



Connecticut Transit (CTTRANSIT) Fuel Cell Transit Bus

Preliminary Evaluation Results

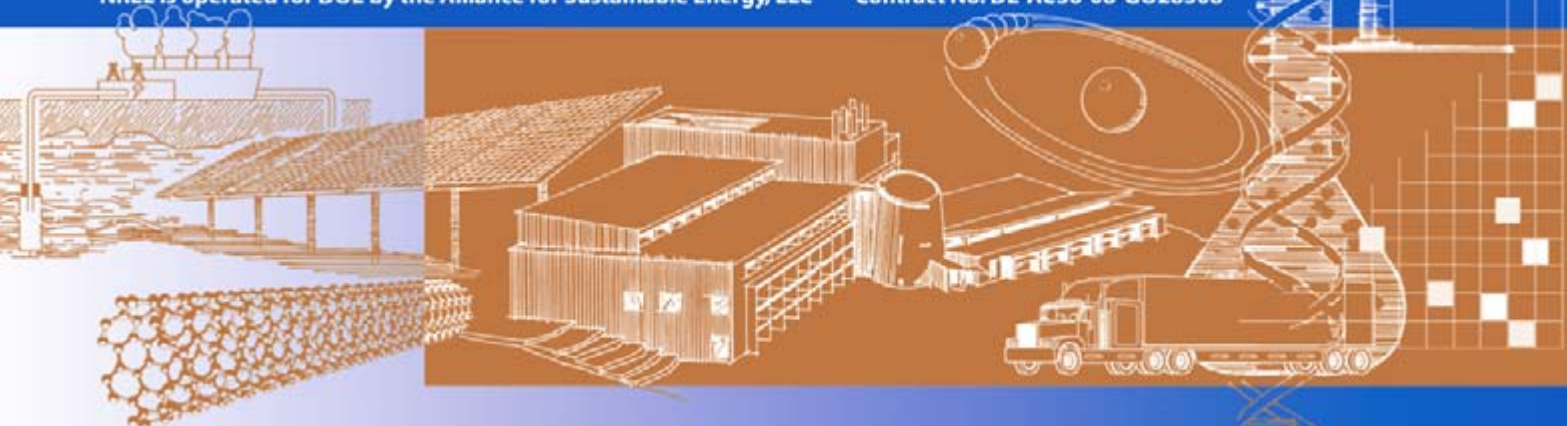
Kevin Chandler
Battelle

Leslie Eudy
National Renewable Energy Laboratory

Technical Report
NREL/TP-560-43847
October 2008



Photo source: CTTRANSIT



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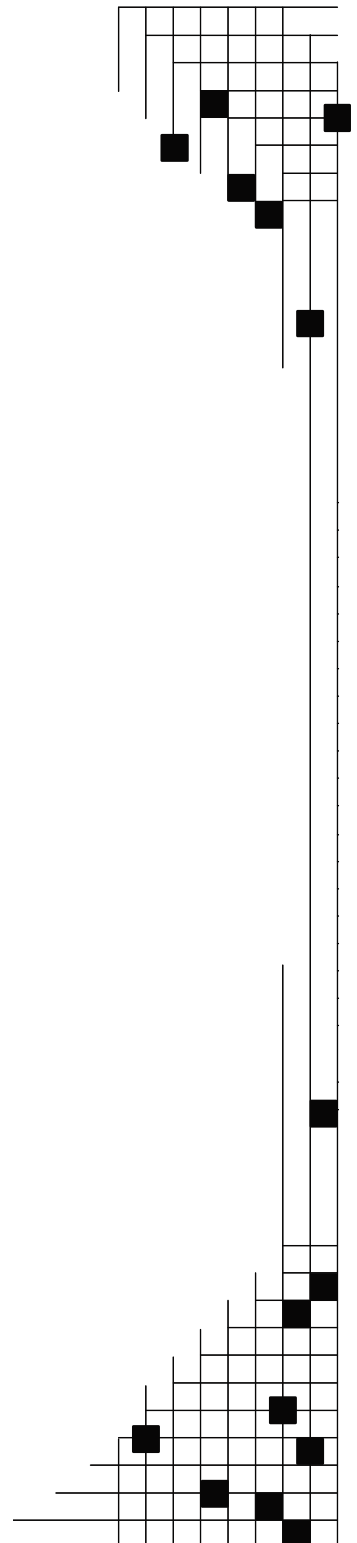
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Prepared under Task No. H270.8200

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NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08-GO28308



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Acknowledgements

This evaluation at Connecticut Transit (CTTRANSIT) would not have been possible without the support and cooperation of many people. The authors thank the following.

U.S. Department of Energy

John Garbak

National Renewable Energy Laboratory

Keith Wipke

George Sverdrup

CTTRANSIT

Stephen Warren

Mitch Howard

Russ Osborn

Nathan Shultz

James Dowd

Thai Ly

UTC Power

Mike Tosca

Matthew Riley

Jennifer Stewart

David Boudreau

Sandra Lajewski

Tiffany Stanley

ISE Corporation

Paul Scott

Gary Wilms

MES-DEA S.A.

Renato Manzoni

Michael Metzger

Acronyms and Abbreviations

AC	alternating current
ConnDOT	Connecticut Department of Transportation
CSA	cell stack assembly
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DPF	diesel particulate filter
ft	feet
FTA	Federal Transit Administration
gal	gallon
HFCIT	Hydrogen, Fuel Cells, and Infrastructure Technology
hp	horsepower
HVAC	heating, ventilation, and air conditioning
in	inches
kg	kilogram
kW	kilowatts
kWh	kilowatt hour
lb	pounds
MBRC	miles between roadcalls
mpg	miles per gallon
mph	miles per hour
NFCBP	National Fuel Cell Bus Program
NREL	National Renewable Energy Laboratory
PEM	proton exchange membrane
PMI	preventive maintenance inspection
psi	pounds per square inch
RC	roadcall
rpm	revolutions per minute
SOC	state of charge

Executive Summary

This report describes operations at Connecticut Transit (CTTRANSIT) in Hartford for one prototype fuel cell bus and three new diesel buses operating from the same location. The report discusses the planned fuel cell bus demonstration and equipment used (bus and hydrogen fueling), and provides the early results and the agency's overall experience with the technology. The evaluation periods presented in this report are as follows.

- **Fuel Cell Bus**—April 2007 through June 2008 (15 months of operation)
- **Diesel Buses**—September 2007 through June 2008 (10 months of operation)

In this evaluation report, the fuel cell bus is considered to be prototype technology that is in the process of being commercialized. The analysis and comparison discussions regarding standard diesel buses help baseline the progress of the fuel cell bus technology. **There is no intent to consider this implementation of fuel cell buses as commercial (or full revenue transit service).** This evaluation focuses on documenting progress and opportunities for improving the vehicles, infrastructure, and procedures.

CTTRANSIT unveiled its new fuel cell bus in April 2007. This was not only a first for the agency, but was also the first fuel cell bus to be operated in New England. Prior to this, most fuel cell buses in the United States were used in demonstration projects in California. The design for CTTRANSIT's bus was leveraged from an earlier procurement of four fuel cell buses now in operation at AC Transit and SunLine in California. Testing the bus in Connecticut provides the project partners with the opportunity to understand how the system operates in a cold and hot, humid climate.

