FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

Connecticut Nutmeg Fuel Cell Bus Project: First Analysis Report

JULY 2012

FTA Report No. 0020
Federal Transit Administration

PREPARED BY

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National Renewable Energy Laboratory

Kevin Chandler
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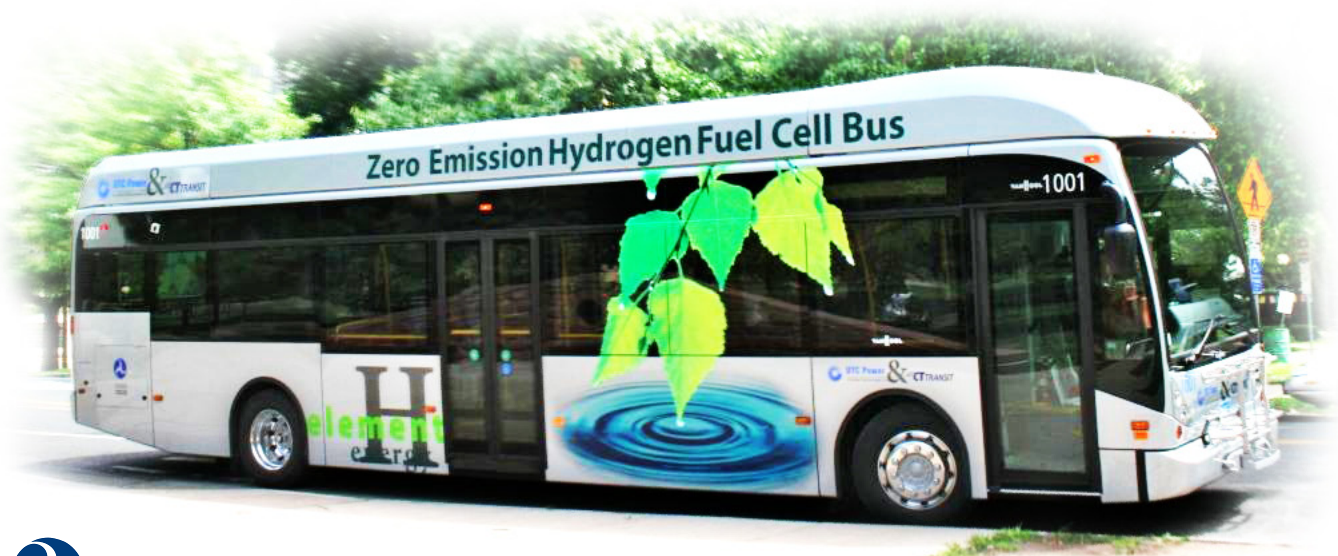

COVER PHOTO

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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
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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13. ABSTRACT

This report summarizes the experience and early results from a fuel cell bus demonstration funded by the Federal Transit Administration (FTA) under the National Fuel Cell Bus Program (NFCBP). A team led by the Northeast Advanced Vehicle Consortium and UTC Power developed a next-generation fuel cell electric bus for demonstration. A total of four buses are being operated in service by Connecticut Transit in Hartford. The National Renewable Energy Laboratory has been tasked by FTA to evaluate the buses in service. This report documents the early development and implementation of the buses and summarizes the performance results through May 2012.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

This report summarizes the experience and early results from the Connecticut Nutmeg Fuel Cell Bus Project, a fuel cell bus demonstration funded by the Federal Transit Administration (FTA) under the National Fuel Cell Bus Program (NFCBP). A team led by the Northeast Advanced Vehicle Consortium and UTC Power developed a next-generation fuel cell electric bus for demonstration. A total of four buses are being operated in service by Connecticut Transit (CTTRANSIT) in Hartford, Connecticut. The National Renewable Energy Laboratory (NREL) has been tasked by FTA to evaluate the buses in service. This report documents the early development and implementation of the buses and summarizes the performance results through May 2012.

EXECUTIVE SUMMARY

This report presents results of the Connecticut Nutmeg Fuel Cell Electric Bus Project, a demonstration (led by UTC Power and the Northeast Advanced Vehicle Consortium – NAVC) of four new fuel cell electric buses (FCEB) operating in Hartford, Connecticut, as part of the Federal Transit Administration (FTA) National Fuel Cell Bus Program (NFCBP). The FCEBs have a fuel-cell-dominant hybrid electric propulsion system in a series configuration. The bus manufacturer—Van Hool— fully integrated the hybrid design using a Siemens ELFA 2 hybrid system, UTC Power's newest-design fuel cell power system, and an advanced lithium-based energy storage system by EnerDel. The new buses feature significant improvements over two previous generations of FCEBs in operation at CTTRANSIT and other agencies. This report provides results from October 2010 through May 2012.

The Nutmeg project, named for Connecticut's state nickname, was initiated to push fuel cell technology for transit buses to the next level of commercialization. While demonstrating the buses for at least two years, the team gathered data to improve reliability and durability of the fuel cell system and components and reduce capital cost. CTTRANSIT, in Hartford, Connecticut, is the first transit site selected to operate the buses. The agency has several years of experience operating a first-generation FCEB and has already made investments to improve its facilities for operating and maintaining hydrogen-fueled buses. The agency recently added a new hydrogen bus storage facility that can house up to six buses and is in the process of installing a hydrogen fueling station.

FTA and the Nutmeg project team are collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. NREL has been evaluating FCEBs under funding from FTA and DOE and uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations.

The four new Nutmeg FCEBs have been operating in Hartford for 20 months and have been working through several early operation issues such as problems with fuel line contamination, fire and gas detection, electric propulsion and battery software, and on-board fuel storage systems. These early operation issues have now been resolved, and the buses are ready for full operation and testing. By the end of May 2012, the FCEBs had accumulated more than 100,000 miles and 7,305 operating hours on the fuel cell systems. The FCEBs were filled 817 times with a total of 16,922 kg of hydrogen. The average availability for the FCEBs was 52 percent. This is lower than the expected availability (which should be above 85 percent) and has been due to start-up issues that are now resolved. The evaluation results for this 20-month period are summarized in Table ES-1.

FTA has an interest in comparing FCEBs to more advanced technology diesel buses, such as diesel hybrids, specifically with respect to fuel economy. This has been a challenge, primarily because few of the agencies demonstrating FCEBs also operate similar diesel hybrid buses. CTTRANSIT has recently procured diesel hybrid buses similarly sized to the FCEBs. Although these buses operate out of a different division, data from standard diesel buses at each division indicate that the duty-cycles are reasonably similar enough to compare. Data collected during the evaluation period show the FCEBs have an average fuel economy that is 97 percent higher than that of the diesel baseline buses and 46 percent higher than that of the diesel hybrid buses. The average fuel economy of the diesel hybrid buses is 35 percent higher than that of the diesel buses.

Table ES-1

Summary of Evaluation Results

Data Item	Fuel Cell	Diesel	NH Diesel Hybrid
Number of buses	4	3	14
Data period	10/10–5/12	10/10–5/12	10/11–5/12
Number of months	20	20	8
Total mileage in period	100,390	193,068	315,911
Average monthly mileage per bus	1,255	3,218	3,147
Total fuel cell operating hours	7,305		
Average bus operating speed (mph)	13.7		
Availability (85% is target)	52		
Fuel economy (miles/kg)	6.86		
Fuel economy (miles/DGE[a])	7.75	3.93	5.31
Miles between roadcalls (MBRC) – all	2,574	4,652	
MBRC – propulsion only	3,238[b]	6,871	
Total maintenance ($/mile)[c]	0.97	0.51	
Maintenance – propulsion only ($/mile)	0.43	0.13	

[a] Diesel gallon equivalent.
[b] For fuel cell propulsion only, MBRC was 8,174.
[c] Work order maintenance cost.

The Nutmeg FCEBs were part of a larger order of buses for AC Transit in Oakland, California. Including the 12 buses at AC Transit, the partners built a total of 16 of these next-generation buses, which accounts for the largest fleet of FCEBs in the United States. As part of the next phase of the Nutmeg demonstration, two of the four FCEBs are planned to operate at other locations to help introduce this new bus propulsion technology to a wider audience. One FCEB was delivered to Flint, Michigan, and began operation on May 29, 2012. Another FCEB is planned for operation in Cleveland, Ohio, in the fall of 2012.

SECTION 1

Introduction

As part of the Federal Transit Administration's (FTA) National Fuel Cell Bus Program (NFCBP), a team led by the Northeast Advanced Vehicle Consortium (NAVC) and UTC Power developed four next-generation fuel cell electric buses (FCEB) for demonstration. This next-generation design features significant improvements over two previous generations of FCEBs that were tested in the United States and Belgium. The National Renewable Energy Laboratory (NREL), one of the Department of Energy's (DOE) national laboratories, is evaluating this technology for FTA as part of the NFCBP. This report documents the early development and implementation of the four buses and summarizes performance results at CTTRANSIT in Hartford, Connecticut.

National Fuel Cell Bus Program

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

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

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

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

A portfolio of 14 projects (managed by the 3 consortia) was competitively selected by FTA to best advance FCEB commercialization, including 8 planned demonstration projects.

