

FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

FTA Fuel Cell Bus Program: Research Accomplishments through 2011

MARCH 2012

FTA Report No. 0014
Federal Transit Administration

PREPARED BY

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U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

Courtesy of Christina Gikakis, Federal Transit Administration

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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
ft³	cubic feet	0.028	cubic meters	m ³
yd³	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)				
°F	Fahrenheit	$5 (F-32)/9$ or $(F-32)/1.8$	Celsius	°C

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ABSTRACT

Prepared by the Federal Transit Administration (FTA) Office of Research, Demonstration, and Innovation (TRI), this report summarizes the accomplishments of fuel-cell-transit-bus-related research and demonstrations projects supported by FTA through 2011. It catalogs fuel cell electric bus research projects in the United States and describes their impact on commercialization of fuel cell power systems and electric propulsion for transit buses. Few barriers remain to reaching full commercialization of fuel cell electric buses. This report documents progress toward overcoming these barriers.

EXECUTIVE SUMMARY

This report summarizes accomplishments of fuel cell transit bus-related research and demonstration projects supported by the U.S. Department of Transportation's (DOT) Federal Transit Administration (FTA) through 2011. It catalogs fuel cell electric bus (FCEB) research projects in the United States and describes their impact on commercialization of fuel cell power systems and electric propulsion for transit buses in general.

FTA conducts most of its FCEB research under the National Fuel Cell Bus Program (NFCBP), a cooperative research, development, and demonstration program to advance commercialization of FCEBs. The NFCBP is a part of a larger FTA research program to improve transit efficiency and contribute to environmentally sustainable transportation. FTA conducts the NFCBP in partnership with industry. Projects target research to improve performance and lower costs of next-generation fuel cell systems for transportation.

Under the NFCBP, the United States is advancing the technologies for fuel cells for transportation. Several U.S. transit agencies have incorporated FCEBs into their fleets, and more will add these buses within the next few years.

Fuel cell electric technology for transit buses enables such benefits as:

- zero tailpipe emissions
- improved fuel economy, compared to current bus technology
- reduced dependence on foreign oil
- quiet, smooth rides for customers
- creation of green technology jobs
- technologies for better-performing, more-efficient hybrid and electric buses
- demonstration of the value of fuel cell technology to a larger, heavy-duty vehicle market

Few barriers remain to reaching commercialization of FCEBs. This report documents progress toward overcoming these barriers:

- **Durability** – The useful life of fuel cell power systems is increasing, but more work is needed to meet transit requirements.
- **Initial purchase costs** – The cost of buses and infrastructure is decreasing incrementally. However, only economies of scale through larger quantity purchases can leverage substantive cost reductions.
- **Production and delivery of hydrogen** – The availability and cost of hydrogen for FCEB operations remain significant barriers. Hydrogen is produced by electrolysis or through natural gas reforming, or it is delivered as a liquid to users. These production and delivery methods pose cost and emission issues that must be resolved before FCEBs are fully commercialized.

FTA's research to develop FCEBs increased significantly through the NFCBP, which has been underway since 2006.¹ The NFCBP requires an equal cost share by project teams for each federal dollar invested, bringing the size of the program to more than \$150 million through FY2011.

The number of FCEBs in operation in the United States increased from 3 in 2005 to 24 in 2011, and it is expected that at least 32 FCEBs will be operating by the end of 2012. Additionally, FCEB are now operated in many areas across the country.

NFCBP program objectives, which apply to all FTA-funded FCEB research, are:

1. Significantly advance development of FCEBs and related infrastructure through innovation of FCEB design, component development, improved systems integration, and real-world implementation and demonstration.
2. Document the state of FCEB technologies development, and examine requirements and next steps for market introduction.
3. Enhance awareness and education related to FCEBs and related infrastructure.

As of this report, FTA successfully completed 17 FCEB research projects and has 25 projects that are ongoing. Accomplishments from these projects are in several categories:

- **NFCBP performance objectives** – FTA developed performance objectives for the NFCBP and related FTA research. FTA made significant progress across all performance objectives, and progress continues.
- **FCEB configurations** – Seven fully-integrated FCEB designs are now available, in either a fuel-cell-dominant or a battery-dominant configuration. In addition, work has progressed on an existing diesel hybrid propulsion system to electrify accessories and implement a small fuel cell power system.
- **New “green” bus manufacturer** – The NFCBP funded Proterra's first bus, a battery-dominant FCEB that operated in Columbia, South Carolina, and will soon operate in Austin, Texas.
- **Largest U.S. FCEB demonstration** – The newest-generation Van Hool/UTC Power FCEB design was delivered, with 12 buses going to the San Francisco Bay Area and 4 buses going to Hartford, Connecticut. These 16 FCEBs are the largest demonstration of one FCEB design in the United States. As of the end of 2011, one of the Bay Area buses has a fuel cell power system with 11,000 hours of operation without significant maintenance (i.e., no change-out of the fuel cell system or individual cells), and other buses in the fleet have fuel cell power systems with 6,000 and 8,000 hours of operation without significant maintenance.

¹ Congress established the NFCBP in the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU).

- **“Buy America” and FCEBs** – FTA has made progress in integrating FCEBs that are “Buy America” compliant. Ballard, a major supplier, is producing systems in Lowell, Massachusetts. UTC Power, another major supplier, is working toward packaging its system for easier integration into buses from U.S. manufacturers.
- **Fueling infrastructure and building modifications** – Ongoing demonstrations are facilitating a better understanding of needed infrastructure and safe operations for existing transit operations.
- **Hybrid electric propulsion improvements** – FTA-funded research is leading to better components and the integration of electric systems for electric propulsion.
- **Awareness and education** – FTA research projects support awareness and education for transit agencies and the public. FTA has funded outreach to share information and lessons learned, both within the United States and internationally, through national and international fuel cell bus workshops and develops research reports for industry.

SECTION 1

Introduction

The Federal Transit Administration's (FTA) fuel cell electric bus (FCEB) research increased significantly with the start of the National Fuel Cell Bus Program (NFCBP) in 2006.² This report summarizes the accomplishments of FCEB-related research and demonstration projects supported by FTA from 2006 through 2011. It catalogs FCEB research projects in the United States and describes their impact on commercialization of fuel cell power systems and electric propulsion in general.

The FTA Office of Research, Demonstration and Innovation funds FCEB research and demonstration projects, including:

- purchase of and improvements for FCEBs
- implementation and demonstration of FCEBs in transit operations, including hydrogen fueling infrastructure
- modifications and improvements of facilities (e.g., maintenance, indoor storage, fueling) to support FCEB operations
- independent analysis and evaluation of transit agency implementation and demonstration of FCEBs and related infrastructure improvements.

FTA-funded FCEB research exists within a larger context of electric propulsion research for bus and rail applications. The objectives of electric propulsion research, in general, are to improve systems and components so as to increase energy efficiency as well as reliability and maintainability. FTA provides research results and lessons-learned reports to transit agencies and the transit industry. The U.S. Department of Energy (DOE), through the National Renewable Energy Laboratory (NREL), publishes status reports on FCEBs.³ NREL reports document operations and near-term research needs for continuing development of commercialized fuel cell power systems for transit buses.

FTA will update this status report as needed with new information about fuel cell transit buses, hydrogen infrastructure, and "green" improvements. FTA will base the updates on progress and funding availability, including funding from the American Recovery and Reinvestment Act of 2009 (ARRA), Transportation Investment Generating Economic Recovery (TIGER) grants, Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) grants, and additional NFCBP funding.

²*Analysis of Electric Drive Technologies for Transit Applications: Battery-Electric, Hybrid-Electric, and Fuel Cells*, 2005, FTA-MA-26-7100-05.1, documents electric propulsion bus development and operations, including fuel cells, prior to 2006. Available at http://www.fta.dot.gov/documents/Electric_Drive_Bus_Analysis.pdf.

³See NREL, "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2011," October 2011. Available at http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

Value and Challenges of Fuel Cell Electric Propulsion for Transit Buses

U.S. interest in hydrogen FCEBs grew over the past 20 years, driven primarily by the desire to reduce both petroleum-based fuel consumption and emissions, particularly greenhouse gas (GHG) emissions. Executive Order (EO) 13514,⁴ “Federal Leadership in Environmental, Energy, and Economic Performance,” October 2009, set policy for federal agencies in sustainability and GHG management. The EO expanded previous policy, calling for significant energy consumption and emissions reductions over 10 years. In addition, in October 2010, the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Transportation (DOT) National Highway Traffic Safety Administration (NHTSA) introduced a program to reduce GHG emissions and improve fuel efficiency of medium- and heavy-duty trucks and buses.⁵ These federal programs will significantly impact transit bus propulsion products in the future.

Transit buses are particularly well suited to demonstrating fuel cell and other advanced technology applications in transportation because they:

- are centrally located and fueled
- are government subsidized
- are professionally operated and maintained
- operate on fixed routes and fixed schedules
- tolerate the weight and volume requirements of advanced systems
- have rigorous start-up and pull-out requirements
- provide public exposure to the benefits of advanced technologies, which leads to greater public acceptance

Benefits of Fuel Cell Electric Transit Buses

Fuel cell electric technology for transit buses also enables such benefits as:

- zero tailpipe emissions
- improved fuel economy, compared to current bus technology
- reduced dependence on foreign oil

⁴Available at <http://www.fedcenter.gov/programs/eo13514/>.

⁵See “EPA and NHTSA Propose First-Ever Program to Reduce Greenhouse Gas Emissions and Improve Fuel Efficiency of Medium- and Heavy-Duty Vehicles: Regulatory Announcement,” available at http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/CAFE_2014-18_Trucks_FactSheet-v1.pdf.

- quiet, smooth rides for customers
- creation of green technology jobs
- technologies for better-performing, more-efficient hybrid and electric buses
- demonstration of the value of fuel cell technology to a larger, heavy-duty vehicle market

Barriers to Commercialization

A few barriers to reaching full commercialization of FCEBs remain. The major barriers include:

- **Durability** – The useful life of fuel cell power systems is increasing, but more work is needed to meet transit requirements.
- **Initial purchase costs** – The cost of buses and infrastructure is decreasing incrementally. However, only economies of scale through larger quantity purchases can leverage substantive cost reductions.
- **Production and delivery of “green” hydrogen** – The availability and cost of hydrogen for FCEB operations remain significant barriers. Hydrogen is produced by electrolysis or through natural gas reforming, or it is trucked as a liquid into operating locations. These production and delivery methods all pose cost and GHG emission issues that must be resolved before FCEBs are fully commercialized.

History and Status of FCEB Research

Section 3 summarizes FCEB research programs and projects, from early research in the 1990s to current research, including the NFCBP, Congressionally-directed research projects funded by FTA and related research supported by DOE and FTA. Appendix A provides more details and status information for all 42 previous and ongoing FCEB research projects.

Early FCEB Research

FTA FCEB propulsion and infrastructure demonstrations began in the early 1990s with buses developed at Georgetown University. These 30- and 40-foot buses were fueled by methanol that was reformed into hydrogen onboard and used in the buses' electric fuel cell propulsion systems. Between 1998 and 2000, FTA supported a second major demonstration of three 40-foot hydrogen fuel cell buses, with Ballard fuel cells, operated by the Chicago Transit Authority (CTA). During this same time period, three fuel cell buses of the same generation also operated in Vancouver, Canada.

FTA's early demonstrations proved the feasibility of fuel cell propulsion for transit buses and identified research needed to:

- reduce the size of fuel cell stacks and balance-of-plant onboard buses
- increase power density of the fuel cell power system
- reduce the weight of fuel cell and electric propulsion systems
- develop a hydrogen fueling infrastructure suitable for transit bus operations

The first "next-generation" FCEB, a 40-foot bus with a Ballard fuel cell power system, operated at SunLine Transit Agency (SunLine) during 2000 and 2001. A second "next-generation" FCEB, a 30-foot bus with a UTC Power fuel cell power system, operated first at SunLine⁶ and then at Alameda-Contra Costa Transit District (AC Transit) during 2002 and 2003.

National Fuel Cell Bus Program

To facilitate development of commercially viable FCEB propulsion technologies and infrastructure, in August 2005 Congress established the National Fuel Cell Bus Technology Development Program. The program was part of the four-year surface transportation authorization, the Safe, Accountable, Flexible, Efficient

⁶Fuel Cell Transit Buses, *ThunderPower Bus Evaluation at SunLine Transit Agency*, November 2003.