Facilities

CTTRANSIT was only required to make minor modifications to allow operation of the fuel cell bus in its maintenance facility. More significant facility modifications were not required as long as the fuel cell bus operated only on battery power and the hydrogen fuel was isolated (turned off) during operation within the building. In comparison to earlier fuel cell bus projects, the cost for these modifications was low. The bus is fueled at an existing hydrogen fueling station located within seven miles of the facility, at UTC Power. The site required only a few modifications to enable bus fueling. The hydrogen is produced at Niagara Falls as part of a chemical process using hydropower, is cleaned and liquefied, and then is trucked to Hartford. So far, the fuel cell bus was filled a total of 109 times with 2,486 kg of hydrogen during the evaluation period.

Training and Public Awareness

To date, CTTRANSIT's experiences with integrating a fuel cell bus into its operation have been exceptionally easy. CTTRANSIT and its project partners organized a comprehensive training program to provide hydrogen familiarization and detailed maintenance and operations for the fuel cell bus to the appropriate staff. CTTRANSIT also has experienced a high level of interest in the fuel cell bus demonstration from the local community and the larger New England region. The fuel cell bus operates on a free downtown circulator/shuttle (Star) route that makes providing rides to visitors extremely simple. The bus also operates in normal revenue service on other CTTRANSIT local routes on the weekends.

Evaluation Results

Based on the reactions of bus operators and of the general riding public, experience in operating the fuel cell bus has been positive regarding the bus and the concept of using hydrogen and fuel-cell propulsion. Some specific problems and limitations reported have included initial quality assurance of the bus manufacturing/integration, traction batteries, heating and air conditioning, operating in slippery conditions, maximum bus operating speed, and degradation of the fuel cell power system. Details of these issues are provided in the Implementation and Experience to Date section.

Table ES-1 provides a summary of results for several of the categories of data presented in this report. During the evaluation period the fuel cell bus accumulated 12,115 miles, and the fuel cell systems accumulated 2,049 hours. These numbers indicate an overall average operating speed of 5.9 mph, which is significantly less than the average service at CTTRANSIT (12 mph) and the Star route (10 mph). Note that the maintenance costs are high for the fuel cell bus because of the amount of participation by the CTTRANSIT mechanics in fuel cell and hybrid propulsion maintenance. These costs were not charged back to the manufacturers as warranty.

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell	Diesel
Number of Buses	1	3
Data Period	4/07–6/08	9/07–6/08
Number of Months	15	10
Total Mileage in Period	12,115	97,447
Total Fuel Cell Hours	2,049	N/A
Average Monthly Mileage per Bus	808	3,248
Average Operating Speed (mph)	5.9	12
Availability (Target is 85%)	54%	N/A ^a
Fuel Economy (Miles/kg)	4.79	N/A
Fuel Economy (Miles/DGE ^b)	5.41	3.60
Miles Between Roadcalls—All	505	8,859
Miles Between Roadcalls—Propulsion Only	577 ^c	13,921
Total Maintenance, \$/Mile ^d	4.59	0.26
Maintenance—Propulsion Only, \$/Mile	3.72	0.07

a. Availability for diesel buses not collected, data was not available

b. Diesel gallon equivalent.

c. For fuel cell propulsion only, Miles Between Roadcalls (MBRC) was 4,038.

d. Work-order maintenance cost.

What's Next for CTTRANSIT?

This initial evaluation report includes the first 15 months of operation of the fuel cell bus at CTTRANSIT. The next evaluation report will add at least six more months of operation, and most likely will be completed in early 2009. The most important aspect of the evaluation is tracking the progress and desire for CTTRANSIT to maximize the usage of the fuel cell bus and determine whether the new version of the fuel cell power system makes significant progress to the expected 4,000 hours of operation. There also are two other fuel cell projects planned at CTTRANSIT, and discussion of those experiences will be published separately as part of the Federal Transit Administration (FTA) National Fuel Cell Bus Program (NFCBP).

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Introduction

This report provides preliminary results from a National Renewable Energy Laboratory (NREL) evaluation of a prototype fuel cell transit bus operating at Connecticut Transit (CTTRANSIT) in Hartford. Descriptions in this report include the planned fuel cell bus demonstration and equipment used (bus and hydrogen fueling), and it provides the early results and the agency's overall experience with the technology for an evaluation period of April 2007 through June 2008.

NREL Evaluations

This evaluation of the CTTRANSIT prototype fuel cell bus is funded through the Department of Energy's (DOE) Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. The HFCIT Program at DOE¹ works with partners to address the technical challenges and accelerate the development and successful market introduction of hydrogen technologies. Technology validation is one of the key elements of this program.² NREL is one of DOE's national laboratories in support of this activity, and evaluates hydrogen and fuel cell vehicles in parallel with hydrogen infrastructure to determine the current status of the technology and assess the progress toward technology readiness.

NREL is also working with the Federal Transit Administration (FTA)—an agency of the Department of Transportation—to evaluate fuel cell buses in transit applications. This work directly supports FTA's National Fuel Cell Bus Program (NFCBP). In addition to the current fuel cell bus operation described in this report, CTTRANSIT is also involved in two of the eight NFCBP demonstration projects. Table 1 provides an overview of the current and planned NREL evaluations for both DOE and FTA.

Using an established protocol for data collection and analysis, NREL provides comprehensive, unbiased results on the implementation, operation, and costs of fuel cell buses in comparison to those of conventional-technology buses operating in the same or similar service. The objectives of the data collection are to validate fuel cell and hydrogen technologies in bus applications to:

- Determine the status of fuel cell systems for buses and corresponding hydrogen infrastructure;
- Provide feedback for DOE and FTA research and development; and
- Provide “lessons learned” on implementing next-generation fuel cell systems into bus operations.

¹ DOE HFCIT Web site, <http://www1.eere.energy.gov/hydrogenandfuelcells/>. Accessed August 14, 2008.

² DOE Multi-Year Research, Development and Demonstration Plan, <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/>. Accessed August 14, 2008.

Table 1. Summary of NREL Hydrogen Projects for DOE and FTA³

Site/Locations	State	Eval. Funding	2008				2009				2010				2011			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
AC Transit /SF Bay Area	CA	DOE Tech. Validation									CA ZEB Advanced Demo 2009							
SunLine /Thousand Palms	CA		FCB Ext. Service															
SunLine /Thousand Palms	CA										Advanced FCB Project							
CTTRANSIT /Hartford	CT		CTTRANSIT FCB Demo															
City of Burbank/Burbank	CA									Burbank								
AC Transit /Oakland	CA	FTA National Fuel Cell Bus Program	Accelerated Testing															
SunLine /Thousand Palms	CA										American FCB Demo							
CTTRANSIT /Hartford	CT										CT Hybrid FCB Demo							
Columbia /site 2/ CTTRANSIT	SC/CT										Dual Variable Output Hybrid FCB							
Logan Airport /Boston	MA										MA H2 FCB Fleet							
TBD/NY	NY										Lightweight FCB Demo							
TBD/NY	NY										NYPA H2 Powered FCB							
SFMTA /San Francisco	CA										FC APU Hybrid							

Demonstration sites color coded by geographic area:

California	Green
New England	Blue
Western NY	Yellow
Southeast	Purple
South	Red

CTTRANSIT Profile

CTTRANSIT⁴ is owned by the Connecticut Department of Transportation (ConnDOT) and provides fixed-route transportation services to three major metropolitan areas in the state: Hartford, New Haven, and Stamford. In 2007, the agency transported nearly 27 million passengers. The Hartford Division is the largest of the three areas, operating a total of 237 buses over 30 local routes and 12 express routes in and around the capital area. The Division service area covers 469 square miles and serves a population of more than 851,000. Figure 1 shows the service area for this Division.