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

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

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

The Surface Transportation Act of 2011 extended the NFCBP authority and provided an additional $13.4 million in funding for the program. FTA again solicited project proposals from the consortia focused on enhancements/extensions to current projects or updated proposals submitted in the previous round. On April 2, 2012, FTA announced the project selections, which included 11 projects. To date, the NFCBP has secured more than $75 million in local and private commitments, which exceeds the federal contribution. A report outlining the overall status of FTA's FCEB-related research through 2011 is also available.[3]

Evaluation Activities

FTA is collaborating with DOE and funding NREL to ensure that data are collected on all FCEB demonstrations in a complete and consistent manner. FTA tasked NREL to be a third-party evaluator for the FCEBs developed and demonstrated under the NFCBP. Data collection, analysis, and reporting are a high priority for FTA to assess the success of the individual projects and the overall progress of fuel cell technology toward commercialization.

Under separate funding from DOE, NREL has been evaluating FCEBs to help determine the status of hydrogen and fuel cell systems in transit applications. NREL uses a standard data collection and analysis protocol that was established for DOE heavy-duty vehicle evaluations more than 10 years ago. In November 2010, NREL published "Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit

[3]"FTA Fuel Cell Bus Program: Research Accomplishments through 2011," DOT/FTA Report No. 0014.

Administration," which outlines the methodology and plans for both the FTA and DOE FCEB evaluations[4] to be performed by NREL.

NREL worked with CTTRANSIT to evaluate one of the early-generation buses in service. The bus, a predecessor to the four FCEBs in this report, began operation in April 2007. NREL documented the performance results of the early-generation bus in three reports, covering a data period from April 2007 through October 2009.[5] This report is focused on the results for the new buses from the start of service through May 2012.

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

[5]All three reports are available on the NREL website at www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

SECTION 2

Connecticut Nutmeg Fuel Cell Electric Bus Project

The Connecticut Nutmeg Fuel Cell Electric Bus Project is one of the demonstration projects awarded when the NFCBP was initiated. The project is managed through NAVC, a public-private partnership with the goal of promoting advanced vehicle technologies in the northeastern United States. As the lead for the project, UTC Power collaborated with Van Hool, a bus original equipment manufacturer (OEM) based in Belgium, to develop a next-generation FCEB for demonstration.

UTC Power

UTC Power is a unit of United Technologies based in South Windsor, Connecticut. UTC Power develops and produces fuel cells for power generation primarily for the stationary power and transportation market. The company's transportation business is focused on fuel cell power systems for the transit bus market, although it also supports fuel cell development for light-duty automobiles. UTC Power's experience with transit buses began in 1988, supplying a phosphoric acid fuel cell for a development and demonstration project led by Georgetown University. After that, UTC Power provided a fuel cell power system for an Iris Bus demonstration in Italy and collaborated on the development of a smaller fuel cell bus in Southern California.

In 2002, UTC Power began working with ISE and Van Hool to develop a new generation FCEB for the U.S. transit market. The first bus was delivered to SunLine Transit agency (Thousand Palms, California) in late 2005, followed by delivery of three more to AC Transit (Oakland, California). A fifth bus, built and delivered to CTTRANSIT in Hartford, Connecticut, gave the team an opportunity to test this FCEB design in a colder climate. Over the next several years, the demonstration teams operated these five buses in service, collecting performance data and further optimizing the bus systems. The early experience with the fleet led UTC Power and its partners to make major design and material modifications to improve the reliability and durability of the system and components.

In response to FTA's first NFCBP solicitation in 2006, UTC Power joined with NAVC on the Connecticut Nutmeg Fuel Cell Bus Project. The Nutmeg project, named for Connecticut's state nickname, was initiated to push fuel cell technology for transit buses to the next level of commercialization. Goals of the project include:

1. Develop fuel cell technology.
2. Manufacture and operate four FCEBs for at least two years.

3. Gather critical data from the buses to improve durability and reliability and reduce capital cost.
4. Operate the buses at various transit agencies to increase visibility and public awareness of the energy efficient FCEB.

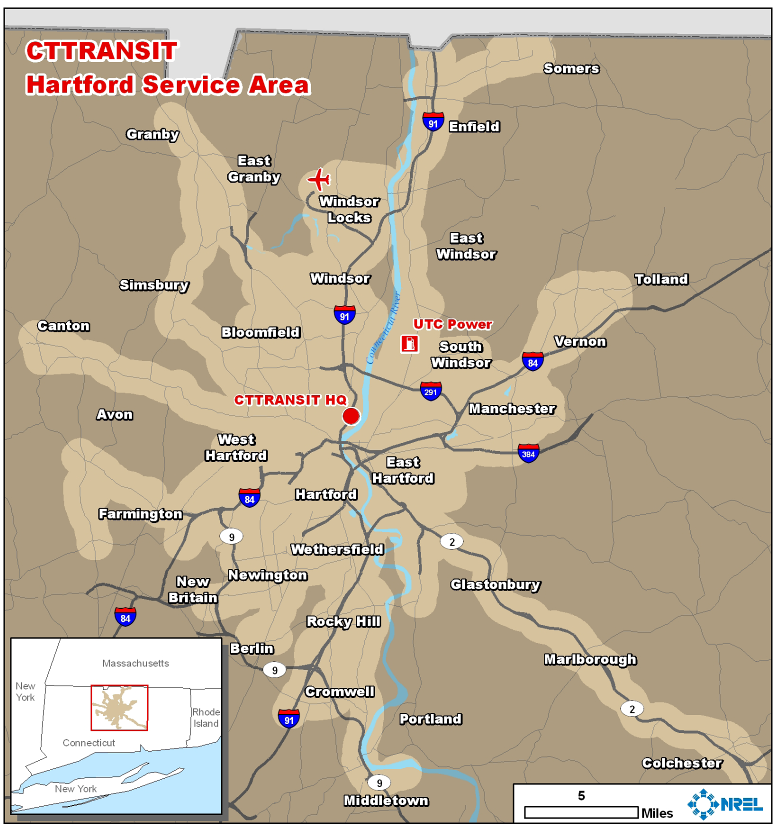
The new design takes FCEBs to an advanced stage, incorporating the lessons learned with the earlier fleet. For this design, Van Hool integrated the Siemens hybrid system and components into the bus chassis. The buses are part of a larger order for a consortium of transit agencies in California under the Zero Emission Bay Area (ZEBA) demonstration. A total of 16 buses of this design were produced—4 for the Nutmeg project and 12 for ZEBA.

CTTRANSIT Profile

Connecticut Transit (CTTRANSIT[6]) is owned by the Connecticut Department of Transportation and provides fixed-route transportation services to three major metropolitan areas in the state: Hartford, New Haven, and Stamford. The Hartford Division is the largest of the three areas, covering a service area of 469 square miles and serving a population of more than 851,000. Figure 2-1 shows the service area for this division.

Figure 2-1

Service area for CTTRANSIT's Hartford Division



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[6]CTTRANSIT website: www.cttransit.com.

CTTRANSIT's experience with the early-generation FCEB made it an excellent choice for operating the new design buses. The agency had more than five years of experience operating and maintaining its first bus. The Hartford bus depot had already been modified to accommodate hydrogen-fueled buses, and the agency was in the process of adding a separate building for housing additional FCEBs. CTTRANSIT's location is in close proximity to UTC Power's South Windsor headquarters where there is a hydrogen station to fuel the buses. In addition, CTTRANSIT has also secured funding through a DOE Clean Cities grant to build a new hydrogen fueling station at the Hartford Division that will be capable of dispensing 30 kg/day of hydrogen on-site. All of these factors provided the development team with a demonstration site that could accommodate and put the buses into service quickly once they were delivered.

Other Operators

The first demonstration site for the Nutmeg FCEBs has been CTTRANSIT. With a goal of introducing hydrogen fuel cell technology to a wider audience, UTC Power has been reaching out to additional agencies for potential demonstration sites. The biggest challenge for introducing FCEBs is access to hydrogen fueling. Because of this, UTC Power looked for areas where fueling was already available or planned for the near term. The transit agency would also need to be motivated and have the resources to take on the challenge of operating a cutting-edge technology. As of this report, two sites have been selected for operating one or more of the Nutmeg FCEBs:

- Mass Transportation Authority (MTA) in Flint, Michigan
- Greater Cleveland Regional Transit Authority (GCRTA) in Cleveland, Ohio

Both transit agencies are forward-looking and very interested in advanced technologies that will reduce bus emissions. This project gives them an opportunity to gain experience with hydrogen and fuel cell technology, which will enable the agency to make informed decisions on adopting this type of bus for future purchases.

One of the Nutmeg FCEBs (bus 1001 has been renumbered to MTA1180) was taken out of service in early April 2012 and shipped to MTA for training and service. That bus was placed into MTA service on May 29, 2012 (see Figure 2-2). As of June 2012, GCRTA is still working to complete its hydrogen fueling before receiving one of the Nutmeg FCEBs. Currently, the plan is for GCRTA to start operating one of the FCEBs in the fall of 2012.