Transportation Equity Act: A Legacy for Users (SAFETEA-LU).⁷ The Act authorized \$49 million in capital funding as part of a competitive grant program for up to three geographically-diverse nonprofit organizations to develop and demonstrate FCEB technologies. It required a minimum 50 percent cost share for all projects, making the initial size of the program almost \$100 million.

Through FTA, DOT released the initial competitive solicitation for the NFCBP on April 10, 2006. Both FTA and DOE, as well as other Federal agencies, participated on a technical team that recommended 14 projects for funding under the program. Projects included partners from industry, government, and transit and provided a balanced portfolio for the NFCBP to advance FCEB commercialization. Since its inception, the value of the NFCBP has been evidenced in the number and diversity of products and technologies being researched, developed, and demonstrated.

The NFCBP continued beyond its initial four years, funded through extensions of SAFETEA-LU for FY2010 and FY2011. Each annual extension added approximately \$13.5 million, for a total of nearly \$76 million in federal funding through FY2011. The 50 percent cost share requirement was also continued for all projects, bringing funding for the program to more than \$150 million. Projects for FY2011 were solicited, and the announcement of awards was made in April 2012. Details on these projects can be found on the FTA website at fta.dot.gov.

The NFCBP has program objectives that apply to all FTA-funded research for FCEBs, hydrogen infrastructure, and demonstrations. Each of FTA's fuel-cell-related research projects supports at least one of the following objectives:

1. Advance development of FCEBs and related infrastructure through innovation of FCEB design, component development, improved systems integration, and real-world demonstration.
2. Document the state of FCEB technology development, and determine next steps for market introduction.
3. Enhance awareness and education about FCEBs and related infrastructure.

Each NFCBP project is managed through one of three non-profit consortia:

- **CALSTART**, a non-profit consortium headquartered in Pasadena, California.⁸ CALSTART represents more than 140 firms. It provides services and consulting to develop clean, advanced transportation technologies for all types of vehicles, including trucks, buses, and military vehicles.
- **Center for Transportation and the Environment (CTE)**, a non-profit consortium headquartered in Atlanta, Georgia.⁹ CTE provides

⁷SAFETEA-LU, Section 3045.

⁸See <http://www.calstart.org/Homepage.aspx>.

⁹See <http://www.cte.tv/>.

research, training, and information exchange for improving transportation infrastructure while preserving the integrity of the environment.

- **Northeast Advanced Vehicle Consortium (NAVC)**, a non-profit, public-private partnership headquartered in Boston, Massachusetts.¹⁰ NAVC conducts research and technology analysis and fosters information sharing and collaboration on advanced vehicle technology projects.

Current FTA FCEB research focuses on developing transit buses that demonstrate full transit operation and service. Current bus configurations have either large fuel cell power systems in hybrid electric propulsion systems or smaller fuel cell power systems in plug-in/battery-dominant hybrid electric propulsion systems. Ongoing research also includes electrifying accessories (e.g., air conditioning) and, in some cases, adding small fuel cell auxiliary power units (APUs) to power the electric accessories. As a result, battery technology has advanced to the point that all-electric propulsion is being tested in the transit environment.

Other Research Funded by FTA

FTA funds several longer-term FCEB-related research projects outside the NFCBP. Congress directed many of these long-term projects for specific university research programs.

Joint FTA-DOE Research

DOE also funds FCEB research. Most of DOE's fuel cell and hydrogen research is done through the Fuel Cell Technologies Program¹¹ within the Office of Energy Efficiency and Renewable Energy (EERE). Research within this program is in eight areas:

1. Hydrogen production
2. Hydrogen delivery
3. Hydrogen storage
4. Fuel cells
5. Technology validation
6. Safety codes and standards
7. Education
8. Systems analysis

DOE's research in fuel cells and hydrogen complements FTA's transit bus research and demonstration, usually through DOE's investment in developing technologies used in the demonstrations. For example, DOE supported hydrogen fueling stations at several demonstration locations in California. In addition, DOE's Clean Cities program provides grants for clean energy projects

¹⁰See <http://www.navc.org/>.

¹¹DOE's Fuel Cell Technologies Program website is at <http://www1.eere.energy.gov/hydrogenandfuelcells/>.

that include a hydrogen fueling station planned for CTTRANSIT in Hartford, Connecticut. Site evaluations funded by DOE or FTA report the intersection of DOE research and FTA transit demonstrations. The Technology Validation area in DOE's Annual Progress Report and Annual Merit Review¹² also provides many FCEB-related results.

For the past 20 years, DOE and FTA have collaborated to evaluate many new and advanced propulsion systems in transit buses. NREL performed most of these evaluations, and NREL's 2010 publication *Hydrogen Fuel Cell Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*¹³ documents them for fuel cell and hydrogen transit technologies.

In June 2010, DOE and FTA jointly sponsored a fuel cell bus workshop to evaluate the status and the technology needs for commercializing fuel cell powered buses.¹⁴ Consensus among workshop attendees was that fuel cell technology 1) is approaching commercial readiness, but 2) needs more research at the systems level, including fuel cell balance-of-plant and power electronics. An outcome of the workshop was an initial set of performance objectives to make FCEBs ready for commercialization within transit operations.

As a follow on to the workshop, in May 2011, DOE and FTA released a request for information (RFI) from the transit industry to refine the initial set of technical and cost objectives for FCEB research and commercialization.¹⁵ Based on the responses, they revised the objectives and added to their lists of needed research and development. DOE and FTA continue to refine FCEB performance objectives, which they reported during the 2011 National Fuel Cell Bus Workshop¹⁶ in October 2011. These new FCEB performance objectives are intended to enhance or replace the existing performance objectives from the NFCBP, reported later in Section 4.

Status of FTA FCEB Research

Table 3-1 summarizes the 42 research projects that include the NFCBP projects, other FTA research, supporting research funded by DOE, and one new FCEB project under TIGGER. The table shows the alignment of each project with the three NFCBP program objectives. As of FY2012, FTA and DOE have 25 ongoing projects, and 17 projects have been successfully completed.

¹²Annual reports are available at http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/transportation_proj.html.

¹³Available at <http://www.nrel.gov/hydrogen/pdfs/49342-1.pdf>.

¹⁴The Joint Fuel Cell Bus Workshop Summary Report and presentations are available at http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_fcbus10.html.

¹⁵A synopsis of the RFI and grant opportunity on grants.gov are available at <http://www.grants.gov/search/search.do?mode=VIEW&opId=92873>.

¹⁶The National Fuel Cell Bus Workshop agenda and presentations are available at <http://www.fuelcellbusworkinggroup.com/schedule.html>.

Each project in Table 3-1 has a unique identifier (e.g., [A1]) at the end of its description. The identifier corresponds to an Appendix location that contains more detailed information about the project.

Table 3-1
FTA FCEB-Related
Research (2006–2011)

No.	Project Description	Stage/ Status	Project Objectives			NFCBP Project?
			1	2	3	
Development and Demonstration						
1	American Fuel Cell Bus Program (CALSTART). 1 new ElDorado National bus operating at SunLine Transit Agency – 40-foot bus, BAE Systems hybrid system, lithium ion batteries, Ballard fuel cell power system. [A1]	Ongoing	X	X	X	Yes
2	Compound Fuel Cell Hybrid Bus (CALSTART). 1 new Orion bus operating at San Francisco Municipal Transportation Agency (SFMTA) – 40-foot bus, BAE Systems hybrid system, lithium ion batteries, Hydrogenics fuel cell APU for electric accessories. [A2]	Ongoing	X	X	X	Yes
3	Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing (CTE). 1 newly-designed Proterra bus operating in Columbia, SC, and Austin, TX – 35-foot bus, battery-dominant hybrid system from Proterra, lithium titanate batteries, Hydrogenics fuel cell power system. [A4]	Ongoing	X	X	X	Yes
4	Austin Demonstration Program Enhancement (CTE). Enhancement to demonstration of the Proterra bus in Austin, TX. Addition to the Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing project. [A5]	Ongoing	X	X	X	Yes
5	Nutmeg Project (NAVC). 4 next-generation Van Hool buses operating in Hartford, CT, and possibly other locations – 40-foot buses, Siemens ELFA hybrid system integrated by Van Hool, lithium ion batteries, UTC Power fuel cell power system. [A6]	Ongoing	X	X	X	Yes
6	Lightweight Battery Dominant Hybrid Fuel Cell Bus (NAVC). Bus development and testing by General Electric (GE) – 35-foot Proterra bus, hybrid system from Proterra, lithium batteries, Ballard fuel cell power system, GE providing integration support. [A7]	Ongoing	X	X	X	Yes
7	Massachusetts Hydrogen Fuel Cell Powered Bus Program (NAVC). 1 new ElDorado bus operating in Boston – 40-foot bus, BAE Systems hybrid system, lithium ion batteries, Nuvera/Fiat fuel cell power system. Fueling infrastructure includes Nuvera PowerTap system. [A8]	Ongoing	X	X	X	Yes
8	University of Delaware Fuel Cell Transit Vehicle. Up to 4 FCEBs developed and demonstrated in Newark, DE – two 22-foot Ebus buses, hybrid system from Ebus, nickel cadmium batteries, Ballard fuel cell power system. [B2]	Ongoing	X	X	X	No

Table 3-1
(continued)

FTA FCEB-Related
Research (2006–2011)

No.	Project Description	Stage/ Status	Project Objectives			NFCBP Project?
			1	2	3	
Development and Demonstration (continued)						
9	Connecticut Hydrogen Transit Vehicle Development Project. 1 new Ebus FCEB operating in New Haven, CT – 22-foot bus, hybrid system from Ebus, nickel cadmium batteries, Ballard fuel cell power system. [B7]	Ongoing	X	X	X	No
10	Missouri S&T Hydrogen Shuttle Project. 1 fuel cell bus. Research on green energy fueling infrastructure. [B9]	Ongoing	X	X	X	No
11	AC Transit Zero Emission Bus Advanced Demonstration. 12 new-design Van Hool FCEBs operating in Oakland, CA. Plan to operate at Santa Clara Valley Transportation Authority (VTA), Golden Gate Transit (GGT), San Mateo County Transit District (SamTrans), and SFMTA – 40-foot buses, Siemens ELFA hybrid systems, lithium ion batteries, UTC Power fuel cell power systems. [C1]	Ongoing	X	X	X	No
12	SunLine Advanced Fuel Cell Bus Demonstration. 1 new New Flyer FCEB operating at SunLine. Similar to FCEBs operating in Whistler, BC, Canada – 40-foot bus, Siemens ELFA hybrid system integrated by Bluways, lithium phosphate batteries, Ballard fuel cell power system. [C2]	Ongoing	X	X	X	No
13	City of Burbank Demonstration. 1 new Proterra battery dominant hybrid fuel cell bus operating in Burbank, CA – 35-foot bus, hybrid system from Proterra, lithium titanate batteries, Ballard fuel cell power system. [C3]	Ongoing	X	X	X	No
14	Lightweight Battery Dominant Hybrid Fuel Cell Bus (NAVC). Bus development and testing by General Electric (GE) – 35-foot Proterra bus, hybrid system from Proterra, lithium batteries, Ballard fuel cell power system, GE providing integration support. [A7]	Start up	X	X	X	Yes
15	Advanced Composite Fuel Cell Bus (CTE). 1 new Proterra battery dominant FCEB will operate in Columbia, SC, and Washington, DC – 35-foot bus, hybrid system from Proterra, lithium titanate batteries, Ballard fuel cell power system. [A11]	Start up	X	X	X	Yes
16	Birmingham Fuel Cell Bus Demonstration (CTE). Battery-dominant FCEB research project in Birmingham, AL – 30-foot EVOAmerica bus, hybrid system from EVOAmerica, lithium titanate batteries, Ballard fuel cell power system. [A12]	Start up	X	X	X	Yes
17	Hybrid Electric Fuel Cell Bus Demonstration (CTE). 1 DesignLine FCEB will operate in Columbus, OH – 40-foot bus, hybrid system from DesignLine, lithium ion batteries, Ballard fuel cell power system. [A13]	Start up	X	X	X	Yes

Table 3-1
(continued)