CTTRANSIT has been investigating new technologies and fuels for its fleet that are more efficient and produce fewer emissions. In November 2006, the agency switched to ultra low-sulfur diesel fuel with 5% biodiesel in its bus fleet to reduce both emissions and petroleum consumption. All new buses procured by the agency are equipped with diesel particulate filters (DPF). To further reduce fleet emissions, CTTRANSIT has a retrofit program in progress to install DPFs on most of its existing bus fleet.

³ "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, May 2008, <http://www.nrel.gov/hydrogen/pdfs/42781-1.pdf>. Accessed August 14, 2008.

⁴ CTTRANSIT Web site <http://www.cttransit.com/>. Accessed August 14, 2008.

CTTRANSIT also conducted a pilot program to evaluate the benefits of hybrid technology for potential future purchases. For this 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 2005⁵.

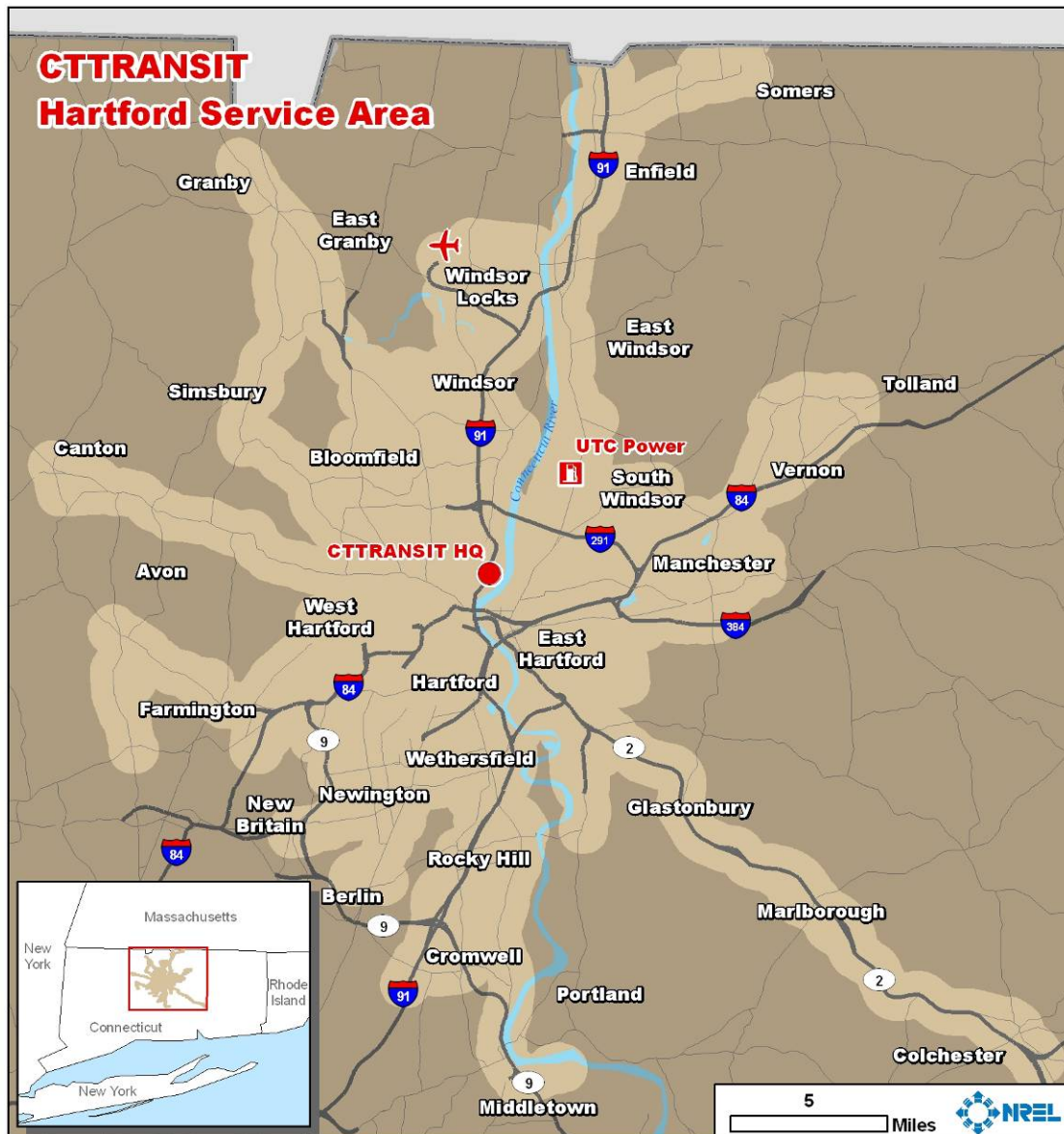


Figure 1. Service area for CTTRANSIT's Hartford Division

⁵ Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses, Connecticut Academy of Science and Engineering, Oct. 2005, www.ctcase.org/reports/diesel-hybrid.pdf. Accessed August 13, 2008.

CTTRANSIT's Fuel Cell Demonstration Project

CTTRANSIT unveiled its new fuel cell bus in April 2007. This not only was a first for the agency, but also was the first fuel cell bus to be operated in New England. Prior to this demonstration, most fuel cell buses in the United States were used in demonstration projects in California. CTTRANSIT's bus design was leveraged from an earlier procurement of four fuel cell buses now in operation at AC Transit and SunLine in California. Testing the bus in Connecticut provides the project partners the opportunity to understand how the system operates in a cold and hot/ humid climate. Table 2 lists the partners involved in the project, and their respective roles.

Table 2. Fuel Cell Bus Demonstration Partners

Demonstration Partner	Role
Federal Transit Administration	Project funding through a grant
Greater Hartford Transit District	Administration for FTA grant and UTC Power contract
ConnDOT	Funding for the bus operation
Van Hool Bus of Belgium	Manufacturer of the bus body and chassis
UTC Power of Connecticut	Manufacturer of the fuel cell power systems
ISE Corporation of San Diego	Integrator of the fuel cell power systems and hybrid-electric drive systems
AC Transit of Oakland	Provide hydrogen safety training and consulting

For several key reasons, CTTRANSIT is an important choice for demonstrating fuel cell technology. Nearly all of the previous fuel cell bus demonstrations in the United States have been in warm-weather climates, and Hartford, Connecticut, provides a colder climate. This climate can be an issue because of the potential for water in the fuel cell systems to freeze, and due to other related issues, such propulsion system operation in adverse weather conditions. Past experience in demonstrating new technologies has given the agency an awareness of what to expect, and insight regarding how these issues could arise in such projects. CTTRANSIT management and staff understand the need to work with the manufacturers to further optimize and develop a product.

One of the most significant reasons for its selection has been CTTRANSIT's close proximity to the location of the fuel cell manufacturer, UTC Power. This proximity enabled easy and fast access to the bus as needed. UTC Power has further enriched its fuel cell bus development program by periodically collecting additional diagnostic data and evaluating possible design enhancements on the CTTRANSIT bus while at UTC Power facility. This approach is more cost effective and resulted in far fewer service disruptions than if the fuel cell power units from distant sites were sent back to the UTC Power facility for the same work. The only other option would be to complete all needed testing in the field—which is difficult, based on the complexity of fuel cell power systems and components integrated into the buses.