Figure 2-2

Nutmeg bus now in service at Flint MTA

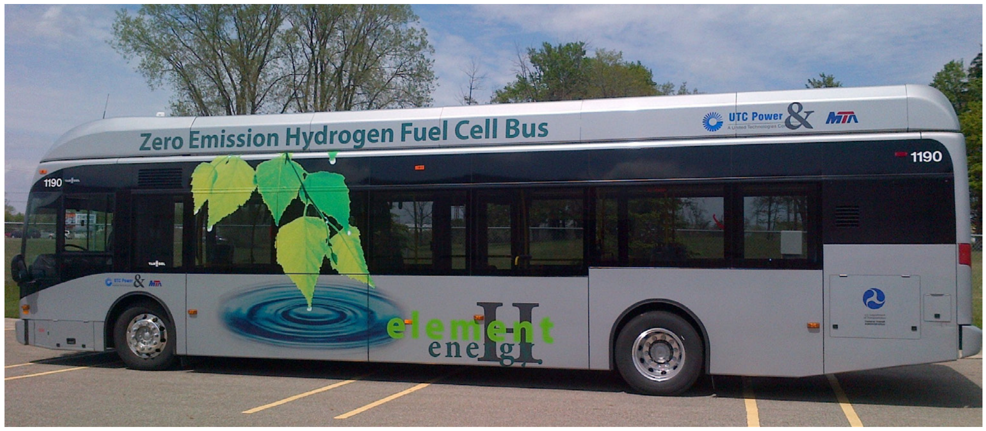


Photo courtesy of UTC Power

SECTION

3

Bus Technology Descriptions

The Nutmeg FCEBs are 40-foot, low-floor buses built by Van Hool[7] with a hybrid electric propulsion system that includes a UTC Power fuel cell power system[8] (proton exchange membrane [PEM] fuel cell). Data are being collected on three diesel buses as a baseline comparison to the FCEBs. The evaluation also includes collecting fuel economy data on a selection of diesel hybrid-electric buses operated in the CTTRANSIT fleet to get a better understanding of how FCEBs compare to the more advanced technology diesel buses. Table 0 1 provides bus system descriptions for the fuel cell and diesel baseline buses that were studied in this evaluation. Additional descriptions of the hybrid buses studied are included in this section.

Table 3-1

Fuel Cell and Diesel Bus System Descriptions

Vehicle System	Fuel Cell Electric Bus	Diesel Bus
Number of buses	4	3
Bus manufacturer and model	Van Hool A300L FC low floor	New Flyer DL 40
Model year	2010	2007
Length/width/height	40 ft/102 in./136 in.	40 ft/102 in./111 in.
GVWR/curb weight	39,350 lb/31,400 lb	43,850 lb/28,850 lb
Wheelbase	269 in.	293 in.
Passenger capacity	33 seated, or 29 seated and 2 wheelchairs	38 seated, or 28 seated and 2 wheelchairs
Engine manufacturer and model	UTC Power PureMotion[9] 120 fuel cell power system	Cummins ISL
Rated power	Fuel cell power system: 120 kW	280 hp @ 2,200 rpm 900 lb-ft @ 1,300 rpm
Accessories	Electrical	Mechanical
Emissions equipment	None	Active DPF
Transmission/retarder	Seico Brake resistors, regenerative braking	Allison B400R/ retarder
Fuel capacity	40 kg hydrogen	125 gal
Bus purchase cost	$2.5 million	$337,000

Fuel Cell Electric Bus Description

One of the four Nutmeg FCEBs is pictured in Figure 3-1. The buses were part of a larger order of buses for AC Transit in Oakland, California. Including the

[7]Described in brochure from Van Hool, http://www.vanhool.be/FRA/transport-public/hybride-pile-a-combustible/Resources/folderFuelCell.pdf.

[8]UTC Power products described at http://www.utcpower.com/products/transportation/fleet-vehicles.

[9]PureMotion is a registered trademark of UTC Power.

12 buses at AC Transit, the partners built a total of 16 of these next-generation buses. This accounts for the largest fleet of FCEBs in the United States. The four buses for the Nutmeg project are owned by UTC Power and operated by CTTRANSIT under a lease agreement.

Figure 3-1

CTTRANSIT Nutmeg Project FCEB

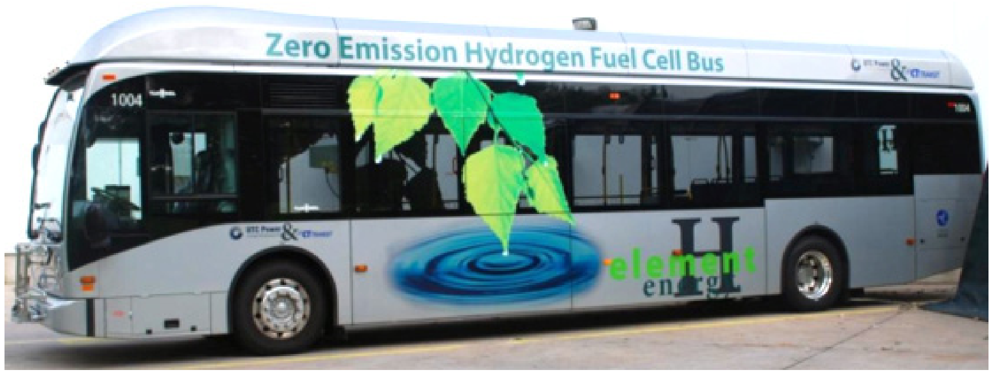


Table 3-2 provides a description of some of the electric propulsion systems for the FCEBs. Note that the diesel buses are not a hybrid configuration and do not have regenerative braking or energy storage for the drive system.

Table 3-2

Additional Electric Propulsion System Descriptions

Propulsion Systems	Fuel Cell Bus
Integrator	Van Hool
Hybrid type	Series, charge sustaining
Drive system	Siemens ELFA 2
Propulsion motor	2-AC induction, 85 kW each
Energy storage	Battery: EnerDel, lithium ion, Rated energy: 21 kWh Rated capacity: 29 Ah Rated power: 76 to 125 kW
Fuel storage	Eight roof-mounted, Dynetek, type 3 tanks; 5,000 psi rated
Regenerative braking	Yes

The new FCEBs have a fuel-cell-dominant hybrid electric propulsion system in a series configuration. Van Hool fully integrated the hybrid design using a Siemens ELFA 2 hybrid system,[10] UTC Power's newest-design fuel cell power system, and an advanced lithium-based energy storage system by EnerDel.[11] UTC Power's fuel cell power system incorporates various advancements based on lessons

[10]Siemens ELFA hybrid system described at http://www.automation.siemens.com/mcms/large-drives/en/hybrid-drives/modular-drive-system/Pages/elfa-system.aspx.

[11]Description of applications for EnerDel products in transportation described at http://www.ener1.com/?q=content/enerdel-applications.

learned from previous operation at CTTRANSIT and other agencies. The new buses feature significant improvements over two previous generations of FCEBs, including a redesigned Van Hool chassis that is 6,000 lb lighter in weight and 3 in. shorter in height and has a higher top speed than that of the earlier-generation buses.

Diesel Baseline Buses

Three diesel buses operating from the same location as the fuel cell bus were selected to use as a baseline comparison. These diesel baseline buses, shown in Figure 3-2, are 40-ft New Flyer buses with Cummins ISL engines. These diesel buses use some of the first model year 2007 diesel ISL engines from Cummins, and they have an actively regenerated diesel particulate filter (DPF).

Figure 3-2
CTTRANSIT conventional diesel bus

Diesel Hybrid Buses

CTTRANSIT's experience with hybrid electric technology began in 2003 with a demonstration to evaluate the benefits of the technology for potential future purchases. For this pilot project, the agency procured two New Flyer 40-foot buses (model year 2003) with Allison diesel hybrid propulsion systems. The agency operated these two buses alongside two standard diesel buses for 18 months. Comparisons were made to evaluate emissions, fuel efficiency, reliability, and cost. The results of the project were reported in October 2005.[12] These buses were an early generation of the technology just beginning to be introduced into the transit market. During the demonstration, the hybrid bus performance was excellent, but the costs were still high. At the conclusion of the demonstration, CTTRANSIT opted to continue operating the two buses while waiting for the technology to further mature and for costs to drop with larger production quantities.

Over the last 10 years, the technology has continued to mature, and the number of diesel hybrid-electric buses in U.S. transit fleets has grown. CTTRANSIT has

[12] "Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses," Connecticut Academy of Science and Engineering, Oct. 2005, http://cslib.cdmhost.com/utils/getfile/collection/p128501coll2/id/28402/filename/271168.pdf.

now made major purchases of diesel hybrids for most of its divisions around the state. Table 0 3 provides descriptions of the 40-foot hybrid buses currently in operation at CTTRANSIT. The first column describes the original pilot buses at the Hartford Division, and the remaining columns describe the newer hybrid buses operating at the New Haven and Stamford Divisions. These buses meet EPA 2010 emission regulations using DPF and selective catalytic reduction (SCR). CTTRANSIT also operates a fleet of 10 Nova 60-foot articulated diesel hybrids at the Hartford Division and 17 New Flyer 35-foot diesel hybrids at the Waterbury Division. CTTRANSIT received a grant through FTA's Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) program to fund 31 of the new hybrid buses, including the buses at New Haven. One of the New Haven Division hybrid buses is pictured in Figure 3-3.