FTA FCEB-Related
Research (2006–2011)

No.	Project Description	Stage/ Status	Project Objectives			NFCBP Project?
			1	2	3	
Development and Demonstration (continued)						
18	American Fuel Cell Buses for SunLine. Develop and begin commercialization of AFCB design for transit. 2 buses matching the NFCBP bus design will be put in service – ElDorado 40-foot bus with BAE Systems hybrid propulsion, lithium ion batteries, and Ballard fuel cell system. [B1]	Awarded	X	X	X	No
19	AC Transit HyRoad: Commercialization of Fuel Cells for Public Transit (CALSTART). Accelerated/maximized operation of 3 FCEBs – 40-foot Van Hool bus, Siemens ELFA hybrid system, ZEBRA batteries, UTC Power fuel cell power system. [A3]	Complete	X	X	X	Yes
20	Fuel Cell Development and Demonstration Program (NAVC). 1 new FCEB was planned. [A9]	Closed	X	X	X	Yes
21	Hydrogen Fuel Cell Plug-In Hybrid Bus in Austin, TX. 1 Ebus operated in Austin, TX – 22-foot bus, hybrid system from Ebus, nickel cadmium batteries, Ballard fuel cell power system. [B1]	Complete	X	X	X	No
22	University of Alabama at Birmingham Hybrid Electric and Fuel Cell Research. Operation of 1 EVAmerica FCEB was planned. Project now part of NFCBP. [B3]	Complete	X	X	X	No
23	Georgetown University Fuel Cell Bus Research. 4 methanol-fueled FCEBs developed and demonstrated at Georgetown University and other locations. [B4]	Complete	X	X	X	No
24	CTTRANSIT Fuel Cell Bus Demonstration. 1 Van Hool FCEB identical to the 3 original FCEBs at AC Transit and 1 FCEB at SunLine. Bus operated in Hartford, CT – 40-foot bus, Siemens ELFA hybrid system, ZEBRA batteries, UTC Power fuel cell power system. Data collection and evaluation for this bus now part of the NFCBP Nutmeg project. [C4]	Complete	X	X	X	No
25	SunLine Fuel Cell Bus Demonstration. 1 Van Hool FCEB identical to the 3 original AC Transit FCEBs and one CTTRANSIT FCEB – 40-foot bus, Siemens ELFA hybrid system, ZEBRA batteries, UTC Power fuel cell power system. Data collection and evaluation for this bus now a part of the SunLine Advanced Fuel Cell Bus Demonstration. [C5]	Complete	X	X	X	No
26	AC Transit HyRoad Demonstration. Demonstration of the 3 original Van Hool FCEBs identical to the 1 SunLine bus and 1 CTTRANSIT bus. Buses operated in Oakland, CA – 40-foot bus, Siemens ELFA hybrid system, ZEBRA batteries, UTC Power fuel cell power system. Data collection and evaluation for these buses continued under the NFCBP. [C6]	Complete	X	X	X	No
27	Santa Clara VTA Fuel Cell Bus Demonstration. 3 fuel cell buses from Gillig operating at Santa Clara VTA – 40-foot, non-hybrid electric propulsion, Ballard fuel cell power system. [C7]	Complete	X	X	X	No

Table 3-1*(continued)*FTA FCEB-Related
Research (2006–2011)

No.	Project Description	Stage/ Status	Project Objectives			NFCBP Project?
			1	2	3	
Component Development						
28	Next-Generation Fuel Cell Power System Development for Fuel Cell Transit Bus Commercialization (CALSTART). Phase I of a UTC Power project to develop a robust, affordable, and reliable fuel cell power system optimized for transit applications (system size and weight) that will be “Buy America” compliant. [A16]	Start up	X	X	X	Yes
29	DC-DC Converter Development Program (CTE). New DC-DC converter to enable more robust and reliable FCEB operation. [A17]	Start up	X	X		Yes
30	Hybrid Fuel Cell Power Converter (CALSTART). Scaled design of an automotive DC-DC high power converter to meet a broader range of heavy-duty hybrid FCEB requirements. [A14]	Complete	X	X		Yes
31	Integrated Auxiliary Module for Fuel Cell Bus (CALSTART). Fabrication and demonstration of a low-cost, compact, water-cooled integrated auxiliary module (IAM) for accessory loads. [A15]	Complete	X	X		Yes
Coordination and Outreach						
32	Coordination of Communications and Outreach for NFCBP (CTE). Mechanism for outreach and coordination nationally and internationally. Provides FTA information on worldwide FCEB technology. [A22]	Start up		X	X	Yes
33	National Fuel Cell Bus Working Group (NAVC). Coordinated and facilitated a working group of U.S.-based FCEB industry stakeholders. [A19]	Complete		X	X	Yes
34	International Fuel Cell Bus Working Group (NAVC). Coordinated activities for an International Fuel Cell Bus Working Group. [A20]	Complete		X	X	Yes
35	International Fuel Cell Bus Workshops (NAVC). Conducted 4 workshops with the International Fuel Cell Bus Working Group. [A21]	Complete		X	X	Yes
Technical Support						
36	NREL Evaluation and Technical Support. Third-party documentation and dissemination of results from all NFCBP development and demonstration projects, including support for outreach activities. [A23]	Ongoing		X	X	No
37	Volpe Center Safety Review and Analysis. Technical support and assistance to FTA and NFCBP project teams in system safety plans and safety of fuel cell projects. [A24]	Ongoing			X	No
38	Survey and Analysis of Bus Demonstrations (CTE). Report of results, key issues, and lessons learned from FCEB demonstrations (more than 20 cities, internationally) between 2002 and 2007. [A18]	Ongoing		X	X	Yes

Table 3-1*(continued)*FTA FCEB-Related
Research (2006–2011)

No.	Project Description	Stage/ Status	Project Objectives			NFCBP Project?
			1	2	3	
General Research						
39	Fueling Station for Hydrogen-Fueled Shuttle Buses. Supports development of a hydrogen-fueled shuttle bus operation. [B6]	Ongoing	X			No
40	University of Alabama Hybrid Electric and Fuel Cell Research. Hybrid and fuel cell propulsion technologies relevant to transit applications. [B10]	Ongoing			X	No
41	East Tennessee Hydrogen Initiative. Hydrogen production, storage, and dispensing technologies and methods for hydrogen fueling infrastructure at the University of Tennessee at Chattanooga. [B8]	Complete	X		X	No
42	Northern Illinois University Fuel Cell Research. Fuel cell system development, including new catalysts, membrane electrode assembly performance, multi-cell analysis and validation, bipolar plates, fuel cell materials durability, and hybrid technology. [B5]	Complete			X	No

SECTION
4

Research Accomplishments

Section 4 discusses the research accomplishments of FTA’s FCEB and infrastructure demonstrations from 2006 through 2011 and FTA’s plans for 2012. Research under the NFCBP shows progress toward commercialization and readiness for implementation of FCEBs in transit operations. Accomplishments are in several categories:

- NFCBP performance objectives
- FCEB configurations
- New “green” bus manufacturer
- Largest U.S. FCEB fleet
- “Buy America” and FCEBs
- Fueling infrastructure and building modifications
- Hybrid electric propulsion improvements
- Awareness and education.

NFCBP Performance Objectives

The NFCBP has seven performance objectives for the research projects it funds. Table 4-1 lists these objectives and summarizes progress-to-date toward meeting them. Although progress is significant, more investment is needed to meet the objectives.

Table 4-1
*Progress Toward
Technical Performance
Objectives*

NFCBP Performance Objective	Progress through FY 2011
1. Less than 5 times the cost of a conventional (commercial diesel) transit bus.	Cost reductions from more than \$3.0 million per bus in 2006 to \$2.3 million for last bus ordered. Battery-dominant bus with smaller fuel cell power system significantly less than \$2.3 million.
2. 4–6 years or 20,000–30,000 hours of durability for the fuel cell power system.	10,000+ hours achieved on fuel cell power system, with durability warranties at 10,000 to 12,000 hours.
3. Double the fuel economy compared to commercial (diesel transit) bus.	Exceed 2 times conventional (diesel transit) bus fuel economy, but depends on route.
4. Bus performance equal to or greater than equivalent commercial (diesel transit) bus.	Operated up to 19 hours/day, with good availability, and miles between road calls at 4,000 miles. Better acceleration. Quiet operation. Weight is still high.
5. Exceed current emissions standards.	Zero emissions.
6. Foster economic competitiveness in FCEB technologies.	Multiple manufacturers and platforms demonstrating buses.
7. Increase public acceptance for FCEB technologies.	Continued progress.

Figure 4-1 shows the number of FCEBs operating in the United States. Between 2005 and 2009, potential regulation by the California Air Resources Board was the impetus for FCEB research, and the first seven FCEBs operated in California at SunLine, Santa Clara VTA, and AC Transit. Beginning in 2007, one FCEB began operating at CTTRANSIT in Hartford, Connecticut.

Funding through the NFCBP was available starting in 2006. However, its influence becomes apparent only in 2010, due to the lag time between designing and building FCEBs and getting them in operation. The projected number (32) of FCEBs that will be in operation by the end of 2012 is conservative.

Figure 4-1
Fuel Cell Electric Buses
Operating in the
United States

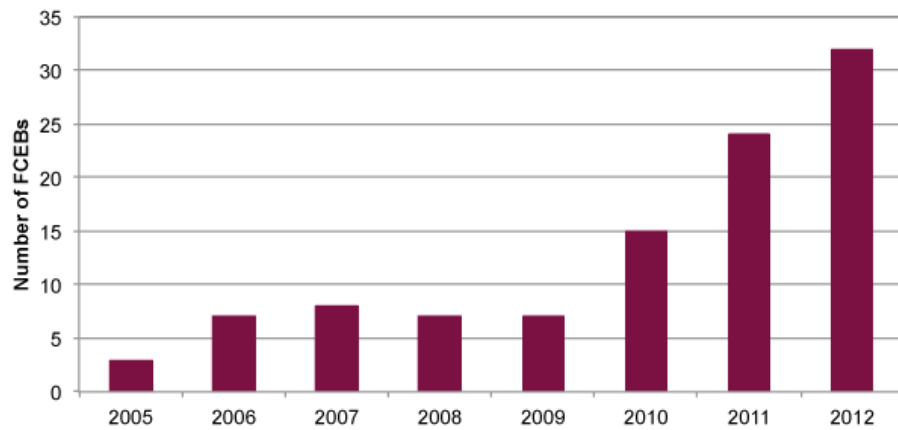
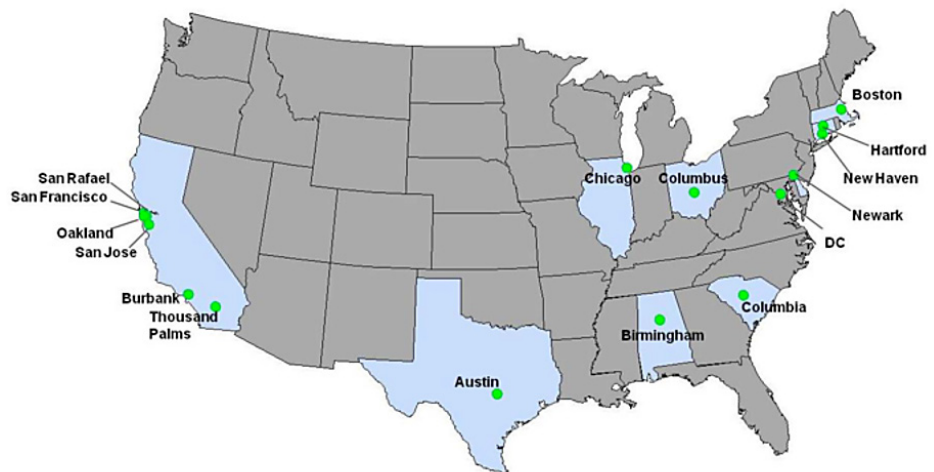


Figure 4-2 is a map of current or planned FCEB operating locations. FCEB demonstrations have expanded and are now located across the United States, not just in California.