An extremely important reason for demonstrating fuel cell buses at CTTRANSIT is the support of the State of Connecticut. Environmental issues have been an important driver for transportation projects and programs in the state. Over the past few years, Connecticut has worked to exceed the federal regulations set by the Clean Air Act Amendments to address the concerns of poor air quality and climate change. The state's efforts include the following.

- In 2001, the New England governors and Eastern Canadian premiers adopted a regional climate-change action plan to reduce greenhouse gasses.
- In 2004, Connecticut passed *An Act Concerning Climate Change* (Public Act 04-252) and became the first state to develop an action plan to address climate-change issues⁶.
- In December 2004, the state adopted California LEV-II vehicle emissions regulations, set to begin with the 2008 model year.
- Established the Connecticut Hydrogen-Fuel Cell Coalition (www.chfcc.org/) to advance the development, manufacture, and deployment of fuel cell and hydrogen technologies and associated fueling systems in Connecticut.
- In May 2006, Public Act 06-187⁷: *The Roadmap to Connecticut's Economic Future* was signed into law. This Act requires the state to investigate the economic potential for hydrogen technology and to develop a roadmap to facilitate the commercialization of fuel cells and hydrogen-based technologies.
- In January 2008, Completion of the Fuel Cell Economic Development Plan—Hydrogen Roadmap.⁸ The plan includes recommendations to increase the number of fuel cell buses in operation in the state. CTTRANSIT expects to participate in the activities from this plan.

Site Evaluation Plan

The evaluation presented in this report includes one prototype fuel cell-powered 40-foot transit bus (Figure 2) operating at CTTRANSIT's Hartford Division. Three diesel buses (*see* Figure 3) were selected from CTTRANSIT's newest order of 65 New Flyer diesel buses operating at the same depot. Data have been collected in parallel to the prototype bus for the evaluation period, April 2007 through June 2008.

Data for this evaluation were taken from CTTRANSIT's data system. Data parameters include:

- Diesel fuel consumption by vehicle and fill;
- Hydrogen fuel consumption by vehicle and fill;
- Mileage data from every vehicle in the study;
- Route assignments for the fuel cell bus;

⁶ Connecticut Climate Change Action Plan, <http://ctclimatechange.com/StateActionPlan.html>. Accessed August 13, 2008.

⁷ Public Act 06-187, *The Roadmap to Connecticut's Economic Future*, <http://www.cga.ct.gov/2006/ACT/PA/2006PA-00187-R00HB-05846-PA.htm>. Accessed August 14, 2008.

⁸ Roadmap, <http://www.ct.gov/ecd/cwp/view.asp?Q=410448&A=1105>. Accessed August 14, 2008.

- Preventive maintenance action work orders, parts lists, labor records, and related documents; and
- Records of unscheduled maintenance, including roadcalls and warranty actions performed by vendors (when available in the data system).

Additional information has been collected on the maintenance/operation experience, issues at the hydrogen fueling station and at CTTRANSIT facilities, and lessons learned at the start of—and during—operation of the fuel cell bus.



Figure 2. CTTRANSIT's fuel cell bus



Figure 3. One of CTTRANSIT's newest diesel buses

Implementation and Experience to Date

This section provides descriptions and details of the implementation of fuel cell bus operations at the CTTRANSIT Hartford Division, as well as the early experiences. The discussion begins with planned service for the fuel cell bus followed by descriptions of the buses, maintenance facility modifications, the hydrogen fueling station at UTC Power, and of training and public awareness activities.

Planned Demonstration Service

CTTRANSIT's fuel cell bus was first placed into transit service on the Star Shuttle route in downtown Hartford starting on April 11, 2007, the day following the official dedication of the new fuel cell bus. The Star route offers free service around downtown Hartford, connecting hotels with the convention center, restaurants, and many other landmarks. The route was designed to reduce traffic in the capital area by providing a convenient alternative to driving. The shuttle operates every weekday and on Saturday afternoons. Figure 4 outlines the route and stops in the area. The Star route is 5.5 miles long and the average operating speed is 10 mph for a typical bus, depending on traffic conditions. This downtown route has been extremely conducive to having visitors ride the bus in service without disrupting CTTRANSIT staff and operations.