Table 3-3

Descriptions of CTTRANSIT's 40-foot Diesel Hybrid-Electric Buses

Vehicle System	Hartford	New Haven	New Haven/Stamford
Number of buses	2	14	4
Bus manufacturer/ model	New Flyer	New Flyer/ Xcelsior	New Flyer/ Xcelsior
Model year	2003	2010	2012
Hybrid type	Parallel	Parallel	Parallel
Hybrid system	Allison H EP 40	Allison H EP 40	Allison H EP 40
Engine manufacturer and model	Cummins ISL	Cummins ISB	Cummins ISB
Rated power	289 hp	280 hp	280 hp
Propulsion motor	2, AC Induction	2, AC Induction	2, AC Induction
Energy storage	NiMH	NiMH	NiMH
Accessories	Mechanical	Mechanical	Mechanical
Emissions equipment	None	DPF and SCR	DPF and SCR
Bus purchase cost	$500,000	$560,000	$580,000

Figure 3-3

New Haven Division diesel hybrid bus

Photo Courtesy of CTTRANSIT

FTA has an interest in comparing FCEBs to these more advanced technology diesel buses, specifically with respect to fuel economy. The primary challenge for adding these data to the evaluations is the fact that few of the agencies demonstrating FCEBs also operate similar diesel hybrid buses. Fuel economy is highly variable based on duty-cycle; the most accurate comparisons require similarly-sized buses operated in the same service. The new hybrid buses at CTTRANSIT provide an opportunity for comparison; however, the hybrids operating alongside the FCEBs at the Hartford division are articulated buses. The 40-foot hybrids operate out of different divisions. The New Haven Division has a more challenging duty-cycle than the Hartford Division does, characterized by more stops. The fuel economy for standard diesel buses at this division is typically lower than that of Hartford Division by 0.1 mpg (or 2–3% lower fuel economy on average at New Haven compared to Hartford). This fact should be noted when comparing the results presented in the report; however, this indicates that the duty-cycles are reasonably similar enough to compare.

SECTION

4

Fueling and Maintenance Facilities

CTTRANSIT benefits from its close proximity to UTC Power headquarters because it can take advantage of the hydrogen fueling station at that location, which is about seven miles from the Hartford Division. The agency was able to make arrangements to use this site to fuel the first bus during the demonstration. The UTC Power fueling station features liquid hydrogen storage and compression. The fuel is vaporized and dispensed into the bus as gaseous hydrogen. The hydrogen, supplied by Praxair from its location near Niagara Falls, is produced renewably as a by-product of a chemical process.

CTTRANSIT Hydrogen Station

To prepare for the arrival of the new FCEBs, CTTRANSIT secured funding through a DOE Clean Cities grant to add a hydrogen fueling station at the Hartford Division. Clean Cities annually funds cost-share projects submitted by its coalitions' public-private partnerships. During 2009, DOE Clean Cities selected 25 projects for nearly $300 million in funding from the American Recovery and Reinvestment Act (ARRA). Among the recipients, the Greater New Haven Clean Cities Coalition, Inc., received $13,195,000 for the Connecticut Clean Cities Future Fuels Project. As part of this project, CTTRANSIT is building the new hydrogen station at Hartford that will be capable of dispensing 30 kg/day of hydrogen on-site. The hydrogen will be generated with an Avalence electrolyzer. The prep work for the site has been completed (platform and electric hookups are pictured in Figure 4-1), and CTTRANSIT is awaiting installation of the electrolyzer, hydrogen storage, and dispensing equipment. The station should be completed in September 2012. The planned hydrogen storage is not currently sufficient to allow full fills of all five buses at once, but it will reduce the need to take all of the buses to UTC Power for fuel. That effort requires considerable labor for CTTRANSIT staff as well as coordination with UTC Power staff to do the fueling.

Figure 4-1

Platform and hookups for CTTRANSIT hydrogen station

Maintenance Facilities

Prior to demonstrating its first-generation FCEB, CTTRANSIT made modifications to its existing diesel bus garage to handle storage and maintenance of a hydrogen-fueled bus. Working closely with a consultant and local fire officials, the agency was able to make minor modifications to allow the FCEB into the garage. The modifications included an upgraded ventilation system, fuel sensors, and alarms. The agency was able to house up to two FCEBs in this garage. To prepare for a larger fleet of hydrogen-fueled buses, the agency worked with the State to design and construct a new storage building at its depot. The funding for this new storage building was secured, and the construction was completed in July 2011. Figure 4-2 shows the new storage facility, which is located at the back of the Hartford property. Figure 4-3 shows the inside of the facility, where the agency can store up to six FCEBs. There are connections along both walls to allow the buses to be plugged in if the temperature gets too low for the fuel cells. The connections are only needed to keep the fuel cells above a certain temperature; the hybrid system is charge-sustaining. Routine maintenance on the buses can be handled in the new facility, and major work is conducted in the maintenance bay within the main bus garage.

Figure 4-2

New storage facility built by CTTRANSIT for FCEBs

Figure 4-3

FCEB storage facility for up to six full-size buses

Stationary Fuel Cell Installation

CTTRANSIT has recently installed a stationary fuel cell to provide power for the Hartford facility. The fuel cell was funded through the same TIGGER grant in 2009 that enabled the agency to purchase hybrid buses. The agency selected UTC Power to manufacture a 400 kW fuel cell system that uses natural gas to replace its current diesel-fueled backup generators. The system was installed in a combined heat and power configuration to not only generate electricity but also provide hot water for the facility. The system is expected to provide non-polluting electricity and save CTTRANSIT thousands of gallons of diesel fuel. The fuel cell system is pictured in Figure 4-4. The agency received another TIGGER grant in 2011 to procure a stationary fuel cell for its New Haven division.

Figure 4-4

CTTRANSIT's recently-installed stationary fuel cell system

Hydrogen Fueling Data Summary

During the evaluation period, CTTRANSIT continued to use the UTC Power hydrogen station to fill the buses. Figure 4-5 shows the total hydrogen dispensed by month and the average daily hydrogen use by the FCEBs (for days when hydrogen was dispensed; zero-use days were excluded). The graph includes fuel data for all four Nutmeg buses as well as the early-generation FCEB that was in operation until June 2011. The first two Nutmeg buses went into service in October 2011 but were temporarily pulled from service for a fuel line contamination issue in November and December (described in the next section). The fuel usage increased as these buses went back into service and the remaining two buses were delivered, and then dropped some starting in April 2012 with the departure of bus 1001 to MTA in Flint, Michigan.

Figure 4-6 shows the distribution of hydrogen amounts per fill. During the evaluation period, the FCEBs were filled 817 times with a total of 16,922 kg of hydrogen, which is an average fill amount of 20.7 kg.

Figure 4-5

Total hydrogen dispensed per month and average hydrogen dispensed per day (excluding 0 kg days)

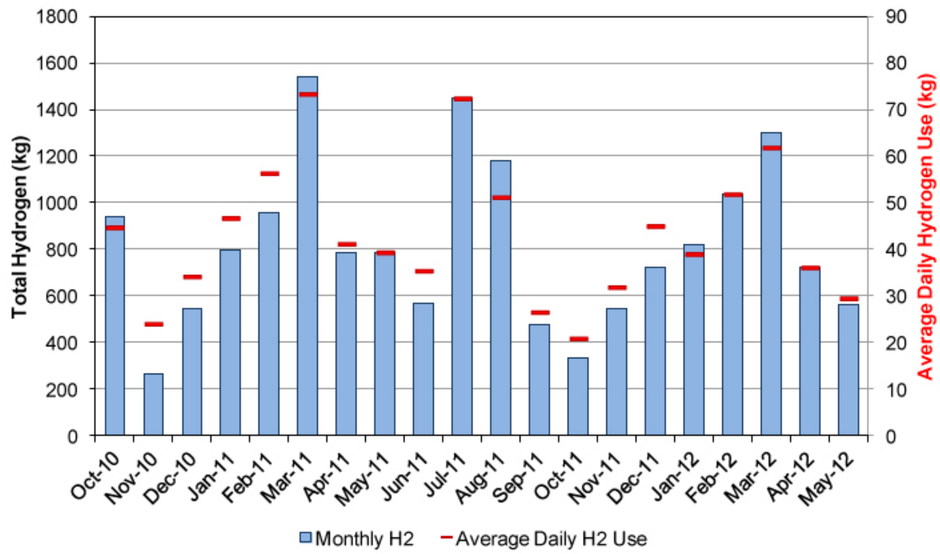
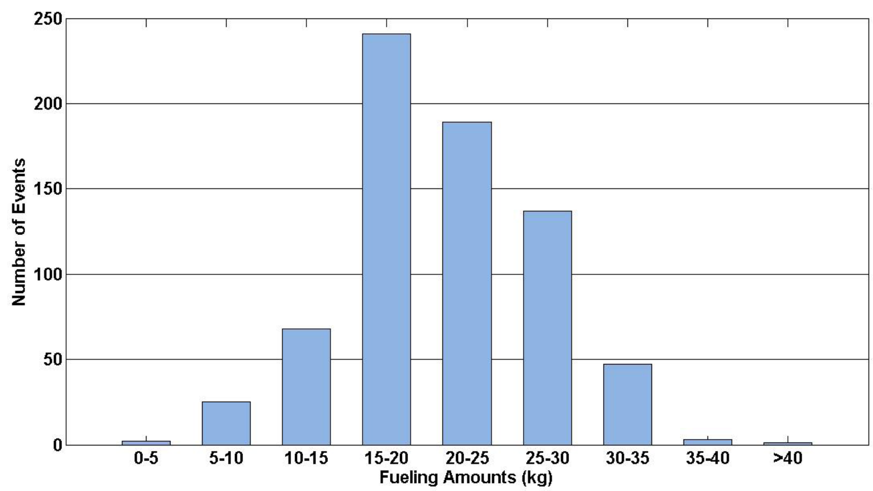


Figure 4-6

Fueling amounts for FCEBs



SECTION

5

Implementation Experience

As mentioned in Section 2, the Nutmeg project buses were part of a larger order of buses for a consortium of transit agencies in California. UTC Power and Van Hool coordinated with CTTRANSIT and AC Transit (the lead agency for the ZEBA Demonstration) to continue developing the FCEB design to meet transit agency requirements and increase reliability and durability. Together, this fleet of 16 FCEBs is the largest fuel cell bus demonstration in the United States.