Figure 4-2
Fuel Cell Electric Bus
Demonstration Sites



FCEB Configurations

The 42 projects discussed in this report represent multiple design configurations for FCEBs. Table 4-2 shows the current fully-integrated FCEB configurations and their manufacturers. Three are fuel cell-dominant configurations, and four are battery-dominant fuel cell configurations. The design configurations represent seven bus manufacturers and three fuel cell power system manufacturers. Another FCEB is planned with a fourth fuel cell power system manufacturer, Nuvera. In addition to those listed in the table, one existing hybrid electric bus design, Orion VII, BAE Systems, was modified using all-electric accessories powered by a small fuel cell power system by Hydrogenics. This modified design also provides some power for all-electric operation of the power plant dominant hybrid.

Table 4-2

Fuel Cell Bus Configurations

Bus Manufacturer	Fuel Cell System	Hybrid System	Hybrid Configuration	Energy Storage	Status
Van Hool 40-ft	UTC Power	Siemens ELFA	Fuel cell-dominant	Lithium-based batteries	Operational
El Dorado 40-ft	Ballard	BAE Systems	Fuel cell-dominant	Lithium-based batteries	Operational
New Flyer 40-ft	Ballard	Siemens ELFA	Fuel cell-dominant	Lithium-based batteries	Operational
Proterra 35-ft	Hydrogenics or Ballard	Proterra integration	Battery-dominant	Lithium-based batteries	Operational
DesignLine 35-ft	Ballard	DesignLine integration	Battery-dominant	Lithium-based batteries	Under development
Ebus 22-ft	Ballard	Ebus integration	Battery-dominant	Nickel cadmium	Operational
EVAmerica 30-ft	Ballard	EVAmerica integration	Battery-dominant	Lithium-based batteries	Under development

New “Green” Bus Manufacturer

In 2007, Proterra, a new “green” bus manufacturer, started design of and delivered its first bus, a battery-dominant hybrid fuel cell bus, for demonstration in Columbia, South Carolina, (completed in 2010) and Austin, Texas (planned to start in 2012). The NFCBP helped Proterra acquire the start-up capital to begin manufacturing this bus. Since then, Proterra has built and delivered two more FCEBs that are essentially the same as the first one. Proterra based its propulsion system on an all-electric design with the capability to add a fuel cell power system as a range extender. Its buses are also designed for opportunity charging while on route. Foothill Transit (West Covina, California) purchased three electric buses

with one of Proterra's fast charging stations. Proterra is assembling another 10 or more buses for transit operations in other locations.

Largest U.S. Fuel Cell Electric Bus Demonstration

Several transit agencies in California began testing FCEBs because of potential state regulation and purchase requirements for zero-emission buses. Beginning in 2005, this testing included a FCEB design from Van Hool, UTC Power, and ISE (now Bluways), with energy storage in ZEBRA batteries. SunLine operated one of these buses and AC Transit operated three more. Two additional buses of this design operated in Belgium and at CTTRANSIT in Hartford, Connecticut.

The NFCBP funded UTC Power and AC Transit to maximize operation of AC Transit's three FCEBs (i.e., accelerated testing) to study reliability, durability, and failure modes of the fuel cell power system. This accelerated testing began in late 2007. The lessons learned and improvements to the design of the UTC Power fuel cell power system increased durability so that one of the systems reached 11,000 operating hours¹⁷ without significant maintenance, and two others have accumulated 6,000 and 8,000 operating hours without significant maintenance. Previous fuel cell power systems reached only about 4,000 operating hours before a low power output level indicated the end of useful life for the systems.

Following these initial testing activities, AC Transit, Van Hool, and UTC Power designed and developed an improved "next-design" FCEB for the Zero Emission Bay Area (ZEBA) advanced demonstration in California. AC Transit is leading a group of San Francisco Bay Area (Bay Area) transit agencies in this demonstration. The demonstration includes 12 new FCEBs and 2 new hydrogen fueling stations at 2 AC Transit operating depots. UTC Power and CTTRANSIT are demonstrating four more "next-design" FCEBs in Hartford, Connecticut. Demonstration of the "next-design" version of Van Hool-UTC Power FCEBs now includes 16 buses in 2 locations, making it the largest FCEB demonstration in the United States.

"Buy America" and Fuel Cell Electric Buses. "Buy America" Requirements (Title 49 CFR Part 661) sets standards for federally-assisted procurements, specifically: "... no funds may be obligated by FTA for a grantee project unless all iron, steel, and manufactured products used in the project are produced in the United States." In 2008, FTA granted a public interest waiver to the FTA "Buy America" requirements for NFCBP projects, so that project teams could access all available technologies and components, regardless of origin, in order to hasten the development of fuel cell technology for transit. This allowed teams to access a full slate of technology, many of which were not readily available domestically, for validating fuel cell bus technology, with the overall goal to stimulate and

¹⁷UTC Power press release. Available at <http://www.utcpower.com/pressroom/pressreleases/utc-power-fuel-cell-system-sets-world-record-achieving-10000-hr-durability>.

further expand the U.S. fuel cell bus industry. Over the past few years, FTA and the consortia have made progress toward meeting “Buy America” requirements:

- FTA funded EIDorado/BAE Systems/Ballard as new manufacturer partners to develop and demonstrate a new FCEB at SunLine and CTA. The new bus meets “Buy America” requirements and is assembled in Riverside, California.
- Increasing orders for FCEBs in the United States led Canadian-based fuel cell manufacturer, Ballard Power Systems, to establish manufacturing capabilities for fuel cell power systems in Lowell, Massachusetts. Fuel cell power systems are the largest cost component of FCEBs. Their availability in the United States helps bus manufacturers meet “Buy America” requirements.
- The UTC Power fuel cell power system is currently available only in Van Hool buses from Belgium. The NFCBP funded a project with Connecticut-based fuel cell manufacturer, UTC Power, to engineer, package, and test a further optimized fuel cell power system that can be installed easily into U.S. bus manufacturer models.

Hybrid Electric Propulsion Improvements

Hybrid electric propulsion for transit buses increases energy efficiency for the buses, but it also introduces complexity. Hybrid electric propulsion has the potential to reduce maintenance costs through fewer moving parts, battery energy storage, and regenerative braking, which reduces both brake wear and brake maintenance. The challenges for hybrid electric propulsion for buses are reliability and durability of the major components and optimized integration, especially software integration.

FTA funding for FCEB research enabled several bus manufacturers and integrators to gain experience in building and optimizing electric propulsion systems. It also enabled BAE Systems, a commercial electric propulsion manufacturer/supplier, to enter the FCEB market. With NFCBP funding, BAE Systems electrified accessories in its Compound Bus 2010 project, which led to an electric accessory package that will be integrated into its commercial hybrid products in the future. In addition, the NFCBP funded development of critical power electronics components for hybrid electric propulsion systems, such as DC-DC convertors. All of this research expands the availability of products to the transit industry.

Fueling Infrastructure and Building Modifications

Hydrogen fuel for FCEB demonstration projects is typically supplied through electrolysis or natural gas reforming, or it is trucked into a fueling site as liquid or high-pressure gas. FTA has invested in all of these methods to support not only the development of hydrogen fueling infrastructure, but also safe operations in and around transit maintenance, storage, and wash facilities. In addition, FTA funded the Volpe Center to review safety plans for transit FCEB operations and

infrastructure as well as to provide technical assistance to each transit agency operator of FCEBs.

Awareness and Education

An objective of all FTA research is to share results and lessons learned. Information sharing is a specific objective of the NFCBP, including lessons learned from FCEB and infrastructure research to facilitate technical progress and future research. FCEB development and demonstration reports document implementation to facilitate understanding of the requirements for market introduction.

All NFCBP demonstration projects also include an awareness and education component. Transit agencies that operate FCEBs are able to educate their passengers and the communities through outreach and public events. Through FY2011, the NFCBP has funded and/or produced 10 brochures and 29 reports about FCEB research.

The NFCBP also established both a national and an international working group for information sharing and cooperation. FTA initiated the International Fuel Cell Bus Working Group and workshops in 2002 to facilitate information sharing on worldwide FCEB demonstrations and to harmonize data collection to better understand the status of the technologies. Since the first workshop in 2002, FTA has facilitated six more workshops. Table 4-3 lists the workshops, including dates, locations, and associated events.

Table 4-3
*International Fuel Cell
Bus Workshops*

Workshop	Date	City	Country	Associated Event
1	November 2003	Anaheim, CA	USA	EVS 20
2	November 2004	Porto	Portugal	CUTE meeting
3	December 2005	Vancouver, BC	Canada	EDTA
4	October 2006	Yokohama	Japan	EVS 22
5	May 2008	Reykjavik	Iceland	CUTE meeting
6	June 2009	Vancouver, BC	Canada	HFC 2009
7	February 2011	San Francisco, CA	USA	None

FTA formed the National Fuel Cell Bus Working Group for information sharing about FCEB demonstrations in the United States. To facilitate participation from transit agencies around the country, the working group usually meets in conjunction with American Public Transportation Association (APTA) conferences. The working group was initiated at the 2002 APTA EXPO in Las Vegas, Nevada, and since that time has held three additional meetings to discuss national demonstrations and progress toward commercialization.

Table 4-4
*National Fuel Cell
 Bus Workshops*

Workshop	Date	City	Associated Event
1	2002	Las Vegas, NV	2002 APTA EXPO
2	May 2008	Austin, TX	2008 APTA Bus and Paratransit
3	May 2009	Seattle, WA	2009 APTA Bus and Paratransit
4	February 2011	San Francisco, CA	None

FTA intends to continue efforts to collaborate and coordinate with industry on FCEBs through outreach efforts with CTE to conduct a series of webinars on FCEB for the transit industry and a new website on worldwide activities and developments on fuel cell buses that will help facilitate national and international data sharing.

National Fuel Cell Bus Program (NFCBP)

- A1 American Fuel Cell Bus Project (CALSTART)
- A2 Compound Fuel Cell Hybrid Bus (CALSTART)
- A3 AC Transit HyRoad: Commercialization of Fuel Cells for Public Transit (CALSTART)
- A4 Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing (CTE)
- A5 Austin Demonstration Program Enhancement (CTE)
- A6 Nutmeg Program (NAVC)
- A7 Lightweight Battery Dominant Hybrid Fuel Cell Bus (NAVC)
- A8 Massachusetts Hydrogen Fuel Cell Powered Bus Program (NAVC)
- A9 Fuel Cell Development and Demonstration Program (NAVC)
- A10 Chicago Transit Authority Fuel Cell Bus Demonstration (CALSTART)
- A11 Advanced Composite Fuel Cell Bus Demonstration (CTE)
- A12 Birmingham Fuel Cell Bus Demonstration (CTE)
- A13 Hybrid Electric Fuel Cell Bus Demonstration (CTE)
- A14 Hybrid Fuel Cell Power Converter (CALSTART)
- A15 Integrated Auxiliary Module for Fuel Cell Bus (CALSTART)
- A16 Next-Generation Fuel Cell Power System Development Toward Commercialization, Phase I (CALSTART)
- A17 DC-DC Converter Development Program (CTE)
- A18 Survey and Analysis of Bus Demonstrations (CTE)
- A19 National Fuel Cell Bus Working Group (NAVC)
- A20 International Fuel Cell Bus Working Group (NAVC)
- A21 International Fuel Cell Bus Workshops (NAVC)
- A22 Coordination of Communications and Outreach for Fuel Cell Bus Program (CTE)
- A23 NREL Evaluation and Technical Support (FTA)
- A24 Volpe Center Safety Review and Analysis (FTA)

A1. American Fuel Cell Bus Project (CALSTART)

Project Type: Development and Demonstration

Project Start Date: 2008

Project Description: Development and demonstration of a fuel cell transit bus to meet “Buy America” requirements. SunLine will demonstrate the bus for at least one year as part of the NFCBP. This project adds EIDorado, a bus manufacturer, and BAE Systems, a commercial hybrid propulsion manufacturer, to the fuel cell transit bus demonstration partners.

- **Bus** – EIDorado, 40-foot bus, series hybrid, charge sustaining
- **Propulsion** – BAE Systems Hybridrive, including power electronics and integration; fuel cell power system from Ballard Power Systems, FCvelocity HD6, 150 kW, 12,000 hour/5-year warranty
- **Energy Storage** – BAE Systems energy storage system using AI23 lithium ion batteries, 200 kW peak

Fueling and Infrastructure: SunLine has a hydrogen fueling station using a HyRadix natural gas reformer.