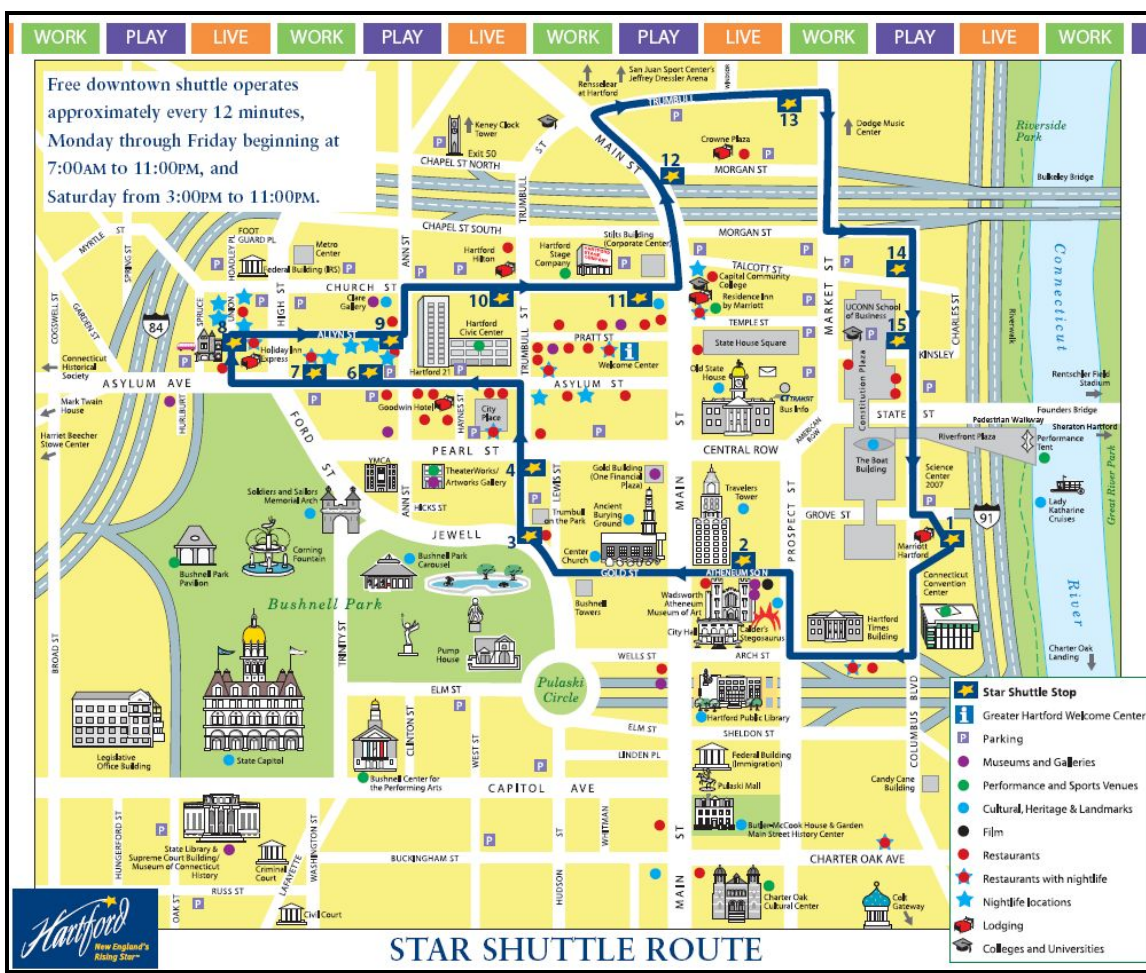


Figure 4. Hartford Downtown Star Shuttle map

Starting in January 2008, CTTRANSIT began operating the fuel cell bus each weekday on two eight-hour shifts of the Star route. The bus also began operation on Saturday for one shift on the Star route. Starting in March 2008, the bus was operated on routes E and F on Saturday and Sunday for up to 16 hours per day in addition to the 16-hour days on the Star route during the week. In the future, the plan is to also operate the bus on additional routes to test performance in a variety of transit-service conditions, such as on steep grades. Currently, the main focus is to use the fuel cell bus in service as much as possible.

Additional weekend service at CTTRANSIT caused some planning issues with off-hours fueling and availability of trained mechanics for potential weekend roadcalls of the fuel cell bus. To support this extended service of the fuel cell bus (up to 16 hours per day), enough time had to be planned to ensure that the bus could be driven to UTC Power to be fueled and brought back to the Division to be plugged into the battery charger station each night. The batteries require between 4 and 4.5 hours to fully charge. During bus operation the batteries are kept at a state of charge (SOC) from 50% to 60% to allow for significant energy regeneration from braking back into the batteries.

The diesel buses are not restricted to specific routes and generally are randomly dispatched seven days per week. This is reflected in the greater bus use (discussed below).

Fuel Cell and Diesel Buses

Table 3 provides bus system descriptions for the fuel cell and diesel buses included in this evaluation. Three diesel buses from the most recent bus order were selected for baseline comparison data.

The fuel cell bus chassis is the same model and design as buses operating at AC Transit in Oakland, California (three buses), and SunLine Transit Agency in the Palm Springs, California, area (one bus). UTC Power purchased a bus as an option from the AC Transit order and then sold it to CTTRANSIT, which makes UTC Power the supplier of record for warranty instead of ISE Corporation, as is the case for the other four California buses.

Table 4 provides a description of some of the electric propulsion systems for the fuel cell buses. 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. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	Operation from Hartford Division	
	Fuel Cell Bus	Diesel Bus
Number of Buses	1	3
Bus Manufacturer and Model	Van Hool A330 Low Floor	New Flyer DL 40
Model Year	2005	2007
Length/Width/Height	40 ft/102 in/139 in	40 ft/102 in/111 in
GVWR/Curb Weight	43,240 lb/36,000 lb	43,850 lb/28,850 lb
Wheelbase	228 in	293 in
Passenger Capacity	30 seated or 26 seated and 2 wheelchairs; 15 standing	38 seated or 28 seated and 2 wheelchairs; 61 standing
Engine Manufacturer and Model	UTC Power PureMotion ⁹ 120 Fuel Cell Power System	Cummins ISL
Rated Power	Fuel cell power system: 120 kW Two Electric Drive Motors: 170 kW total (continuous)	280 hp @ 2,200 rpm 900 lb-ft @ 1,300 rpm
Accessories	Electrical	Mechanical
Emissions Equipment	None	Active DPF
Transmission/Retarder	Gearbox/Flenders Regenerative braking	Allison B400R/retarder
Fuel Capacity	50 kg hydrogen	125 gal
Bus Purchase Cost	\$2.4 million	\$337,000

Table 4. Additional Electric Propulsion System Descriptions

Propulsion Systems	Fuel Cell Bus
Manufacturer/Integrator	ISE Corporation
Hybrid Type	Series, charge sustaining
Drive System	Siemens ELFA/ISE
Propulsion Motor	2-AC induction, 85 kW each
Energy Storage	Battery: 3 modules/216 cells sodium/nickel chloride ZEBRA; 53 kWh capacity
Fuel Storage	Eight, roof mounted, SCI, type-3 tanks; 5,000 psi rated
Regenerative Braking	Yes

Fuel Cell Bus Propulsion System Description – The prototype fuel cell bus in service at CTTRANSIT was designed by UTC Power, ISE Corporation, and Van Hool. The bus uses a fuel cell power system manufactured by UTC Power in a hybrid electric drive system designed by ISE.

The ISE hybrid system (Figure 5) is a series configuration—the fuel cell power system is not mechanically coupled to the drive axle. The fuel cell power system and energy storage system work together to provide power to two electric drive motors, which are coupled to the driveline through a combining gearbox. This hybrid system also is capable of regenerative braking, which captures the energy typically expended during braking and uses it to recharge the energy storage system. Each component of the propulsion system is controlled through an ISE-developed software operating system.

⁹ PureMotion is a registered trademark of UTC Power.

The primary power source for the hybrid system is UTC Power's PureMotion 120 Fuel Cell Power System, which produces 120 kW from its proton exchange membrane (PEM) fuel cell stacks. UTC Power's fuel cells operate at near-ambient pressure, which eliminates the need for a compressor. This not only increases the efficiency of the system, but also results in quiet operation. The energy storage system consists of three ZEBRA (sodium/nickel chloride) batteries.

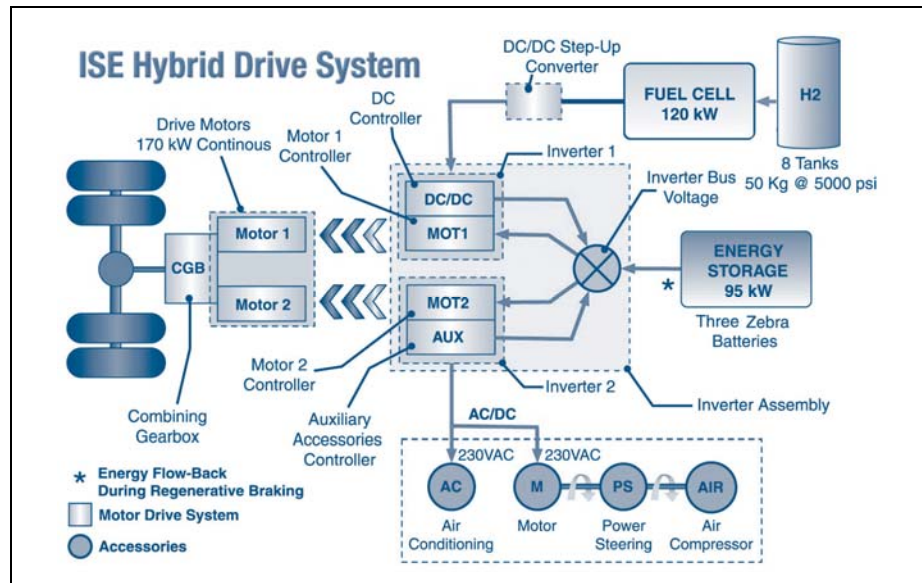


Figure 5. Hybrid propulsion system diagram

Bus Experience – CTTRANSIT has reported several issues with the fuel cell bus operation and availability. In general, operators and the riding public have had positive comments regarding the bus and the concept of using hydrogen and fuel cell propulsion. Some specific problems and issues reported have included quality assurance of the bus manufacturing, traction batteries, heating and air conditioning, operation in slippery conditions, maximum bus operating speed, and degradation of the fuel cell power system.