The Nutmeg FCEBs were built at the Van Hool plant in Belgium along with the ZEBA program buses. The manufacturer had two fuel cell power plants (FCPPs) on site for testing the buses. Once each bus was completed and tested, the test FCPP was removed and the bus was shipped to Connecticut (or to California for the ZEBA demonstration). Once the bus arrived in Hartford, the maintenance staff and the UTC Power engineer installed a new FCPP.

The first Nutmeg bus was delivered in June 2010, followed by the second bus in July. The final two buses were delivered by the end of October 2010. The 12 ZEBA buses were delivered to California between May 2010 and September 2011. NREL is evaluating the results from both programs and began collecting data on each bus as it was placed into service. The FCEB fleet has been going through a shakedown period during which the manufacturers work with the agency to further optimize the bus systems and make needed modifications. This is typical of all bus fleets regardless of the propulsion system; however, it can take additional time to accomplish this for advanced propulsion systems.

While the bus design is based on the earlier demonstration buses, the configuration for the new fleet has some significant changes. For one, the hybrid system and components were integrated into the bus by the manufacturer (Van Hool). In addition, the energy storage system was replaced with lithium-based batteries from EnerDel. These kinds of design changes are significant and can require additional time to work through the optimization stage. Once the final changes are made, the demonstration team selects a "clean point" for data collection. The clean point for the Nutmeg demonstration has not been finalized. For this report, the evaluation period began in October 2010 for the first two buses and January 2011 for the last two.

One key challenge for UTC Power and the development team was increasing the durability and reliability of the fuel cell system to meet FTA life cycle requirements for a full-size bus—12 years or 500,000 miles. Because transit agencies typically rebuild diesel engines at approximately mid-life, a fuel cell power system should be able to operate for at least half the life of the bus. FTA has set an early performance target of 4–6 years (or 20,000–30,000 hours) durability for the fuel cell propulsion system. Since the team first began developing fuel cell technology for transit buses, the FCEBs are now demonstrating some of the highest hours in service. These high-hour FCPPs are operating in the new ZEBA buses at AC Transit. At the time the first new bus bodies were delivered, three FCPPs from AC Transit's first-generation demonstration were reaching very high hours without significant degradation. To further test this FCPP version, the manufacturers installed them into the new ZEBA buses being delivered. In all, three older FCPPs were installed into the new buses. Those three FCPPs continue to operate and accumulate hours in service. The top FCPP has now achieved more than 12,000 hours[13] without major repair or cell replacements. The second FCPP is nearing 10,000 hours, and the third is just under 8,000 hours. UTC Power reports that these FCPPs continue to provide the rated power of 120 kW. This is a significant achievement toward meeting a target of 25,000 hours. The FCPPs in the Nutmeg buses are the same version as in the ZEBA buses, and they are also expected to reach in excess of 10,000 hours in service.

Bus-Related Issues

During the shakedown period for this new design, the buses experienced several issues that needed to be resolved. Some of the issues and resolutions are presented here.

- **Fuel line contamination** – Some of the stainless steel tubing used for the fueling system onboard the buses had manufacturing process control issues. Some of the tubing was not properly cleaned out by the supplier before being delivered to Van Hool for installation. The problem was not discovered until after the first few buses were delivered. The tubing was inspected and replaced as needed during October and November 2010.
- **Fuel flow issue** – A few of the fuel cell buses had a problem with the fuel supply valve restricting fuel flow. This problem was particularly pronounced on one of the ZEBA buses but was noted to some degree on all of the buses. Once the issue was resolved with the first ZEBA bus (in April 2011), the remainder of the buses were repaired during scheduled monthly maintenance.
- **Fire detection system** – In a couple of cases, the fire suppression system indicated a fire and displayed system trouble alarms and dash lights, causing the bus to be roadcalled. There was no actual fire, and the problem was repaired and is being monitored and reviewed regularly to verify the resolution.
- **Stalling issues and traction battery software** – The battery software was updated to balance the life of the batteries and maximize fuel economy. An integration problem was identified as an issue between the hybrid system

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[13]"This FCPP achieved 10,000 hours in August 2011; see press release from UTC Power, http://www.utcpower.com/pressroom/pressreleases/utc-power-fuel-cell-system-sets-world-record-achieving-10000-hr-durability.

and the batteries that was addressed. The communication problem was causing the bus to stall or shut down because of an unexpected condition.

- **On-board hydrogen fuel storage system** – There was a problem with hydrogen leaking from the manual valve on the storage tanks. The manufacturer replaced the part that allowed the leak.
- **Parts availability** – Long lead times for getting parts, especially for those from Europe, have been a challenge and added to the downtime for the buses.

Operation Plans

The Nutmeg buses were designed to have reduced height and weight, allowing for a faster top speed. As a result, these buses are able to operate on most of the routes in the CTTRANSIT service area. The agency selected several routes for the Nutmeg bus demonstration. Some of the routes, such as the Star Shuttle, take the buses through the downtown for maximum public exposure to the technology. The Nutmeg FCEBs had some restrictions from the long-distance commuter runs because of the reduced number of seats.

SECTION 6

Evaluation Results

The results presented in this section are from October 2010 through May 2012. As mentioned previously, the starting point coincides with the first two FCEBs going into service, and the second two FCEBs started service in January 2011. In addition, fuel economy data were collected and are presented for 14 diesel hybrid-electric buses operating at the New Haven district for comparison with the FCEBs and diesel buses at the Hartford district. A summary of the results shown in this section is provided in Appendix A, and the first page of the summary is repeated in Appendix B with results in SI units.

Route Assignments

The four FCEBs operate from CTTRANSIT's Hartford garage. The average speed for these buses is 15.9 mph, which results in a more accurate comparison with the diesel baseline buses (average speed is 15.5 mph). For the evaluation period, the four FCEBs operated 100,390 miles and 7,305 hours, for a 13.7 mph average speed. This average speed is lower than the planned average speed due to having the fuel cell system operating when the bus is not in service (such as for training, events, and extended idling because there are no tailpipe emissions).

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage may indicate downtime for maintenance or purposeful reduction of planned work for the buses. This section summarizes bus usage and availability for the two groups of buses.

Table 6-1 summarizes average monthly mileage for the buses through May 2012. Overall, the monthly average miles for the FCEBs are 43 percent of the monthly average miles for the diesel buses. This lower monthly mileage for the FCEBs has been due to time spent working out the early issues with this newly-designed hybrid electric propulsion system and drive train. Now that these early implementation issues (as discussed above) have been resolved, the usage is expected to increase to full service.

Table 6-1

Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage
1001	994	21,643	20,649	19	1,142
1002	642	34,033	33,391	20	1,670
1003	486	32,300	31,814	17	1,871
1004	0	13,572	14,536	17	855
Fuel Cell Total	-	-	100,390	73	1,375
725	124,214	189,333	65,119	20	3,256
726	125,608	191,924	66,316	20	3,316
727	128,353	189,986	61,633	20	3,082
Diesel Total			193,068	60	3,218

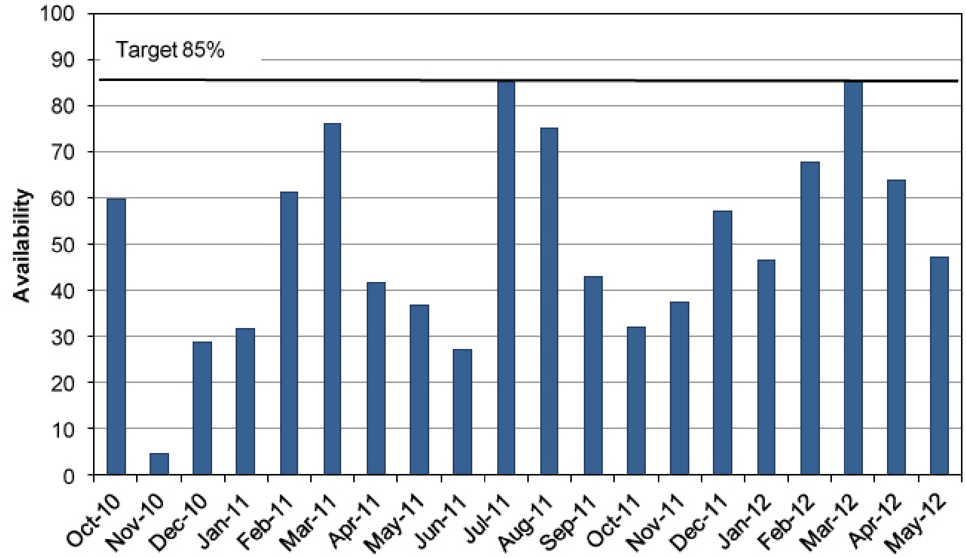
Another measure of reliability is availability, the percentage of days that the buses are planned for operation compared with the days the buses are actually available. Table 6-2 summarizes the reasons for availability and unavailability for the fuel cell and diesel buses. During this reporting period, the average availability for the FCEBs was 52 percent. This lower-than-expected availability (which should be above 85%) has been due to start-up issues that are now resolved. When the FCEBs were available, they were in service 88 percent of the time. When the FCEBs were unavailable for service, the problems were primarily bus-related maintenance (at 66% of the time) but also included hybrid propulsion issues (20% of the time). Figure 6-1 shows the Nutmeg FCEB monthly availability for the data period.

