only if the bus operated in service on those days. If a bus does not operate on the weekend or a holiday, it is not counted as unavailable. During the demonstration period, the bus had an average availability of 53 percent. Table 6-2 provides a summary of the bus use when it was available and the reasons for unavailability. The biggest issue with the bus during the demonstration was with the hybrid propulsion system, primarily because of the DC-DC converter.

Table 6-1

Summary of In-Use Data for Hydrogen Hybrid Bus

Data Item	FCB
Starting odometer	3,849
Ending odometer	6,796
Total mileage	2,947
Monthly average miles	491
Average availability	53%
Total days on route	41
Average time/day (h)	5.4
Longest operation day (h)	8.0

Table 6-2

Summary of Reasons for Availability and Unavailability for Service

Category	Hydrogen Hybrid Bus	
	Number	Percent
Planned work days	86	
Days available	46	53
Available	**46**	**100**
On-route	41	89
Event/demonstration	5	11
Training	0	0
Not used	0	0
Unavailable	**40**	**100**
Fuel cell propulsion	2	5
Hybrid propulsion	28	70
Traction batteries	10	25
Maintenance	0	0
Fueling unavailable	0	0

Fuel Economy and Cost

During the six-month demonstration period, the bus accumulated 2,947 miles and used 399.7 kg of hydrogen for an average fuel economy of 7.37 miles/kg, which equates to 8.33 miles per diesel gallon equivalent (DGE). Table 6-3 summarizes the fuel use and fuel economy during the demonstration.

Figure 6-1 shows the monthly average fuel economy and total charge energy for the bus.

Table 6-3

Fuel Use and Economy

Data Item	FCB
Mileage (fuel base)	2,947
Hydrogen (kg)	399.7
Miles per kg	7.37
Miles per gallon (DGE)	8.33
Total charge energy (kW)	1,751.3
Hydrogen cost ($ per kg)*	$9.93
Average electricity cost ($/kWh)**	$0.05
Fuel cost per mile	$1.38

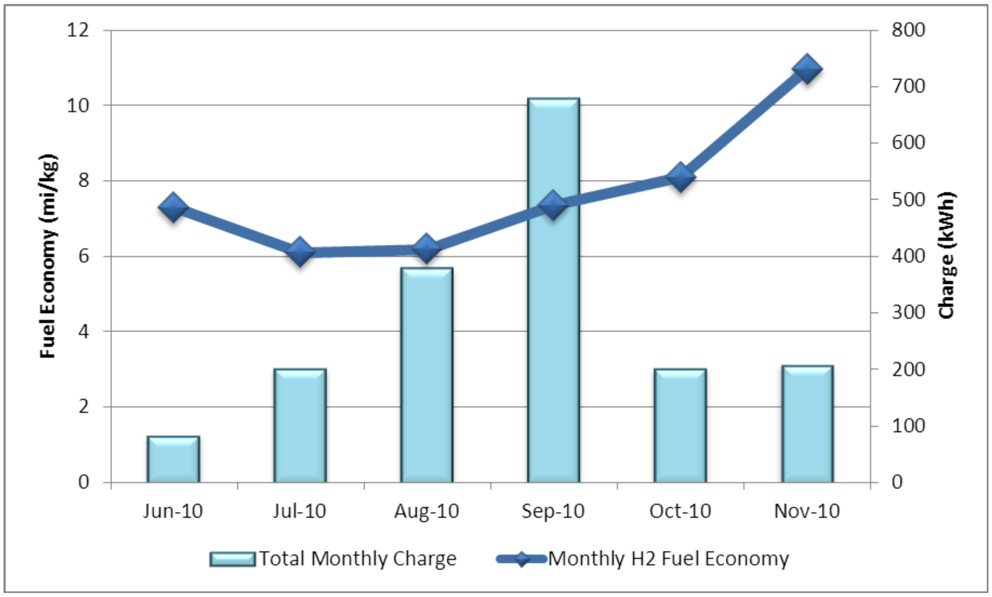
* Hydrogen cost does not include monthly tube trailer lease or delivery charge.

** Average cost of electricity for CMRTA

The charging energy, when converted to DGE, is equivalent to 46.1 gallons of diesel fuel. When this is added to the fuel consumed, the adjusted fuel economy is 7.4 miles/DGE with all energy used for bus operation included.

Figure 6-1

Monthly Average Fuel Economy in mi/kg and Total Monthly Charge in kWh



SECTION

7

What's Next for This Project?

At the end of the scheduled demonstration in Columbia, the bus was shipped to Proterra's Greenville, South Carolina, facility for upgrades and repairs in preparation for the next phase of the demonstration. The manufacturer is using the early test results to determine which components need to be replaced or modified to meet performance objectives. Upgraded components include:

- Borg-Warner 3-speed transmission that is quieter and more durable than the previous component
- New, Proterra-developed battery management system (packaging and monitoring and control software) – intended for production
- Generation 3 DC-DC converters, upgraded to meet power requirements

Once the modifications are complete, the bus will be shipped to Austin, Texas, for the second phase of the demonstration. New demonstration partners include the local transit agency, Capital Metropolitan Transportation Authority (Capital Metro), and the University of Texas Center for Electromechanics (UT-CEM). The bus is expected to operate on a variety of routes in Austin and on the UT campus. Capital Metro will be responsible for operation and will provide space to house and maintain the bus.

UT-CEM will assist in route selection using modeling software as well as aid in data collection. It has experience with fuel cell buses through an earlier FTA-funded project. During that project, a hydrogen station was built to supply fuel. This station currently is being upgraded to better meet fueling needs for the Proterra fuel cell bus. GTI, the original station provider, is on board for the new project and is leading the upgrade. A grant from the Texas Commission on Environmental Quality will fund the station upgrades. Some delays in availability of the State funding have been experienced. The Phase 2 demonstration may use a mobile hydrogen fueling solution at the beginning of testing and operation until the permanent station upgrades can be completed. NREL is funded by FTA to continue data collection and analysis on the bus in service and will publish a second report outlining the Phase 2 experience after the demonstration ends.

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Acronyms and Abbreviations

APU	auxiliary power unit
BMS	battery management system
CMRTA	Central Midlands Regional Transit Authority
CTE	Center for Transportation and the Environment
DC	direct current
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
FMVSS	Federal Motor Vehicle Safety Standards
FTA	Federal Transit Administration
GTI	Gas Technology Institute
h	hours
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
LHV	lower heating value
MDL	mobile development laboratory
mph	miles per hour
NAVC	Northeast Advanced Vehicle Consortium
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PEM	proton exchange membrane
psi	pounds per square inch
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SCRA	South Carolina Research Authority
USC	University of South Carolina
UT-CEM	University of Texas Center for Electromechanics
VPMS	Vehicle Management & Parking Services

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[2] Chandler, K., and L. Eudy (2010). National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2 and Appendices. NREL/TP-560-48106-1, NREL/TP-560-48106-2. Golden, CO: NREL.

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Reports from DOE/NREL evaluations can be downloaded via the following websites:

[13] Hydrogen and fuel-cell-related:
www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

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