- **Quality Assurance for the Bus** – There were issues with quality control of the final manufacturing of the fuel cell bus. These issues included loose wiring and incorrect wiring such as that of cooling fans. This was reported as an issue because of hurried final manufacturing to deliver the bus in a short period and meet contractual and funding needs of CTTRANSIT. All issues identified are believed to have been resolved.
- **Traction Battery Failures** – The ZEBRA batteries have experienced significant issues in this application; three traction batteries on the bus are operated in parallel. A cell in a ZEBRA battery will typically fail during a short circuit. A battery with failed cells has reduced voltage, although it can still be operated. Because the batteries are operated with a direct parallel connection, when the number of failed cells within each of the batteries is too different among the three batteries, it causes an unbalancing of the SOC. This imbalance makes it difficult to keep the batteries in the recommended operating range. The present SOC balancing algorithm will temporarily disconnect a battery to keep the SOC balanced.

This situation may mislead over-volt errors in the propulsion system, causing a shutdown of the bus. The battery manufacturer (MES-DEA), UTC Power, and ISE have been working on the issue for some time. Because failed cells are related to a stress condition due to the battery usage, some progress has been made with controller software changes to improve battery operation by refining some operational limits. In the test period, an intermediate version of the software caused some additional failures of the battery controller electronics, and an updated version has been released. Other options for a balancing strategy are under discussion. More replacement batteries are kept in stock to increase the number of available better matched batteries and to reduce the amount of downtime of the fuel cell buses both at CTTRANSIT and in California. In the meantime, as general improvements, MES-DEA introduced modifications to the design and the manufacturing process to improve the reliability of ZEBRA batteries.

- **Insufficient Heating** – Operators of the fuel cell bus have reported an issue with the bus not providing enough heat during the winter. This has been an issue for all hybrid electric transit buses operated in cold weather, regardless of the powerplant (diesel engine or fuel cell). The issue is that the powerplant in a hybrid configuration does not develop enough waste heat (because of the high efficiency of the powerplant operation) to warm the passenger compartment in a timely manner. UTC Power and Van Hool continue to work on this issue.
- **Air Conditioning Noise** – Hybrid electric propulsion systems in transit buses tend to be extremely quiet compared to conventional buses. This has resulted in other “noises” within the bus becoming more noticeable. In the case of this fuel cell bus, the air conditioning fans were noticeably loud. UTC Power engineers set out to quiet the air conditioning by adding baffling and other fixes to the system. The air conditioning on the bus now is significantly quieter. In the next few months, UTC Power intends to implement several other changes in hopes of quieting the system further.
- **Operating in Slippery Conditions** – The electric propulsion system on the fuel cell bus has some issues with slipping in snowy or icy conditions. This has only caused a significant problem with operation of the bus a few times since the start of operations. ISE continues to study the issue and is considering a software change to the operation of the bus, but is not yet drawing any conclusions.
- **Incorrect Drive Axle and Limited Maximum Speed** – The one significant difference between the CTTRANSIT fuel cell bus and the California buses was the drive axle installed. The drive axle on the CTTRANSIT fuel cell bus has a maximum speed of 48 mph. This change originally was viewed by the fleet as a mistake to be corrected by installing the same drive axle as the California fuel cell buses, which has a maximum speed of 65 mph. Van Hool, however, recently (March 2008) decided to require that all of these fuel cell buses be controlled down to 48 mph (via software control for the California buses). Van Hool is concerned that the center of gravity of the bus is higher than that of a standard bus, because of the height of the fuel cell bus and the weight of the fuel tanks and other equipment on the top of the bus; combined, these issues might allow the bus to tip over when moving at a high speed. For CTTRANSIT, the fuel cell bus cannot be operated on many of the routes in the service area because of the need to travel on the freeway, which requires operation speed of at least 55 mph. The manufacturer team has been discussing the possibility of allowing the

California buses to operate at up to 55 mph. CTTRANSIT has been considering available routes that the bus could be assigned, based on the inability to operate faster than 48 mph.

- **Unanticipated Performance Loss for UTC Power Fuel Cell Power System** – UTC Power monitors the performance of the fuel cell power system to analyze actual performance versus predicted performance. The cell stack assemblies (CSAs) showed power degradation early in the operation of this bus. When the power degradation of the CSAs falls below 90 kW to 95 kW of the original 120 kW, the system is considered to be at the end of its life and should be replaced. This early power degradation was reported with the California fuel cell buses as well, and UTC Power reports the problem as an issue of contamination within the CSAs causing the premature degradation beyond end of life (at about 800 hours of operation instead of the expected 4,000 hours or more). UTC Power used the CTTRANSIT fuel cell bus to study the early power degradation issues at its facility over several weeks, and has made some operations control changes. The CSAs on the CTTRANSIT fuel cell bus were replaced with a new version on January 15, 2008. UTC Power has reported that this early power degradation issue appears to have been resolved for the CTTRANSIT and California fuel cell buses.
- **ISE Drive Motor Failure** – The fuel cell bus had a problem during May and June 2008 that took some time to resolve. The problem started as an indication of an inverter failure. Ultimately, it was a drive motor failure. In addition, there was some confusion in providing replacement parts. The first replacement parts for both the inverter and then the drive motor were both incorrect and the correct part was delivered on the second try.

Facilities

CTTRANSIT manages the day-to-day operations for the Hartford Division buses from its facility located a few miles north of the downtown city center. The site includes offices for management and staff as well as maintenance bays, a bus wash, and indoor bus parking. To demonstrate the fuel cell bus, CTTRANSIT needed to address hydrogen fueling infrastructure and modifications to existing facilities for safe storage and maintenance of the bus. For past fuel cell bus projects, this has proved to be one of the most challenging aspects of the demonstration. CTTRANSIT's ease in accomplishing this portion of the project is a striking contrast to other transit agency experience.

CTTRANSIT Maintenance Facility Modifications – At the onset of the project, CTTRANSIT hired a consultant to investigate what modifications were necessary to enable a hydrogen vehicle to be operated, maintained, and parked in the existing bus facility. Recommendations from the consultant included an upgraded ventilation system, fuel sensors, and alarms. Total cost for the upgrades (including the consultant's fee) was \$150,000. CTTRANSIT worked closely with local fire officials early in the process, and was not required to make extensive electrical or ventilation upgrades. This fuel cell bus design includes the ability to move the bus on electric power only—the hydrogen and fuel cell system is temporarily disabled. Because of this, the upgrades required by local officials were simple and inexpensive, and the fuel cell bus must be operated in electric-only mode while inside the facility.

Maintenance specifically performed on the hydrogen or fuel cell system is handled at UTC Power facilities, and routine bus maintenance is conducted at the CTTRANSIT facility. The bus

is brought into the shop with the hydrogen-fuel cell system locked out. For maintenance tasks that involve hot work (which could cause a spark), the bus is defueled prior to being brought into the building. The safe operating procedures for the bus are posted in the maintenance bay. Figure 6 shows the maintenance bay at the CTTRANSIT facility.