Table 6-2

Summary of Reasons for Availability and Unavailability of Buses for Service

Category	FCEB # Days	Percent
Planned work days	1,530	
Days available	795	52
Available	795	100
On route	697	88
Event/demonstration	36	4
Training	18	2
Not used	44	6
Unavailable	735	100
Fuel cell propulsion	43	6
Hybrid propulsion	145	20
Traction battery issues	44	6
Bus maintenance	486	66
Fueling unavailable	17	2

Figure 6-1
Monthly availability for FCEBs



Fuel Economy and Cost

As discussed above, hydrogen fuel is provided by a fueling station at UTC Power. The hydrogen is dispensed at up to 350 bar (5,000 psi). Table 6-2 shows fuel consumption and fuel economy for the FCEBs, diesel buses, and diesel hybrid buses. As mentioned earlier, the 14 diesel hybrid buses were operated from another district; however, the duty-cycle is similar to that operated from the Hartford district. Overall, the FCEBs averaged 6.86 miles per kilogram of hydrogen, which equates to 7.75 miles per diesel gallon equivalent (DGE). The energy conversion from kilograms of hydrogen to DGE appears at the end of Appendix A.

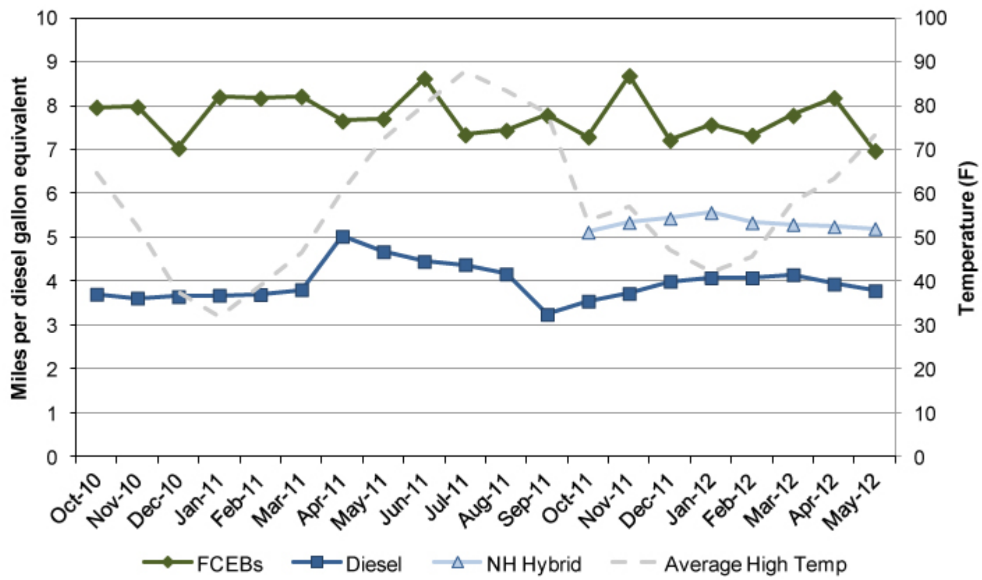
Table 6-3 *Fuel Use and Economy (Evaluation Period)*

Bus	Mileage (fuel base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (gallon)	Miles per Gallon (mpg)
1001	20,649	3,625.1	5.70	3,208.1	6.44
1002	33,391	4,934.4	6.77	4,366.7	7.65
1003	31,814	3,630.0	8.76	3,212.4	9.90
1004	14,536	2,444.0	5.95	2,162.8	6.72
FCEB Total	100,390	14,633.5	6.86	12,950.0	7.75
725	64,390			15,418.3	4.18
726	65,205			16,850.2	3.87
727	61,200			16,328.0	3.75
Diesel Total	190,795			48,596.5	3.93
Hybrid Total	315,911			59,453.3	5.31

The table shows that the average fuel economy of the FCEBs is 97 percent higher than that of the diesel baseline buses for the evaluation period. The average fuel economy of the diesel hybrid buses is 35 percent higher than that of the diesel baseline buses, and the average fuel economy of the FCEBs is 46 percent higher than that of the diesel hybrid buses. Figure 6-2 shows monthly fuel economy for each of the three bus groups. The average monthly high temperature is included in the graph to track any seasonal variations in the fuel economy due to heating or cooling of the bus, which might require significant additional energy use.

Figure 6-2

Monthly fuel economy for FCEB and diesel buses



The cost of hydrogen purchased from UTC Power has been $6.85 per kg, and this does not include the capital costs of the fuel station. The hydrogen fuel cost per mile is $1.00. As mentioned earlier, the hydrogen fueling is provided at UTC Power, so CTTRANSIT did not need to invest in a fuel station of that size. However, the cost of shuttling the buses for the data period has included 1,130 hours of mechanic time. At $50 per hour, the operation during the evaluation period adds $0.56 per mile in fuel cost. Diesel fuel cost during the reporting period was $3.32 per gallon and calculates to $0.85 per mile.

Maintenance Analysis

All work orders for the study buses were collected and analyzed for this evaluation. For consistency, the maintenance labor rate was set at $50 per hour for all work; this does not reflect an average rate for CTTRANSIT. Warranty costs are generally not included in the maintenance costs presented in this section.

Total Maintenance Costs

Total maintenance costs include the price of parts and labor rates at $50 per hour; they do not include warranty costs. Cost per mile is calculated as follows:

Cost per mile = [(labor hours * 50) + parts cost] / mileage

Table 6-4 shows total maintenance costs for the fuel cell and diesel buses. Scheduled and unscheduled maintenance cost per mile is provided for each bus and study group of buses. Note that the fuel cell bus maintenance is supported by one of UTC Power's engineers; however, CTTRANSIT mechanics have completed most of the maintenance activities. During the evaluation period, the FCEBs had a 92 percent higher maintenance cost per mile when compared to the three baseline diesel buses. Maintenance issues for the FCEBs included fuel cell system and balance of plant, hydrogen leaks at the storage tanks, fire and gas leak detection system, and air compressor issues.

Table 6-4 *Total Maintenance Costs (Evaluation Period)*

Bus	Mileage	Parts ($)	Labor Hours	Total Cost per Mile ($)	Scheduled Cost per Mile ($)	Unscheduled Cost per Mile ($)
1001	20,649	5,381.08	493.6	1.46	0.33	1.13
1002	33,391	2,033.44	402.9	0.66	0.26	0.40
1003	31,814	2,734.06	430.8	0.76	0.23	0.53
1004	14,536	1,863.63	383.5	1.45	0.36	1.09
Total Fuel Cell	100,390	12,021.21	1,710.8	0.97	0.28	0.69
725	65,119	8,479.98	454.5	0.48	0.13	0.35
726	66,316	10,566.14	499.2	0.54	0.14	0.40
727	61,633	8,100.85	473.8	0.52	0.17	0.35
Total Diesel	193,068	27,146.97	1,427.5	0.51	0.15	0.36

Maintenance Costs Categorized by System

Table 6-5 shows maintenance costs by vehicle system and bus study group (without warranty costs). The vehicle systems shown in the table are as follows:

- Cab, body, and accessories: Includes body, glass, and paint repairs following accidents, cab and sheet metal repairs on seats and doors, and accessory repairs such as hubodometers and radios
- Propulsion-related systems: Repairs for exhaust, fuel, engine, electric motors, fuel cell modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, and transmission
- Preventive maintenance inspections (PMI): Labor for inspections during preventive maintenance

- Brakes
- Frame, steering, and suspension
- Heating, ventilation, and air conditioning (HVAC)
- Lighting
- Air system, general
- Axles, wheels, and drive shaft
- Tires

The systems with the greatest percentage of maintenance costs for the fuel cell and diesel buses were propulsion-related, PMI, and cab, body, and accessories.

Table 6-5

Maintenance Cost per Mile by System (Evaluation Period)

System	FCEB Cost per Mile ($)	FCEB Percent of Total (%)	Diesel Cost per Mile ($)	Diesel Percent of Total (%)
Propulsion-related	0.42	43	0.13	25
Cab, body, and accessories	0.22	23	0.11	21
PMI	0.28	29	0.08	16
Brakes	0.00	0	0.05	10
Frame, steering, and suspension	0.03	3	0.03	6
HVAC	0.01	1	0.06	12
Lighting	0.01	1	0.01	2
Air, general	0.00	0	0.02	4
Axles, wheels, and drive shaft	0.00	0	0.01	2
Tires	0.00	0	0.01	2
Total	*0.97*	*100*	*0.51*	*100*

Propulsion-Related Maintenance Costs

Propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. These systems have been separated to highlight maintenance costs most directly affected by the advanced propulsion system changes for the buses.

Table 6-6 shows the propulsion-related system repairs by category for the two study groups during the evaluation period. The maintenance costs do not include the work done by the UTC Power personnel. The FCEBs have maintenance costs more than three times that of the diesel buses. The FCEB maintenance costs were directly caused by fuel cell system and balance of plant, fuel storage leaks, fire and gas leak detection system, and high-power system connection repairs. Many of these repairs and costs are now reported to be resolved and should not continue to be maintenance issues for the FCEBs.