Third-Party Assessment: FTA will analyze and report operations data and results.

Project Stage/Status: Ongoing. The bus was delivered to SunLine in October 2011 and is now in service.

Figure A-1
SunLine’s American
Fuel Cell Bus



A2. Compound Fuel Cell Hybrid Bus (CALSTART)

Project Type: Development and Demonstration

Project Start Date: 2007

Project Description: This project researches electrification of accessories and use of a smaller fuel cell system. BAE Systems integrated and packaged the accessories. SFMTA will demonstrate the bus.

- **Bus** – Orion VII, 40-foot bus, series hybrid, charge sustaining
- **Propulsion** – BAE Systems Hybridrive, including power electronics, electric accessories, and integration; fuel cell power system from Hydrogenics, HyPM HD, two 12 kW units in series
- **Energy Storage** – BAE Systems energy storage system using A123 lithium ion batteries, 200 kW peak

Fueling and Infrastructure: Coordinating access to fueling infrastructure.

Third-Party Assessment: FTA will analyze and report operations data and results.

Project Stage/Status: Ongoing. The bus was delivered and prepared for service. Problems obtaining hydrogen fuel delayed service start.

Fact Sheet: *Compound Fuel Cell Hybrid Bus Hits the Streets of San Francisco*, DOT/FTA-NFCBP-FS2, 2011

Figure A-2
Compound Fuel Cell
Hybrid Bus



A3. AC Transit HyRoad: Commercialization of Fuel Cells for Public Transit (CALSTART)

Project Type: Development and Demonstration

Project Start Date: 2007

Project Description: This project maximized operation of three FCEBs at AC Transit in Oakland, California. UTC Power examined failure modes within the fuel cell power systems. The project bridges to an expanded program of 12 new FCEBs as described in Project C1.

- **Bus** – Van Hool, 40-foot, hybrid propulsion and power electronics integrated by ISE Corp. (now Bluways)
- **Propulsion** – hybrid system is Siemens ELFA system; fuel cell system is UTC Power PureMotion 120 kW
- **Energy Storage** – three ZEBRA sodium nickel chloride, high-temperature batteries, 53 kWh

Fueling and Infrastructure: Chevron designed and built a hydrogen fueling station for AC Transit. The station produced hydrogen using natural gas reformers and then compressed the hydrogen to 5,000 psi for delivery. The station was decommissioned in August 2010 and removed. AC Transit will build a new station at the same location. AC Transit also built a second fueling station for the new FCEB demonstration.

Third-Party Assessment: FTA analyzed and reported operations data and results.

Figure A-3

AC Transit's First-Generation Fuel Cell Electric Bus



Project Stage/Status: Complete. FTA completed data analysis and reporting, and operations transitioned to new ZEBA FCEBs. The three original FCEBs are out of service. Their fuel cell power systems were transferred to newer buses, and two are still in service at AC Transit. As of December 2011, one of the power systems at AC Transit had completed 11,000 hours of operation without significant maintenance, and that system continues to operate. Two other buses at AC Transit have fuel cell power systems that have exceeded 6,000 and 8,000 hours of operation.

Reports:

- *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2*, NREL, 2010
- *National Fuel Cell Bus Program: Accelerated Testing Evaluation Report*, NREL, 2009

A4. Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing (CTE)

Project Type: Development and Demonstration

Project Start Date: 2007

Project Description: FTA supported the start-up of a new bus manufacturer, Proterra, and funded Proterra's first bus for this demonstration. The 35-foot battery dominant fuel cell Proterra bus was purpose built as an all-electric or hybrid electric bus. The bus was operated in Columbia, South Carolina, at Central Midlands Regional Transit Authority (CMRTA) and the University of South Carolina through 2010. The bus was then returned to Proterra for modifications and upgrades. In January 2012, the bus was delivered to a second demonstration site in Austin, Texas. It is scheduled to go into service in the first quarter of 2012 and to operate for one year.

- **Bus** – Proterra, 35-foot, battery dominant, plug-in hybrid propulsion and power electronics design, integrated by Proterra
- **Propulsion** – fuel cell power system from two Hydrogenics fuel cells, 16 kW each
- **Energy Storage** – Altairnano lithium titanate batteries, 54 kWh

Fueling and Infrastructure: The bus was fueled by a tube trailer of hydrogen trucked into the station in Columbia, South Carolina. The hydrogen was from landfill gas. In Austin, Texas, a Gas Technology Institute (GTI) station will produce hydrogen on-site with a natural gas reformer. A tube trailer will provide fuel while the station is being built and whenever the reformer is not operational. Both the trailer and the station will dispense hydrogen at up to 5,000 psi.

Third-Party Assessment: FTA will analyze and report operations data and results.

Figure A-4

Proterra's Fuel Cell Hybrid Bus



Project Stage/Status: Ongoing. The bus was delivered to CMRTA in August 2009 and the demonstration was completed in 2010. The bus then operated in Victoria, British Columbia, during the Winter Olympics, and was returned to Columbia, South Carolina, in early April 2010. In January 2012, the bus was delivered to Austin, Texas. Proterra is currently building additional electric buses for several fleets, many of which are funded by FTA's TIGGER Program.

Report: *National Fuel Cell Bus Program: Proterra Fuel Cell Hybrid Bus Report, Columbia Demonstration*, FTA Report No. 0003, October 2011

A5. Austin Demonstration Program Enhancement (CTE)

Project Type: Enhancement to A4

Project Start Date: 2011

Project Description: The Proterra bus originally demonstrated in Columbia, South Carolina, and will operate in Austin, Texas. Based on lessons learned from the first demonstration, FTA added funding to this project to insure the bus and to purchase in advance spare parts that have long procurement lead-times.

Project Stage/Status: Ongoing.

A6. Nutmeg Program (NAVC)

Project Type: Development and Demonstration

Project Start Date: 2007

Project Description: Led by UTC Power, this project includes the purchase and operation of four next-generation FCEBs. The buses are the same design as the 12 new FCEBs that will be operated at AC Transit in the Bay Area. These four buses will operate at CTTRANSIT. One may also operate in other locations.

- **Buses** – Van Hool, 40-foot, hybrid propulsion and power electronics integration by Van Hool
- **Propulsion** – hybrid electric using Siemens ELFA system, UTC Power PureMotion 120 kW fuel cell power system
- **Energy Storage** – lithium ion batteries from EnerDel, 17.4 kWh, 29 Ah

Fueling and Infrastructure: The fueling station at UTC Power will be the primary station used by the buses operated from CTTRANSIT. In addition, CTTRANSIT has a hydrogen dispensing station on-site in Hartford, Connecticut.

Third-Party Assessment: FTA will analyze and report operations data and results.

Project Stage/Status: Ongoing. The four new buses were delivered and in service by the end of 2010.

Fact Sheet: *Connecticut Nutmeg Fuel Cell Bus Project, DOT/FTA-NFCBP-FS3-July 2011*

Figure A-5
Next-Generation Fuel
Cell Electric Bus for
Nutmeg Project



A7. Lightweight Battery Dominant Hybrid Fuel Cell Bus (NAVC)

Project Type: Development and Demonstration

Project Start Date: 2008

Project Description: Led by GE, the project develops and demonstrates a commercially-viable FCEB with a lightweight body. The project includes the development of a testing vehicle that uses a Hydrogenics fuel cell power system for development work. In addition, a new bus for demonstration will use a Ballard fuel cell power system. The project includes development of model alternatives and a prototype, and assembly and demonstration of a new bus. The demonstration, at the University of Delaware, will last three months.

- **Bus** – Proterra, 35-foot, plug-in hybrid propulsion and power electronics design and integration by Proterra
- **Propulsion** – planned as a plug-in series hybrid, fuel cell power system from Ballard, integration support from GE
- **Energy Storage** – planned as a dual battery using a lithium ion battery pack and a metal halide battery pack

Fueling and Infrastructure: The University of Delaware will access a hydrogen station operated near campus by Air Liquide.

Third-Party Assessment: FTA will analyze and report operations data and results.

Project Stage/Status: Ongoing. Modeling of fuel cell power systems and testing of the prototype bus are complete. The project team is building the new lightweight bus.

A8. Massachusetts Hydrogen Fuel Cell Powered Bus Program (NAVC)

Project Type: Development and Demonstration

Project Start Date: 2008

Project Description: Led by Nuvera, this project will demonstrate a new, innovative approach to hydrogen fuel production and dispensing. It includes demonstration of a fuel cell bus with a project team lead by Nuvera and natural-gas-based hydrogen fueling either at Logan International Airport (operated by MassPort) or at an MBTA operating facility. The demonstration is expected to begin in 2013.

- **Bus** – ElDorado, 40-foot bus, series hybrid, charge sustaining
- **Propulsion** – fuel cell power system from Nuvera/Fiat, 82 kW; hybrid system from BAE Systems
- **Energy Storage** – planned as lithium ion batteries from AI23

Fueling and Infrastructure: The hydrogen station will use the Nuvera PowerTap natural gas reformer. The reformer will be co-located with an existing compressed natural gas (CNG) fueling station at Logan Airport or at an MBTA facility.

Third-Party Assessment: FTA will analyze and report operations data and results.

Project Stage/Status: Ongoing. This project did not receive significant funding until Year Three (2008). The Nuvera fuel cell stack is complete and in testing.

A9. Fuel Cell Development and Demonstration Program (NAVC)

Project Type: Development and Demonstration

Project Start Date: 2007

Project Description: New York Power Authority (NYPA) was to lead the development and demonstration of a FCEB. Due to teaming and cost-share complications, this project was discontinued.

Project Stage/Status: Closed.

A10. Chicago Transit Authority Fuel Cell Bus Demonstration (CALSTART)

Project Type: Development and Demonstration

Project Start Date: 2011

Project Description: This project will introduce a “Buy America” compliant FCEB to a large transit agency. The bus will be the same basic design as the American Fuel Cell Bus Project (see A1). The demonstration at CTA will validate the FCEB systems in a cold climate, which will facilitate introduction of FCEBs in more northern U.S. locations. Ballard will use the data to develop the next-generation stack for transit bus applications.

- **Bus** – ElDorado, 40-foot bus, series hybrid, charge sustaining
- **Propulsion** – BAE Systems Hybridrive including power electronics and integration; fuel cell power system from Ballard Power Systems, FCvelocity HD7, 150 kW, 12,000 hour/5-year warranty
- **Energy Storage** – BAE Systems energy storage system using A123 lithium ion batteries, 200 kW peak

Fueling and Infrastructure: Hydrogen fuel for demonstration is in the planning stage.

Third-Party Assessment: FTA will analyze and report operations data and results.

Project Stage/Status: Start up.

A11. Advanced Composite Fuel Cell Bus Demonstration (CTE)

Project Type: Development and Demonstration

Project Start Date: 2010

Project Description: This project uses the bus design developed under the Variable Output Fuel Cell Hybrid Bus Project (see A4). The project will modify the original design, including a Ballard fuel cell system instead of the original Hydrogenics fuel cell system. The bus will be demonstrated at Columbia, South Carolina, and Washington, DC.

- **Bus** – Proterra, 35-foot, plug-in hybrid propulsion and power electronics design and integration by Proterra
- **Propulsion** – fuel cell power system from Ballard Power Systems, 75 kW, HD6 module
- **Energy Storage** – Altairnano lithium titanate battery pack

Project Stage/Status: Start up.

A12. Birmingham Fuel Cell Bus Demonstration (CTE)

Project Type: Development and Demonstration

Project Start Date: 2011

Project Description: This project began as an FTA university research project in 2009 (see Project B3), where most of the design was completed. Teaming problems caused delay in the follow-on project. The 2010 NFCBP award allows completion of the work to demonstrate the bus in service in Birmingham, Alabama.

- **Bus** – EVAmerica 30-foot, plug-in hybrid propulsion and power electronics design and integration
- **Propulsion** – fuel cell power system from Ballard Power Systems, 75 kW, HD6 module
- **Energy Storage** – Altairnano lithium titanate battery pack

Project Stage/Status: Start up. The bus is in the build/test stage and will be ready for demonstration by the second quarter of 2012.