Figure 6. CTTRANSIT fuel cell bus maintenance bay (lower left), operating procedures (upper left), and alarm control system (right)

CTTRANSIT currently has two senior-level technicians assigned to work on the fuel cell bus. In addition to all the standard bus maintenance, these technicians conduct much of the hybrid system repairs (including warranty work for ISE) and actively participate in fuel cell system work. The agency thought that hands-on experience with the new technology is very important and the staff was willing to do as much of the work as the manufacturers would allow. UTC Power has provided maintenance and repair of the fuel cell power system.

There is no on-site ISE staff, so most work on the hybrid system is performed by the CTTRANSIT technicians. The agency reports excellent and responsive support from both UTC Power and ISE (located in San Diego, CA). The biggest challenge has been troubleshooting issues from opposite sides of the country (and sometimes across the world).

Hydrogen Fueling Station – For CTTRANSIT, providing hydrogen for its first fuel cell bus was relatively easy. The agency is located about seven miles away from one of its primary demonstration partners, UTC Power, which already had a hydrogen supply available. The site

required only a few upgrades to enable bus fueling: UTC Power installed a hydrogen storage buffer, a dispenser, and a grounding pad. The upgrades were accomplished and the station was ready for bus fueling by March 2007. The funding for the upgrade was provided through the FTA grant.

The UTC Power fueling station features liquid hydrogen storage, compression, and dispensing. Praxair delivers the hydrogen, which is produced in western New York as a by-product of a chemical process. Chemical companies use renewable hydropower from the NY Power Authority at Niagara Falls to operate electrolyzers that run a chloralkali process on naturally occurring brine in the area. The chloralkali process creates caustic soda and chlorine for use in other chemical processes, and also produces hydrogen gas. The hydrogen gas then is sent to Praxair's facility (located near Niagara Falls) where the gas is purified and turned into a liquid, utilizing renewable hydropower from Niagara Falls. Figure 7 shows the fueling facility and dispenser at UTC Power headquarters.



Figure 7. Fueling facility (left) and dispenser (right) at UTC Power headquarter

Hydrogen Fueling Experience – When the fuel cell bus needs hydrogen, a CTTRANSIT staff member drives it to the UTC Power facility, which is about seven miles northeast of the bus depot. The station is located behind locked gates in a secure area of the UTC Power property. The bus driver calls ahead to ensure that trained staff are available to provide access to this secure area and to operate the station. At this point in the demonstration, only trained UTC Power employees fuel the bus.

Early in the project, the process for fueling the bus took approximately one hour. This mainly was due to procedures developed for safety, which included placing traffic cones to block other vehicle access, hook up, fuel dispensing, and sometimes also was due to station start-up time. The time needed to drive the bus to and from the site required significant resources from the transit agency. As the project partners have become more comfortable with the fueling process, UTC Power has worked to streamline the procedures and reduce the overall time. Fueling times are now approximately 20 minutes.

Figure 8 shows the monthly total hydrogen use by CTTRANSIT's fuel cell bus. The fuel usage starts out low and then increases from June through August 2007, as operation of the fuel cell bus increased. Fuel usage decreased toward the end of 2007 due to problems with the traction batteries and power degradation of the fuel cell power system CSAs (discussed above). From January 2008 through March 2008 fuel usage increased dramatically, but it then decreased again. The lack of usage was mostly because of a bad traction motor and the ongoing issues with the traction batteries. These issues were resolved by June 2008, and usage returned to the levels seen earlier in 2008.

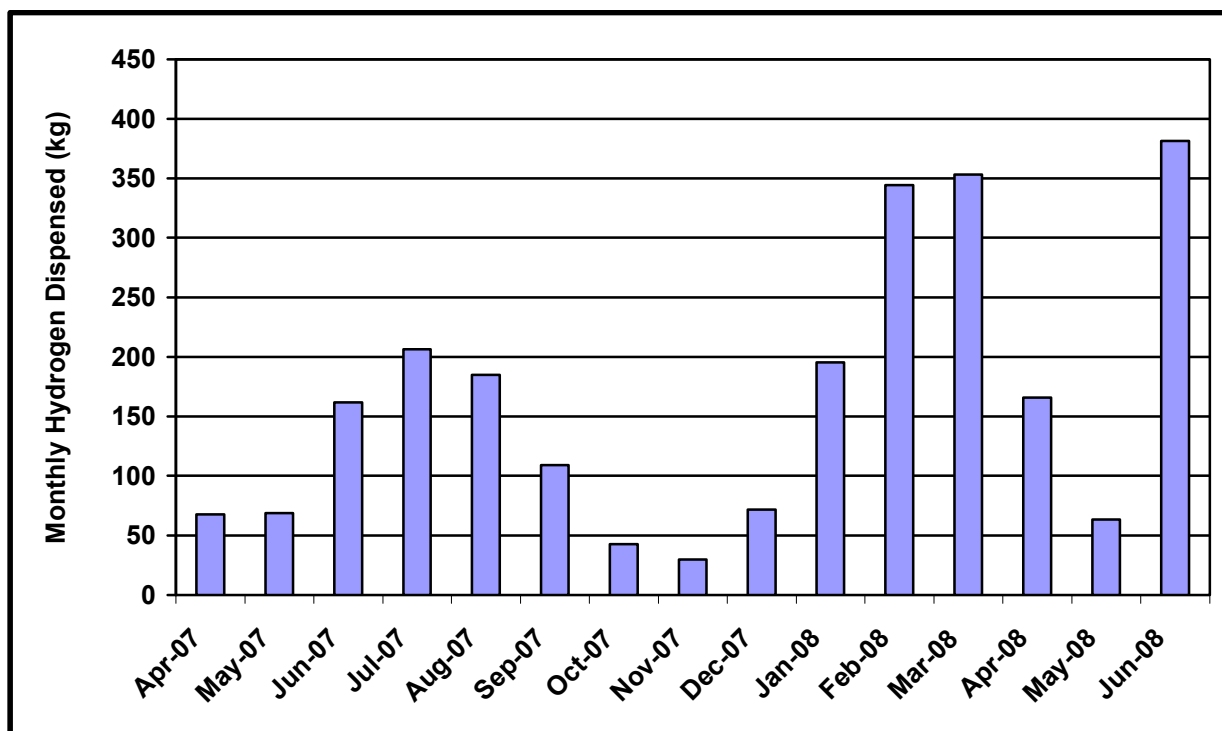


Figure 8. Monthly total hydrogen use by CTTRANSIT's fuel cell bus

Figure 9 shows the distribution of hydrogen amounts per fill. The fuel cell bus was filled 109 times with a total of 2,486 kg of hydrogen during the evaluation period, and an average fill amount of 22.8 kg. Figure 10 shows the number of fueling events and average time per fill per month. As noted, the 60-minute average fueling time seen at the beginning of the evaluation period was reduced over time to an average of 22 minutes per fill. Overall during the evaluation period, the average fueling time was 36 minutes per fill. Note that the fueling time includes the time required to set up safety measures around the fueling station to keep other vehicles out of the area.