Table 6-6

Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	100,390	193,068
Total Propulsion Related Systems (Roll up)		
Parts cost ($)	3,219.99	9,902.69
Labor hours	790.4	305.3
Total cost ($)	42,730.49	25,166.19
Total cost ($) per mile	0.42	0.13
Exhaust System Repairs		
Parts cost ($)	0.00	80.73
Labor hours	2.0	10.7
Total cost ($)	100.00	614.23
Total cost ($) per mile	0.00	0.00
Fuel System Repairs		
Parts cost ($)	916.15	718.25
Labor hours	275.0	1.5
Total cost ($)	14,665.15	793.25
Total cost ($) per mile	0.15	0.00
Powerplant System Repairs		
Parts cost ($)	705.00	4,018.34
Labor hours	244.2	159.6
Total cost ($)	12,915.00	11,997.84
Total cost ($) per mile	0.13	0.06
Electric Motor and Propulsion Repairs		
Parts cost ($)	1,117.60	0.00
Labor hours	180.8	0.0
Total cost ($)	10,155.60	0.00
Total cost ($) per mile	0.10	0.00
Non Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	287.90	1,192.17
Labor hours	59.5	30.9
Total cost ($)	3,262.90	2,738.67
Total cost ($) per mile	0.03	0.01
Air Intake System Repairs		
Parts cost ($)	0.00	1,523.16
Labor hours	0.0	33.5
Total cost ($)	0.00	3,198.16
Total cost ($) per mile	0.00	0.02

Table 6-6
(continued)

Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Cooling System Repairs		
Parts cost ($)	186.34	752.77
Labor hours	28.9	33.6
Total cost ($)	1,631.84	2,431.77
Total cost ($) per mile	0.02	0.01
Transmission Repairs		
Parts cost ($)	0.00	1,445.30
Labor hours	0.0	26.0
Total cost ($)	0.00	2,745.30
Total cost ($) per mile	0.00	0.01

Roadcall Analysis

A roadcall (RC) or revenue vehicle system failure (as named in the National Transit Database) is defined as a failure of an in-service bus that causes the bus to be replaced while it is on route or one that causes a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is maintained, then this is not considered an RC. The analysis provided here includes only RCs that were caused by "chargeable" failures. Chargeable RCs include systems that can physically disable the bus from operating while it is on route, such as interlocks (doors, air system) or engine, or things that are deemed safety issues if operation of the bus continued, such as headlights and windshield wipers. Chargeable RCs do not include roadcalls for things such as problems with radios or destination signs.

Table 6-7 shows the RCs and miles between roadcalls (MBRC) for the FCEBs and diesel buses, categorized by all RCs and propulsion-related-only RCs. The RCs for the diesel buses included the entire New Flyer 40-foot bus fleet operating from Hartford for a 12-month period (June 2011 through May 2012). It was easier for CTTRANSIT to provide the data for the entire fleet than to provide individual bus RCs. The diesel buses have much better MBRC rates for both categories. The fuel cell system MBRC is included for the FCEBs to provide an indication of reliability for that system. Figure 6-3 shows the monthly average MBRC for the two study groups of buses during the evaluation period.

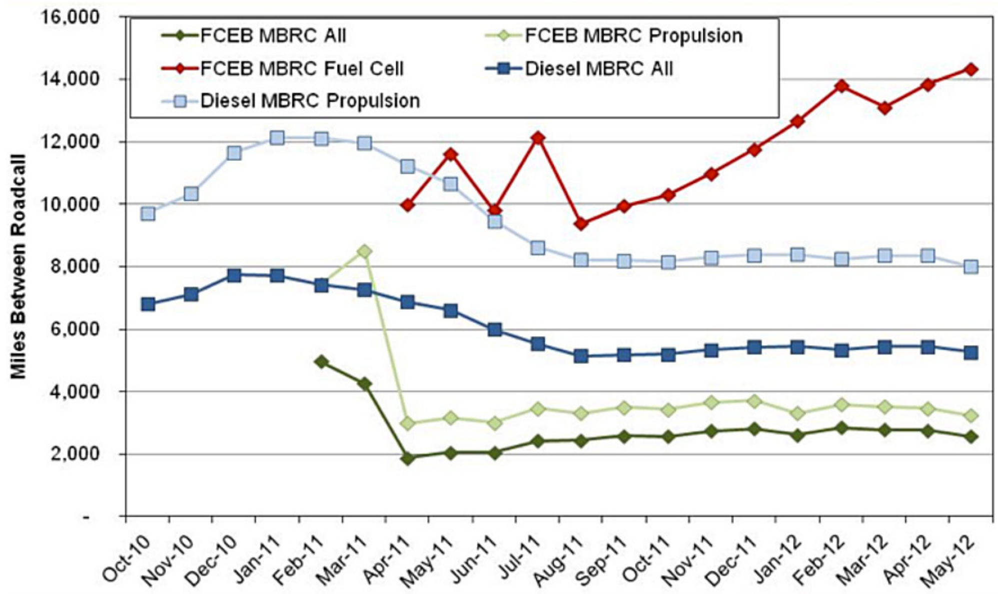
Table 6-7

Roadcalls and MBRC (Evaluation Period)

	FCEB	Diesel
Mileage	100,390	10,910,570
All roadcalls	39	2,068
All MBRC	2,574	5,276
Propulsion-related roadcalls	31	1,363
Propulsion-related MBRC	3,238	8,005
Fuel-cell-related roadcalls	7	
FC system MBRC	14,341	

Figure 6-3

Monthly MBRC for FCEBs and diesel buses



SECTION

7

What's Next for This Project

As mentioned earlier in the report, one of UTC Power's goals for the project was to introduce the technology to other interested transit fleets. The company has finalized arrangements with Flint MTA for a one-year demonstration. Bus 1001 has been shipped to Flint and is being used for operator and maintenance training. That bus started operation at MTA on May 29, 2012. UTC Power is working on a similar agreement with GCRTA and will eventually ship a bus to that agency for a one-year period, currently planned for the fall of 2012.

CTTRANSIT is committed to the technology and would like to operate fuel cell buses for as long as possible. The two remaining buses will continue to operate at the agency, as will the first-generation fuel cell bus. CTTRANSIT is also negotiating the contract to purchase another fuel cell bus. In addition, the agency will receive another new FCEB in one of the recently-awarded NFCBP projects.

Figure 7-1

Nutmeg FCEB operating on Downtown Star Shuttle Route

APPENDIX

A

Fleet Summary Statistics

Table A-1

Fleet Operations and Economics, FCEBs and Diesel Buses

	Fuel Cell Buses	Diesel Buses
Number of vehicles	4	3
Period used for fuel and oil op analysis	10/10–5/12	10/10–5/12
Total number of months in period	20	20
Fuel and oil analysis base fleet mileage	100,390	190,795
Period used for maintenance op analysis	10/10–5/12	10/10–5/12
Total number of months in period	20	20
Maintenance analysis base fleet mileage	100,390	193,068
Average monthly mileage per vehicle	1,255	3,218
Availability	52%	N/A
Fleet fuel usage in H_2 kg/Diesel gal	14,634	48,597
Roadcalls	39	
RCs MBRC	2,574	4,652
Propulsion roadcalls	31	
Propulsion MBRC	3,238	6,871
Fleet miles/kg hydrogen	6.86	
(1.13 kg H_2/gal diesel fuel)		
Representative fleet MPG (energy equiv)	7.75	3.93
Hydrogen cost per kg	6.85	
Diesel gal cost		3.32
Fuel cost per mile	1.00	0.85
Total scheduled repair cost per mile	0.28	0.15
Total unscheduled repair cost per mile	0.69	0.36
Total maintenance cost per mile	0.97	0.51
Total operating cost per mile	*1.97*	*1.36*

Table A-2

Maintenance Costs, FCEBs and Diesel Buses

	Fuel Cell Buses	Diesel Buses
Fleet mileage	100,390	193,068
Total parts cost	12,021.21	27,146.97
Total labor hours	1,710.8	1,427.5
Average labor cost (@ $50.00 per hour)	85,540.00	71,375.00
Total maintenance cost	97,552.21	98,521.97
Total maintenance cost per bus	24,388.05	32,840.66
Total maintenance cost per mile	*0.97*	*0.51*

Table A-3

Breakdown of Maintenance Costs by Vehicle System, FCEBs and Diesel Buses

	Fuel Cell Buses	Diesel Buses
Fleet mileage	100,390	193,068
Total Engine/Fuel Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)		
Parts cost	3,212.99	9,902.69
Labor hours	790.4	305.3
Average labor cost	39,517.50	15,263.50
Total cost (for system)	42,730.49	25,166.19
Total cost (for system) per bus	10,682.62	8,388.73
Total cost (for system) per mile	0.43	0.13
Exhaust System Repairs (ATA VMRS 43)		
Parts cost	0.00	80.73
Labor hours	2.0	10.7
Average labor cost	100.00	533.50
Total cost (for system)	100.00	614.23
Total cost (for system) per bus	25.00	204.74
Total cost (for system) per mile	0.00	0.00
Fuel System Repairs (ATA VMRS 44)		
Parts cost	916.15	718.25
Labor hours	275.0	1.5
Average labor cost	13,749.00	75.00
Total cost (for system)	14,665.15	793.25
Total cost (for system) per bus	3,666.29	264.42
Total cost (for system) per mile	0.15	0.00
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts cost	705.00	4,018.34
Labor hours	244.2	159.6
Average labor cost	12,210.00	7,979.50
Total cost (for system)	12,915.00	11,997.84
Total cost (for system) per bus	3,228.75	3,999.28
Total cost (for system) per mile	0.13	0.06
Electric Propulsion Repairs (ATA VMRS 46)		
Parts cost	1,117.60	0.00
Labor hours	180.8	0.0
Average labor cost	9,038.00	0.00
Total cost (for system)	10,155.60	0.00
Total cost (for system) per bus	2,538.90	0.00
Total cost (for system) per mile	0.10	0.00

Table A-3
(continued)