A13. Hybrid Electric Fuel Cell Bus Demonstration (CTE)

Project Type: Development and Demonstration

Project Start Date: 2011 (partial funding)

Project Description: DesignLine will integrate a Ballard fuel cell into its hybrid electric powertrain and install the equipment into a 35-foot bus chassis redesigned to reduce weight. The bus will operated in service in The Ohio State University campus shuttle system in Columbus, Ohio. DesignLine is the most recent FCEB manufacturer added to the NFCBP partners.

- **Bus** – DesignLine, 35-foot bus, battery dominant series hybrid
- **Propulsion** – DesignLine hybrid system design and integration; fuel cell power system from Ballard Power Systems
- **Energy Storage** – lithium ion batteries

Project Stage/Status: Start up.

A14. Hybrid Fuel Cell Power Converter (CALSTART)

Project Type: Component Development

Project Start Date: 2007

Project Description: U.S. Hybrid completed this project to scale the design of an existing automotive fuel cell DC-DC high-power converter to meet a broader range of heavy-duty hybrid fuel cell transit bus requirements. The resulting bi-directional DC-DC converter (BDC) is programmable and is compatible with several energy storage devices (batteries and ultracapacitors) and fuel cell power system products. It can replace the custom designs currently offered by drive train suppliers for hybrid fuel cell vehicle systems.

Project Stage/Status: Complete.

Report: *Hybrid Fuel Cell Power Converter Program, Final Report*, U.S. Hybrid/CALSTART, February 2009

A15. Integrated Auxiliary Module for Fuel Cell Bus (CALSTART)

Project Type: Component Development

Project Start Date: 2007

Project Description: This project fabricated and demonstrated a low-cost, compact, water-cooled integrated auxiliary module (IAM). The IAM from U.S. Hybrid contains a DC-DC converter and two small electric motors for auxiliary loads. The converter provides low voltage power to auxiliary systems. The electric motors drive hydraulic and air systems onboard the bus. The converter and drive motors are integrated into a single modular enclosure and controlled through an automotive controller area network (CAN) bus interface (SAE J1939). This integration will increase efficiency and reduce cost compared to current auxiliary systems.

Project Stage/Status: Complete.

Report: *Integrated Auxiliary Module for Fuel Cell Bus, Final Report*, U.S. Hybrid/CALSTART, February 2009

A16. Next-Generation Fuel Cell Power System
Development toward Commercialization,
Phase I (CALSTART)

Project Type: Component Development

Project Start Date: 2011

Project Description: This project is Phase I of a comprehensive plan to increase the durability and reliability of fuel cell power systems while reducing size and cost. The goal is to accelerate the development of a “Buy America” compliant, commercial fuel cell power plant that can be installed in multiple bus platforms.

Project Stage/Status: Start up.

A17. DC-DC Converter Development Program (CTE)

Project Type: Component Development

Project Start Date: 2011

Project Description: This project will develop a DC-DC converter that is suitable for interfacing a fuel cell to a hybrid propulsion system. Existing converters are problematic when used in a battery dominant hybrid powertrain. This project will resolve problems with current FCEB designs. The new DC-DC converter will be available for new designs under development.

Project Stage/Status: Start up.

A18. Survey and Analysis of Bus Demonstrations (CTE)

Project Type: Analysis and Technical Support

Project Start Date: 2007

Project Description: Between 2002 and 2007, CTE and Breakthrough Technologies Institute (BTI) developed a report that collected results, lessons learned, and problems from FCEB demonstrations in more than 20 cities around the world.

Project Stage/Status: Complete.

Report: *A Report on Worldwide Hydrogen Bus Demonstrations, 2002-2007*, CTE, BTI, March 2009

A19. National Fuel Cell Bus Working Group (NAVC)

Project Type: Outreach

Project Start Date: 2007

Project Description: NAVC coordinated and facilitated meetings of a working group of U.S.-based FCEB industry stakeholders. NAVC facilitated seven meetings (see Table 4-3) and developed a website to share FCEB operating data among the working group members.

Project Stage/Status: Complete.

A20. International Fuel Cell Bus Working Group (NAVC)

Project Type: Outreach

Project Start Date: 2007

Project Description: NAVC coordinated the International Fuel Cell Bus Working Group, including collaboration and outreach for international FCEB demonstrations. NAVC facilitated seven International Fuel Cell Bus Workshops, four of which were funded under this project. These meetings were held in Yokohama, Japan, in October 2006; Reykjavik, Iceland, in May 2008; Vancouver, British Columbia, Canada, in June 2009; and San Francisco, California, in February 2011. NAVC developed a website to share FCEB operating data among the working group members.

Project Stage/Status: Complete.

A21. International Fuel Cell Bus Workshops (NAVC)

Project Type: Outreach

Project Start Date: 2007

Project Description: The Electric Drive Transportation Association (EDTA) conducted four workshops with the International Fuel Cell Bus Working Group in the following locations: Yokohama, Japan, in October 2006; Reykjavik, Iceland, in May 2008; Vancouver, British Columbia, Canada, in June 2009; and San Francisco, California, in February 2011.

Project Stage/Status: Complete.

A22. Coordination of Communication and Outreach for Fuel Cell Bus Program (CTE)

Project Type: Outreach

Project Start Date: 2011

Project Description: This project is follow-on to earlier projects A20 and A21. It will update the Survey and Analysis Report (Project A18) to include more recent worldwide FCEB demonstration projects. In addition, it will facilitate coordination with ongoing international and national FCEB demonstration projects for data and information sharing on the current status of technologies.

Project Stage/Status: Start up. The first National Fuel Cell Bus Workshop was held in conjunction with the October 2011 APTA EXPO in New Orleans, Louisiana.

A23. NREL Evaluation and Technical Support (FTA)

Project Type: Analysis and Technical Support

Project Start Date: 2006

Project Description: This project provides third-party evaluation and dissemination of results. NREL evaluations are comprehensive, unbiased assessments of fuel cell and hydrogen bus development and performance compared to conventional diesel and compressed natural gas (CNG) buses. Transit agencies use the evaluations in considering future procurements. Manufacturers need to understand the status of the technology for transit applications. Government agencies use the evaluations in making policy decisions and determining future research needs.

Project Stage/Status: Ongoing. For NFCBP, NREL supports the outreach and information dissemination projects and performs evaluations of the development and demonstration projects. So far, one of the eight planned evaluations is complete—AC Transit accelerated testing—and three are under way—CTE/Proterra, Nutmeg, and AFCB. The CTE/Proterra bus has moved to the second demonstration site and is expected to go into service there in early 2012. The BAE Systems APU bus for SFMTA has been delivered and should also begin service in early 2012.

Reports:

- *Fuel Cell Transit Bus Evaluations*, Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-5600-49342, 2010
- *Hydrogen and Fuel Cell Transit Bus Evaluations*, Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-560-42781, 2008

A24. Volpe Center Safety Review and Analysis (FTA)

Project Type: Analysis and Technical Support

Project Start Date: 2008

Project Description: The Volpe Center is providing technical support to FTA (and grantees) for review of system safety plans and other safety aspects of fuel cell projects.

Project Stage/Status: Ongoing.

Other FTA FCEB or Hydrogen-Related Research Projects

- B1 Hydrogen Fuel Cell Plug-In Hybrid Bus, Austin, TX
- B2 University of Delaware Fuel Cell Vehicle Project
- B3 University of Alabama at Birmingham Hybrid Electric and Fuel Cell Research
- B4 Georgetown University FCEB Research
- B5 Northern Illinois University Fuel Cell Research
- B6 Fueling Station for Hydrogen-Fueled Shuttle Buses
- B7 Connecticut Hydrogen Transit Vehicle Development Project
- B8 East Tennessee Hydrogen Initiative
- B9 Missouri S&T Hydrogen Shuttle Project
- B10 University of Alabama Hybrid Electric and Fuel Cell Research
- B11 American Fuel Cell Buses for SunLine

B1. Hydrogen Fuel Cell Plug-In Hybrid Bus in Austin, TX

Project Type: Development and Demonstration

Project Start Date: 2006

Project Description: The University of Texas at Austin Center for Electromechanics (UT-CEM) (see <http://www.utexas.edu/research/cem/>) completed an earmark project for FTA to demonstrate and assess advanced hybrid electric technologies including hybrid hydrogen fuel cell propulsion. This project had two goals:

1. Evaluate the performance of one plug-in FCEB
2. Extrapolating from the demonstration, develop a computer simulation model to examine configuration options for the hybrid bus and energy storage systems.

From October 2007 through June 2008, UT-CEM demonstrated and evaluated a 22-foot plug-in FCEB manufactured by Ebus and leased from GTI. The bus used a 19 kW Ballard fuel cell system and nickel cadmium batteries, with integration of the hybrid propulsion system by Ebus. Project results included simulation modeling of the Ebus design with options for the hybrid and energy storage systems for optimization.

Fueling and Infrastructure: UT-CEM stored the FCEB indoors and upgraded the storage/maintenance facility with several safety and monitoring systems for hydrogen. A tube trailer that stored 40,000 scf of hydrogen at 2,400 psi supplied hydrogen fuel for the bus.

Third-Party Assessment: None. UT-CEM evaluated the operation of the FCEB.

Project Stage/Status: Complete. UT-CEM continues its research. UT-CEM will build a new fueling station; the station has been designed by GTI and includes a natural gas reformer for hydrogen production.

Report: *Heavy Hybrid Vehicles Technology Program, Final Report*, University of Texas at Austin, October 2008

Figure B-1

University of Texas
Fuel Cell Bus



B2. University of Delaware Fuel Cell Transit Vehicle Project

Project Type: Development and Demonstration

Project Start Date: 2005

Project Description: The University of Delaware (UD) Department of Mechanical Engineering, Center for Fuel Cell Research (see www.me.udel.edu/research_groups/prasad/index.html), received several earmark grants from FTA starting in 2004. The grants established five phases of FCEB research:

- **Phase 1:** Develop a plug-in FCEB—22-foot FCEB from Ebus with a 19.3 kW Ballard Mark 9 fuel cell and 60 kWh SAFT Ni-Cd (nickel cadmium) batteries for energy storage. The bus was delivered to UD in February 2007. The bus has data logging capabilities and operates in the campus shuttle bus system.
- **Phase 2:** Develop a plug-in FCEB – 22-foot FCEB from Ebus with a dual fuel cell system providing 40 kW (Ballard fuel cell systems) and 60 kWh Ni-Cd SAFT battery energy storage. The bus was delivered to UD in the spring of 2009. The bus has data logging capabilities and operates in the campus shuttle bus system.
- **Phase 3:** Develop a plug-in FCEB – 30-foot FCEB from Ebus with a dual fuel cell system providing 40 kW (Ballard fuel cell systems) and 33 kWh Li-Ti (lithium titanate) battery energy storage. The bus is planned for delivery in the spring of 2012.
- **Phase 4:** Develop a plug-in FCEB – 30-foot FCEB similar to the Phase 3 bus. The bus will incorporate lessons learned from the earlier buses, e.g., advances in the fuel cell system, improved energy storage, more efficient balance of plant for the fuel cell systems, a new control algorithm, and state-of-the-art sensors for real-time performance evaluation of the propulsion and bus systems.
- **Phase 5:** Upgrade Phase 1 and Phase 2 buses and continue to demonstrate and evaluate the four-bus fleet.

Figure B-2

University of Delaware
Fuel Cell Bus



Fueling and Infrastructure: An Air Liquide station provides hydrogen fueling at the Delaware Research and Technology Center. This slow-fill station stores hydrogen as a cryogenic liquid then heats and compresses the hydrogen as a gas for dispensing. The station was upgraded with a high-pressure storage buffer so that fueling is accomplished in approximately 15 minutes. Two more Air Liquide hydrogen fueling stations are planned in Wilmington, Delaware, and Dover, Delaware. UD may use these fueling stations for the demonstration of their four FCEBs.

Third-Party Assessment: None planned. UD monitors and evaluates the operation of their FCEBs.

Project Stage/Status: Ongoing. Two of the FCEBs are in operation; the other two are planned for 2012. Phase 5 was proposed to FTA but is not yet approved.

B3. University of Alabama at Birmingham Hybrid Electric and Fuel Cell Research

Project Type: Development and Demonstration

Project Start Date: 2009

Project Description: The University of Alabama at Birmingham (UAB) (see <http://www.uab.edu/engineering/departments-research/civil>) received an earmark grant from FTA to develop and demonstrate a 30-foot plug-in FCEB. The project team includes UAB, EVAmerica as the FCEB manufacturer, Birmingham-Jefferson County Transit for bus operations, and CTE.