Breakdown of Maintenance Costs by Vehicle System, FCEBs and Diesel Buses

	Fuel Cell Buses	Diesel Buses
Electrical System Repairs (ATA VMRS 30 Electrical General, 31 Charging, 32-Cranking, 33 Ignition)		
Parts cost	287.90	1,192.17
Labor hours	59.5	30.9
Average labor cost	2,975.00	1,546.50
Total cost (for system)	3,262.90	2,738.67
Total cost (for system) per bus	815.73	912.89
Total cost (for system) per mile	0.03	0.01
Air Intake System Repairs (ATA VMRS 41)		
Parts cost	0.00	1,523.16
Labor hours	0.0	33.5
Average labor cost	0.00	1,675.00
Total cost (for system)	0.00	3,198.16
Total cost (for system) per bus	0.00	1,066.05
Total cost (for system) per mile	0.00	0.02
Cooling System Repairs (ATA VMRS 42)		
Parts cost	186.34	752.77
Labor hours	28.9	33.6
Average labor cost	1,445.50	1,679.00
Total cost (for system)	1,631.84	2,431.77
Total cost (for system) per bus	407.96	810.59
Total cost (for system) per mile	0.02	0.01
Hydraulic System Repairs (ATA VMRS 65)		
Parts cost	0.00	171.97
Labor hours	0.0	9.5
Average labor cost	0.00	475.00
Total cost (for system)	0.00	646.97
Total cost (for system) per bus	0.00	215.66
Total cost (for system) per mile	0.00	0.00
General Air System Repairs (ATA VMRS 10)		
Parts cost	0.00	2,106.78
Labor hours	7.8	49.5
Average labor cost	387.50	2,475.00
Total cost (for system)	387.50	4,581.78
Total cost (for system) per bus	96.88	1,527.26
Total cost (for system) per mile	0.00	0.02

Table A-3 *(continued)*

Breakdown of Maintenance Costs by Vehicle System, FCEBs and Diesel Buses

	Fuel Cell Buses	Diesel Buses
Brake System Repairs (ATA VMRS 13)		
Parts cost	0.00	4,275.22
Labor hours	0.0	98.8
Average labor cost	0.00	4,942.00
Total cost (for system)	0.00	9,217.22
Total cost (for system) per bus	0.00	3,072.41
Total cost (for system) per mile	0.00	0.05
Transmission Repairs (ATA VMRS 27)		
Parts cost	0.00	1,445.30
Labor hours	0.0	26.0
Average labor cost	0.00	1,300.00
Total cost (for system)	0.00	2,745.30
Total cost (for system) per bus	0.00	915.10
Total cost (for system) per mile	0.00	0.01
Inspections Only - no parts replacements (101)		
Parts cost	0.00	0.00
Labor hours	564.5	324.8
Average labor cost	28,224.00	16,237.50
Total cost (for system)	28,224.00	16,237.50
Total cost (for system) per bus	7,056.00	5,412.50
Total cost (for system) per mile	0.28	0.08
Cab, Body, and Accessories Systems Repairs		
Parts cost	6,304.28	6,731.84
Labor hours	308.7	301.4
Average labor cost	15,436.50	15,068.00
Total cost (for system)	21,740.78	21,799.84
Total cost (for system) per bus	5,435.20	7,266.61
Total cost (for system) per mile	0.22	0.11
HVAC System Repairs (ATA VMRS 01)		
Parts cost	0.00	1,607.47
Labor hours	10.4	199.8
Average labor cost	521.00	9,991.50
Total cost (for system)	521.00	11,598.97
Total cost (for system) per bus	130.25	3,866.32
Total cost (for system) per mile	0.01	0.06

Table A-3
(continued)

Breakdown of Maintenance Costs by Vehicle System, FCEBs and Diesel Buses

	Fuel Cell Buses	Diesel Buses
Lighting System Repairs (ATA VMRS 34)		
Parts cost	207.99	523.95
Labor hours	8.0	26.1
Average labor cost	400.00	1,303.50
Total cost (for system)	607.99	1,827.45
Total cost (for system) per bus	152.00	609.15
Total cost (for system) per mile	0.01	0.01
Frame, Steering, and Suspension Repairs (ATA VMRS 14 Frame, 15 Steering, 16 Suspension)		
Parts cost	2,286.95	1,765.47
Labor hours	17.1	58.7
Average labor cost	854.00	2,933.50
Total cost (for system)	3,140.95	4,698.97
Total cost (for system) per bus	785.24	1,566.32
Total cost (for system) per mile	0.03	0.03
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11 Front Axle, 18 Wheels, 22 Rear Axle, 24 Drive Shaft)		
Parts cost	0.00	233.55
Labor hours	0.7	17.5
Average labor cost	33.00	877.00
Total cost (for system)	33.00	1,110.55
Total cost (for system) per bus	8.25	370.18
Total cost (for system) per mile	0.00	0.01
Tire Repairs (ATA VMRS 17)		
Parts cost	0.00	0.00
Labor hours	3.3	45.7
Average labor cost	166.50	2,283.00
Total cost (for system)	166.50	2,283.00
Total cost (for system) per bus	41.63	761.00
Total cost (for system) per mile	0.00	0.01

Notes:

1. To compare the hydrogen fuel dispensed and fuel economy to diesel, the hydrogen dispensed was also converted into diesel energy equivalent gallons. Actual energy content will vary by locations, but the general energy conversions are as follows:
   - Lower heating value (LHV) for hydrogen = 51,532 Btu/lb
   - LHV for diesel = 128,400 Btu/lb
   - 1 kg = 2.205 * lb
   - 51,532 Btu/lb * 2.205 lb/kg = 113,628 Btu/kg
   - Diesel/hydrogen = 128,400 Btu/gal /113,628 Btu/kg = 1.13 kg/diesel gal
2. The propulsion-related systems were chosen to include only those systems of the vehicles that could be affected directly by the selection of a fuel/advanced technology.
3. ATA VMRS coding is based on parts that were replaced. If there was no part replaced in a given repair, then the code was chosen by the system being worked on.

Notes *(continued)*

4. In general, inspections (with no part replacements) were included only in the overall totals (not by system). Category 101 was created to track labor costs for PM inspections.
5. ATA VMRS 02-Cab and Sheet Metal represents seats, doors, etc.; ATA VMRS 50-Accessories represents things like fire extinguishers, test kits, etc.; ATA VMRS 71-Body represents mostly windows and windshields.
6. Average labor cost is assumed to be $50 per hour.
7. Warranty costs are not included.
8.

APPENDIX

B

Fleet Summary Statistics – SI Units

Table B-1

Fleet Operations and Economics, FCEBs and Diesel Buses

	Fuel Cell Buses	Diesel Buses
Number of vehicles	4	3
Period used for fuel and oil op analysis	10/10–5/12	10/10–5/12
Total number of months in period	20	20
Fuel and oil analysis base fleet kilometers	161,558	307,046
Period used for maintenance op analysis	10/10–5/12	10/10–5/12
Total number of months in period	20	20
Maintenance analysis base fleet kilometers	161,558	310,704
Average monthly kilometers per vehicle	2,019	5,178
Availability	52%	N/A
Fleet fuel usage in H_2 kg	14,634	183,940
Roadcalls	39	
RCs KMBRC	4,143	7,486
Propulsion roadcalls	31	
Propulsion KMBRC	5,212	11,058
Fleet kg hydrogen/100 km	9.06	
(1.13 kg H_2/gal diesel fuel)		
Rep. fleet fuel consumption (L/100 km)	30.34	59.91
Hydrogen cost per kg	6.85	
Diesel cost/liter		0.88
Fuel cost per kilometer	0.62	0.52
Total scheduled repair cost per kilometer	0.17	0.09
Total unscheduled repair cost per kilometer	0.43	0.23
Total maintenance cost per kilometer	0.60	0.32
Total operating cost per kilometer	*1.22*	*0.84*

Table B-2

Maintenance Costs, FCEBs and Diesel Buses, SI Units

	Fuel Cell Buses	Diesel Buses
Fleet mileage	161,558	310,704
Total parts cost	12,021.21	27,146.97
Total labor hours	1,710.8	1,427.5
Average labor cost (@ $50.00 per hour)	85,540.00	71,375.00
Total maintenance cost	97,561.21	98,521.97
Total maintenance cost per bus	24,390.30	32,840.66
Total maintenance cost per kilometer	*0.60*	*0.32*

ACRONYMS AND ABBREVIATIONS

AC	Alternating current
AC Transit	Alameda-Contra Costa Transit District
Ah	Amp-hours
CTE	Center for Transportation and the Environment
CTTRANSIT	Connecticut Transit
DC	Direct current
DGE	Diesel gallon equivalent
DOE	U.S. Department of Energy
DPF	Diesel particulate filter
FCEB	Fuel cell electric bus
FCPP	Fuel cell power plant
ft	Feet
FTA	Federal Transit Administration
gal	Gallons
GCRTA	Greater Cleveland Regional Transit Authority
HP	horsepower
HVAC	Heating, ventilation, and air conditioning
in.	Inches
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
lb	Pounds
MBRC	Miles between roadcalls
mph	Miles per hour
MTA	Mass Transportation Authority (Flint, MI)
NAVC	Northeast Advanced Vehicle Consortium
NiMH	Nickel metal hydride
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
PEM	Proton exchange membrane
PMI	Preventive maintenance inspection
psi	Pounds per square inch
RC	Roadcall
rpm	Revolutions per minute
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SCR	Selective catalytic reduction
SI	International System of Units
TIGGER	Transit Investments for Greenhouse Gas and Energy Reduction
ZEBA	Zero Emissions Bay Area

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