Fueling and Infrastructure: None determined.

Third-Party Assessment: None.

Project Stage/Status: Closed. With the addition of funding from the NFCBP (2010 funds), this project will be combined with a NFCBP project. The combined project will include both the new FCEB and fueling infrastructure.

B4. Georgetown University Fuel Cell Bus Research

Project Type: Development and Demonstration

Project Start Date: 1994

Project Description: Georgetown University (see <http://fuelcellbus.georgetown.edu/>) received earmarks and discretionary grants from FTA for more than 15 years to study fuel cell propulsion in transit buses operating on liquid fuel (methanol) instead of gaseous hydrogen. The methanol is reformed onboard the bus to extract and supply hydrogen to the fuel cell power system. This chemical processing adds complexity and cost. However, it replaces the hydrogen fueling infrastructure. The infrastructure for fueling methanol is not as complex or expensive as the infrastructure for fueling hydrogen. Currently, this project is the only one in the United States attempting a FCEB not fueled by gaseous hydrogen onboard the bus. The project developed five FCEBs fueled by methanol.

Fueling and Infrastructure: Methanol liquid fueling system on-site. Bus maintenance and storage facilities similar to gasoline with no other changes needed.

Third-Party Assessment: None.

Project Stage/Status: Complete.

Brochure: *Advanced Vehicle Development, The Fuel Cell Bus Program*, Georgetown University, April 2006

Figure B-3

Three Fuel Cell Buses
Developed as Part of
Georgetown Program



B5. Northern Illinois University Fuel Cell Research

Project Type: General Research

Project Start Date: 2008

Project Description: Northern Illinois University (College of Engineering & Engineering Technology, <http://www.niu.edu/CEET/>) received an earmark grant (IL-26-7006) from FTA for research in the following areas:

- New catalysts
- Membrane electrode assembly performance
- Multi-cell analysis and validation
- Bipolar plates
- Fuel cell materials durability
- Hybrid technology

Project Stage/Status: Complete.

Report: *Final Report, Fuel Cells for Transportation Applications*, Northern Illinois University, February 2009

B6. Fueling Station for Hydrogen-Fueled Shuttle Buses

Project Type: Development and Demonstration

Project Start Date: 2009

Project Description: Da Vinci Discovery Center of Science and Technology (Da Vinci Center) and Air Products received an earmark grant from FTA to develop a hydrogen fueling station and to purchase hydrogen internal combustion engine shuttle buses for service to the Da Vinci Center and Lehigh Valley Hospital Cedar Crest in Allentown, Pennsylvania. This project includes data collection and reporting to FTA.

Fueling and Infrastructure: Air Products designed and installed a liquid hydrogen storage station with compression and the ability to deliver compressed hydrogen gas to the shuttle buses. The station is located on Air Products' Trexlertown, Pennsylvania, campus.

Third-Party Assessment: None planned.

Project Stage/Status: Ongoing.

Figure B-4
*Hydrogen ICE Buses
at Hydrogen Station*



B7. Connecticut Hydrogen Transit Vehicle Development Project

Project Type: Development and Demonstration

Project Start Date: 2005

Project Description: The Greater New Haven Transit District (GNHTD) (see project website at <http://www.hyride.org/>) received an earmark grant from FTA to develop one bus and hydrogen fueling infrastructure in the New Haven, Connecticut, area. The project goal is “to develop, test and commercialize a hydrogen-fueled transit vehicle in Connecticut” and to use “green” energy when possible. The FCEB began operation in August 2011 as a shopping shuttle for older adults in Hamden, Connecticut.

- **Bus** – Ebus, 22-foot, plug-in hybrid propulsion and power electronics design and integration
- **Propulsion** – fuel cell power system from Ballard PEM Mark 9, 19.3 kW
- **Energy Storage** – SAFT nickel-cadmium, 50 kWh

Fueling and Infrastructure: The planned hydrogen fueling station will use electrolysis and “green” electricity, most likely wind. The station will be completed in fall 2011. The project will also modify a maintenance facility for use by hydrogen-fueled buses.

Third-Party Assessment: None planned.

Project Stage/Status: Ongoing. The hydrogen fueling infrastructure and maintenance facility modifications began in fall 2011. GNHTD purchased a 22-foot Ebus FCEB and started operation on August 8, 2011.

Figure B-5

Greater New Haven
Transit District's
Fuel Cell Electric Bus



B8. East Tennessee Hydrogen Initiative

Project Type: General Research

Project Start Date: 2008

Project Description: The University of Tennessee at Chattanooga, Center for Energy, Transportation and the Environment (see <http://www.utc.edu/Research/CETE/>), received an earmark grant from FTA to research hydrogen production, storage, and dispensing technologies and methods to provide hydrogen fueling in the Chattanooga, Tennessee area. This project included the following:

- Compare methods for producing hydrogen, including nuclear energy, coal gasification, natural gas reformation, and electrolysis.
- Develop a simulation model to relate energy consumption to power and energy storage requirements for transit vehicle operations.
- Develop an economic model to analyze and estimate the cost of hydrogen production by electrolysis compared to large scale production costs associated with coal gasification and natural gas reformation.
- Describe the decision-making process used to select technologies for configuring a hydrogen fueling system optimized to support research on hydrogen for transit vehicle operations.
- Investigate methods and materials for onboard storage of hydrogen at potentially lower pressure than currently used (up to 5,000 psi or 10,000 psi).
- Develop a case study for transitioning a medium-sized transit agency from diesel and compressed natural gas buses to hydrogen buses.
- Complete the installation of a 1 to 2 kg/day hydrogen fueling station on the University of Tennessee campus.
- Develop and demonstrate a new hydrogen-powered, battery-centric, hybrid internal combustion engine (HHICE) shuttle bus that can be operated in public transit service at Chattanooga Area Regional Transit Authority as part of the university shuttle system.

Project Stage/Status: Complete.

Report: *East Tennessee Hydrogen Initiative, Chattanooga, Charting a Course for the Region's Hydrogen Transportation Infrastructure*, University of Tennessee at Chattanooga, Center for Energy, Transportation and the Environment, September 2009

B9. Missouri S&T Hydrogen Shuttle Project

Project Type: Development and Demonstration

Project Start Date: 2009

Project Description: Missouri University of Science and Technology (formerly University of Missouri at Rolla, now Missouri S&T) and Missouri Transportation Institute (see <http://mti.mst.edu/>) received an earmark grant from FTA to research green energy use for infrastructure and hydrogen fuel production and dispensing. A small FCEB is under consideration for addition to the project.

Fueling and Infrastructure: This project adds an electrolyzer to existing hydrogen fueling. Electricity for the electrolyzer comes from “green energy,” including solar panels and a wind turbine purchased and installed as part of the project.

Third-Party Assessment: None.

Project Stage/Status: Ongoing. Additions of green energy for the electrolyzer are in process.

B10. University of Alabama Hybrid Electric and Fuel Cell Research

Project Type: General Research

Project Start Date: 2006

Project Description: The University of Alabama, Center for Advanced Vehicle Technologies (see <http://cavt.eng.ua.edu/>), received an earmark grant from FTA to research hybrid electric and fuel cell transit bus systems and integration.

Project Stage/Status: Ongoing.

B11. American Fuel Cell Buses for SunLine

Project Type: Development and Demonstration

Project Start Date: Late 2011 (part of TIGGER)

Project Description: SunLine and its manufacturer partners from the American Fuel Cell Bus Project will build two FCEBs for operation at SunLine. The project will demonstrate the FCEBs for commercialization, taking the buses designed under the NFCBP from demonstration to commercial products.

Fueling and Infrastructure: SunLine has a hydrogen fueling station that uses a natural gas reformer from HyRadix.

Third-Party Assessment: FTA will fund evaluation of this project through its TIGGER assessment project with DOE/NREL.

Project Stage/Status: Start up.

Figure B-6
SunLine's American
Fuel Cell Bus



Evaluations of Other FCEB Demonstrations

- C1 AC Transit Zero Emission Bay Area Demonstration
- C2 SunLine Advanced Technology Fuel Cell Bus Demonstration
- C3 City of Burbank, California Demonstration
- C4 Connecticut Transit Fuel Cell Bus Demonstration
- C5 SunLine Fuel Cell Bus Demonstration
- C6 AC Transit HyRoad Demonstration
- C7 Santa Clara Valley Transportation Authority Fuel Cell Bus Demonstration

C1. AC Transit Zero Emission Bay Area Demonstration

Project Type: Development and Demonstration

Project Start Date: 2010

Project Description: Led by AC Transit (see www.actransit.org), the ZEBA advanced FCEB demonstration includes four other Bay Area transit agencies: Golden Gate Transit (GGT); SamTrans; SFMTA; and Santa Clara VTA. Beginning in mid-2010, AC Transit and the ZEBA group began demonstration of the new FCEBs. ZEBA is demonstrating a total of 12 buses.

- **Buses** – Van Hool, 40-foot, hybrid propulsion and power electronics integration by Van Hool
- **Propulsion** – hybrid electric using Siemens ELFA system, UTC Power PureMotion 120 kW fuel cell power system
- **Energy Storage** – lithium ion batteries from EnerDel, 17.4 kWh, 29 Ah

Fueling and Infrastructure: The FCEB operation first used a temporary hydrogen fueling station provided by Air Products at AC Transit's East Oakland Division. This temporary station was decommissioned, and Linde will design and construct a new fueling station in its place. The new station is scheduled for operation by the end of 2012. In addition, Linde designed and constructed another fueling station at AC Transit's Emeryville Division. This station is fully operational.

Third-Party Assessment: DOE/NREL is analyzing and reporting data and results.

Project Stage/Status: Ongoing. All 12 buses were delivered and are in service. Full data collection and analysis is underway, with a report scheduled for June 2012.

Figure C-1

Next-Generation Fuel Cell Electric bus for the ZEBA Project



Report: *Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: First Results Report*, NREL/TP-5600-52015, 2011

Fact Sheet: *Bay Area Transit Agencies Propel Fuel Cell Buses Toward Commercialization*, NREL, DOE/GO-102010-3067, 2010

C2. SunLine Advanced Fuel Cell Bus Demonstration

Project Type: Development and Demonstration

Project Start Date: 2010

Project Description: SunLine Transit Agency purchased a pilot bus from an order of 20 FCEBs delivered to BC Transit in Whistler, British Columbia, Canada. The bus is an updated design from Bluways, New Flyer, and Ballard.

- **Bus** – New Flyer, 40-foot, hybrid propulsion and power electronics integration by Bluways
- **Propulsion** – hybrid electric using Siemens ELFA system, Ballard FCvelocity HD6 150 kW fuel cell power system
- **Energy Storage** – Valance phosphate-based lithium ion batteries, 47 kWh

Fueling and Infrastructure: SunLine has a hydrogen fueling station that uses a natural gas reformer from HyRadix.

Third-Party Assessment: DOE/NREL has evaluated and reported results.

Project Stage/Status: Ongoing. The FCEB was moved from BC Transit to Bluways for upgrades, was prepared for and delivered to SunLine, and started service in late May 2010.

Reports:

- *SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Second Results Report*, NREL/TP-5600-52349, 2011
- *SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation: First Results Report*, NREL/TP-5600-50500, 2011

Brochure: *SunLine Leads the Way in Demonstrating Hydrogen-Fueled Bus Technologies*, NREL, DOE/GO-102011-3181, 2011

Figure C-2
Advanced Technology
Fuel Cell Bus



C3. City of Burbank Demonstration

Project Type: Development and Demonstration

Project Start Date: 2010

Project Description: The City of Burbank purchased one fuel cell plug-in hybrid bus (the second Proterra FCEB) as part of a California Air Resources Board (CARB) project. The city will conduct a one-year demonstration to investigate operating cost and reliability of the propulsion technology.

- **Bus** – Proterra, 35-foot, plug-in hybrid propulsion and power electronics design and integration by Proterra
- **Propulsion** – fuel cell power system from two Hydrogenics systems, 16 kW each
- **Energy Storage** – Altairnano lithium titanate batteries, 54 kWh

Fueling and Infrastructure: The city has a hydrogen fueling station. The station currently provides hydrogen from a natural gas reformer with a tube trailer as back-up.

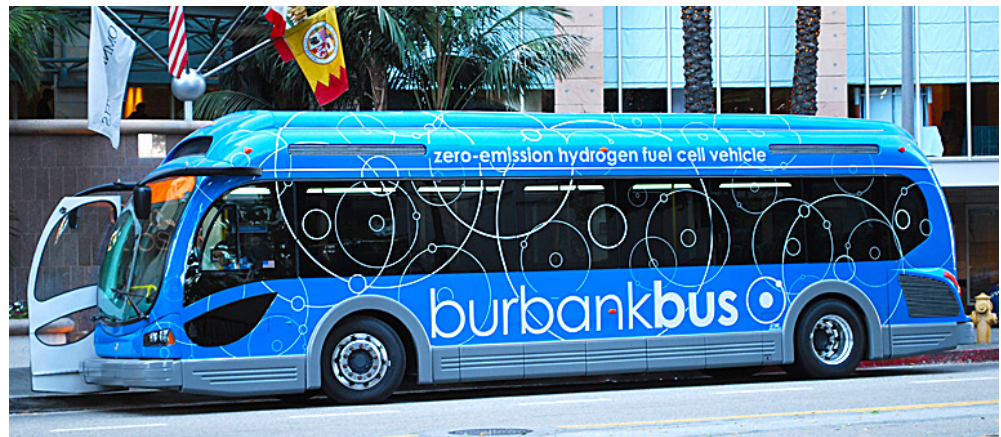
Third-Party Assessment: DOE/NREL will evaluate and report results.

Project Stage/Status: Ongoing. The FCEB was delivered in April 2010. Problems with the bus delayed the in-service operation. Proterra is upgrading the bus based on lessons learned in the Columbia, South Carolina, demonstration (see project A4). Burbank estimates a second quarter 2012 service start.

Fact Sheet: *Fuel Cell Bus Takes a Starring Role in the BurbankBus Fleet*, NREL, DOE/GO-102010-3035, 2010

Figure C-3

*Proterra Fuel Cell
Electric Bus for
Burbank, California*



C4. Connecticut Transit Fuel Cell Bus Demonstration

Project Type: Development and Demonstration

Project Start Date: 2006

Project Description: CTTRANSIT placed one FCEB into operation in Hartford, Connecticut, in April 2007, and the bus is still operating. CTTRANSIT exceeded its goal of operating the bus for two years in a cold and sometimes snowy environment. The bus design is the same as the three buses that operated at AC Transit (see project C6) and the one bus operating at SunLine (see project C5).

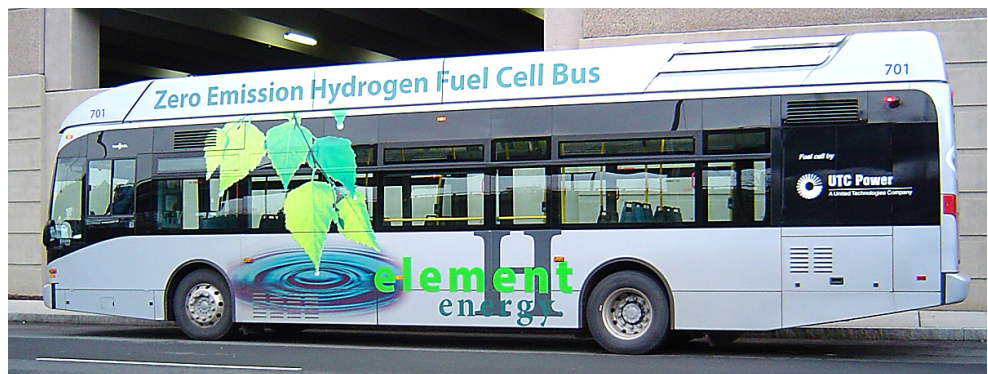
- **Bus** – Van Hool, 40-foot, hybrid propulsion and power electronics integrated by ISE Corp. (now Bluways)
- **Propulsion** – hybrid system is Siemens ELFA system, fuel cell system is UTC Power PureMotion 120 kW
- **Energy Storage** – three ZEBRA sodium nickel chloride, high-temperature batteries, 53 kWh

Fueling and Infrastructure: UTC Power provides hydrogen fueling at their headquarters facility near CTTRANSIT's Hartford operations. The fueling station has liquid storage and delivers gas into the bus at up to 5,000 psi. CTTRANSIT added ventilation capacity and combustible detection systems to its maintenance and storage facilities to accommodate operation of the FCEB on battery power while inside the buildings.

Third-Party Assessment: DOE/NREL evaluated and reported results for this project.

Project Stage/Status: Complete. The FCEB is still in service in Hartford. DOE/NREL documented its evaluations in three reports. NREL continues to monitor the bus with funding from FTA's NFCBP.

Figure C-4
CTTRANSIT's Early-
Generation Fuel Cell
Electric Bus



Reports:

- *Connecticut Transit (CTTRANSIT), Fuel Cell Transit Bus: Third Evaluation Report, NREL/TP-560-47334, 2010;*
- *Connecticut Transit (CTTRANSIT), Fuel Cell Transit Bus: Second Evaluation Report, NREL/TP-560-45670, 2009*
- *Connecticut Transit (CTTRANSIT), Fuel Cell Transit Bus: Preliminary Evaluation Results, NREL/TP-560-43847, 2008*

Fact Sheet: *CTTRANSIT Operates New England's First Fuel Cell Hybrid Bus, DOE/GO-12008-2529, 2008*

C5. SunLine Fuel Cell Bus Demonstration

Project Type: Development and Demonstration

Project Start Date: 2005

Project Description: SunLine operated a FCEB in the hot desert climate of Palm Springs, California, from January 2006 until December 2011, thus exceeding its goal to operate the bus for two years. This bus design was the same as that of the three buses that operated at AC Transit (see project C6) and the bus that operated at CTTRANSIT (see project C4).

- **Bus** – Van Hool, 40-foot, hybrid propulsion and power electronics integrated by ISE Corp.
- **Propulsion** – hybrid system is Siemens ELFA system, fuel cell system is UTC Power PureMotion 120 kW
- **Energy Storage** – three ZEBRA sodium nickel chloride, high-temperature batteries, 53 kWh

Fueling and Infrastructure: SunLine has a hydrogen fueling station that uses a natural gas reformer from HyRadix.

Third-Party Assessment: DOE/NREL evaluated and reported results for this project.

Project Stage/Status: Complete. SunLine removed the FCEB from service in December 2011 when the fuel cell reached the end of life. DOE/NREL documented its evaluation in five reports.

Figure C-5

*SunLine's
Early-Generation
Fuel Cell Bus*



Reports:

- *SunLine Transit Agency, Fuel Cell Transit Bus: Fifth Evaluation Report*, NREL/TP-560-46346, 2009
- *SunLine Transit Agency, Fuel Cell Transit Bus: Fourth Evaluation Report*, NREL/TP-560-44646, 2009
- *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Third Evaluation Report*, NREL/TP-560-43741, 2008
- *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Evaluation Results Update*, NREL/TP-560-42080, 2007
- *SunLine Transit Agency, Hydrogen-Powered Transit Buses: Preliminary Evaluation Results*, NREL/TP-560-41001, 2007

Fact Sheet: *SunLine Expands its Horizons with Fuel Cell Bus Demo*, DOE/GO-102006-2287, 2006

C6. AC Transit HyRoad Demonstration

Project Type: Development and Demonstration

Project Start Date: 2005

Project Description: AC Transit operated three FCEBs beginning in March 2006 and exceeded its goal of operating these buses for two years. AC Transit took the buses out of service only as newer FCEBs for the ZEBRA demonstration were delivered. The bus design for these three buses was the same as for the bus that operated at SunLine (see project C5) and the one still operating at CTTRANSIT (see project C4).

- **Bus** – Van Hool, 40-foot, hybrid propulsion and power electronics integrated by ISE (now Bluways)
- **Propulsion** – hybrid system is Siemens ELFA system, fuel cell system is UTC Power PureMotion 120 kW
- **Energy Storage** – three ZEBRA sodium nickel chloride, high-temperature batteries, 53 kWh

Fueling and Infrastructure: AC Transit used a hydrogen fueling station designed and built by Chevron. The station used natural gas reformers to produce the hydrogen. The station then compressed the gas for delivery at up to 5,000 psi. The station was decommissioned and removed from AC Transit's East Oakland Division.

Third-Party Assessment: DOE/NREL evaluated and reported results for this project.

Project Stage/Status: Complete. The three FCEBs completed service in Oakland, California. DOE/NREL documented its evaluation in three reports.

Figure C-6

AC Transit
Early-Generation
Fuel Cell Electric Bus



Reports:

- *Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Third Evaluation Report and Appendices*, NREL/TP-560-43545, 2008
- *Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Evaluation Results Update*, NREL/TP-560-42249, 2007
- *AC Transit, Fuel Cell Transit Buses: Preliminary Evaluation Results*, NREL/TP-560-41041, 2007

Fact Sheet: *AC Transit Demos Three Prototype Fuel Cell Buses*, DOE/GO-102006-2286, 2006

C7. Santa Clara Valley Transportation Authority Fuel Cell Bus Demonstration

Project Type: Development and Demonstration

Project Start Date: 2004

Project Description: Santa Clara VTA and SamTrans worked together to demonstrate fuel cell buses at VTA. The project began in February 2005.

- **Bus** – Gillig, 40-foot, direct electric drive installed by Gillig
- **Propulsion** – fuel cell power system from Ballard, P5-2, 300 kW
- **Energy Storage** – none, no regenerative braking

Fueling and Infrastructure: Air Products designed and built the hydrogen fueling station. The station provided liquid storage on-site and dispensed high-pressure (up to 5,000 psi) hydrogen into buses. The project included a specially designed maintenance facility and modified bus wash facilities to accommodate the taller fuel cell buses.

Third-Party Assessment: DOE/NREL evaluated and reported results for this project.

Project Stage/Status: Complete. Santa Clara VTA retired all three buses from service. In addition, the fueling station was decommissioned, although the equipment is still in place. DOE/NREL documented its evaluation in two reports.

Figure C-7

Two of VTA's
Fuel Cell Buses



Reports:

- *Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Evaluation Results*, NREL/TP-560-40615, 2006
- *Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Preliminary Evaluation Results*, NREL/TP-560-39365, 2006

Fact Sheet: *VTA, SamTrans Look into Future with Bus Demo*, DOE/GO-102005-2147, 2005

Acronyms and Abbreviations

AC	Alternating current
AC Transit	Alameda-Contra Costa Transit District
APTA	American Public Transportation Association
APU	Auxiliary power unit
ARRA	American Recovery and Reinvestment Act of 2009
BDC	Bi-directional DC-DC converter
BTI	Breakthrough Technologies Institute
CAN	Controller area network
CARB	California Air Resources Board
CMRTA	Central Midlands Regional Transit Authority
CNG	Compressed natural gas
CTA	Chicago Transit Authority
CTE	Center for Transportation and the Environment
CTTRANSIT	Connecticut Transit
DC	Direct current; District of Columbia
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
EO	Executive Order
EPA	U.S. Environmental Protection Agency
FCEB	Fuel cell electric bus
FTA	Federal Transit Administration
FY	Fiscal year
GE	General Electric
GGT	Golden Gate Transit
GNHTD	Greater New Haven Transit District
GTI	Gas Technology Institute

HHICE	Hydrogen-powered, battery-centric, hybrid internal combustion engine
IAM	Integrated auxiliary module
NAVC	Northeast Advanced Vehicle Consortium
NFCBP	National Fuel Cell Bus Technology Development Program; National Fuel Cell Bus Program
NHTSA	National Highway Transportation Safety Administration
NREL	National Renewable Energy Laboratory
NYPA	New York Power Authority
RFI	Request for information
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SamTrans	San Mateo County Transit District
SFMTA	San Francisco Municipal Transportation Agency
SunLine	SunLine Transit Agency
TIGER	Transportation Investment Generating Economic Recovery
TIGGER	Transit Investments for Greenhouse Gas and Energy Reduction
UAB	University of Alabama at Birmingham
UD	University of Delaware
UT-CEM	University of Texas at Austin Center for Electromechanics
VTA	Santa Clara Valley Transportation Authority
ZEBA	Zero Emission Bay Area



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