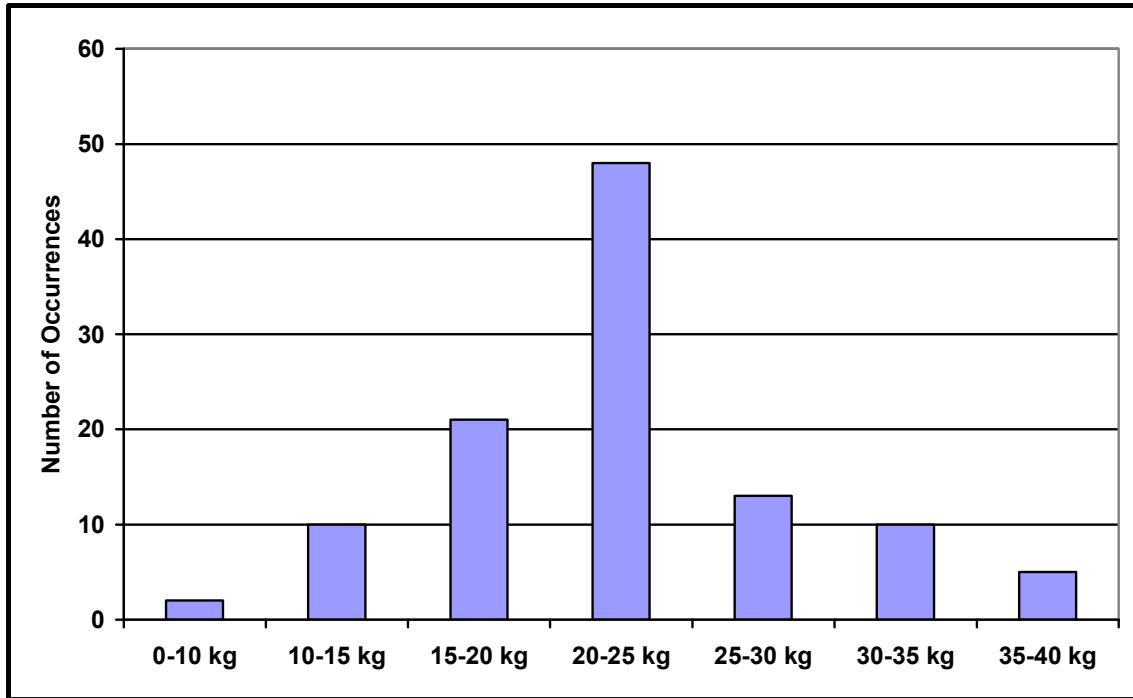


Figure 9. Distribution of average fill amounts for the fuel cell bus

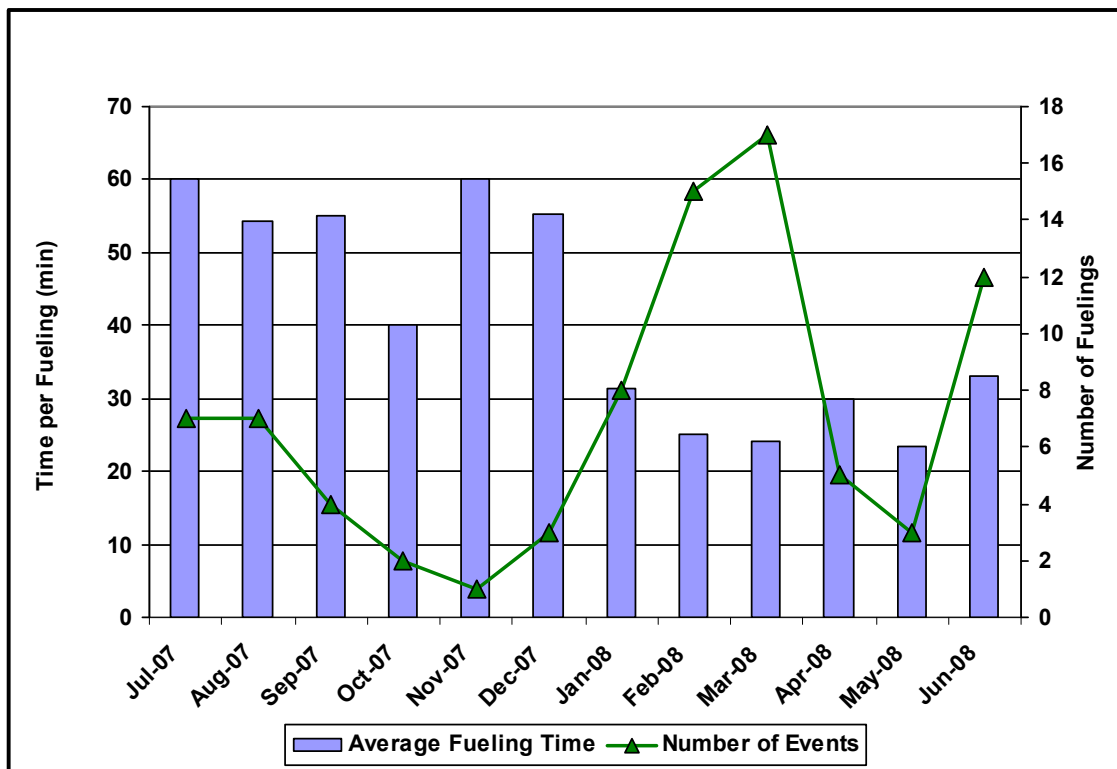


Figure 10. Average time per fueling and number of fueling events per month

Training and Public Awareness

CTTRANSIT has invested in training activities to support the fuel cell bus demonstration, and in resources to participate in public-awareness events. Training activities included hydrogen safety, bus propulsion systems, and bus operation. Public awareness activities include hosting tours of facilities at CTTRANSIT and making the fuel cell bus available for tours and rides.

Training Activities – To date, CTTRANSIT’s experiences with integrating a fuel cell bus into its operation have been exceptionally easy. Careful project planning, a forward-thinking agency and state, and proactive project partners all have contributed to the early success. The agency also has taken advantage of opportunities to learn from other early adopters of the technology, specifically AC Transit. Training for staff and local officials has been particularly important for the agency, and was initiated prior to arrival of the bus. CTTRANSIT and its project partners organized a comprehensive training program to provide hydrogen familiarization and detailed maintenance and operations information for the fuel cell bus to the appropriate staff.

- **Hydrogen Safety Training**—The ability to operate the fuel cell bus safely is extremely important to CTTRANSIT, therefore hydrogen familiarization and safety was the first training session conducted. The agency arranged for two experts from Schatz Energy Research Center and Humboldt State University to provide the training. Two sessions were held, one for agency staff and another for local firefighters and first responders. The sessions were videotaped to use in ongoing sessions at CTTRANSIT.
- **Bus-Level Training**—AC Transit staff provided training on the Van Hool bus to CTTRANSIT’s maintenance personnel. The eight-hour session was split into two sections: a classroom portion followed by hands-on training on the fuel cell bus. The classroom instruction included a general overview of the bus and its systems, and instruction on bus operation and maintenance.
- **Hybrid-System Training**—ISE provided detailed training on the hybrid system. This training was held in two phases, each of which lasted about eight hours. Phase I training began with a classroom portion which provided a general overview of the hybrid systems. Information provided in this training included an overview of hybrid vehicles, safety systems, vehicle operations, vehicle care and maintenance, and emergency procedures. As with the bus-level training, the hybrid-system classroom instruction was followed by a session on the bus. This hands-on training included location and identification of system components, problem diagnosis, and actual bus operation. Phase II training focused on advanced system analysis and preventative maintenance for the hybrid system. This two-day class provided extensive hands-on training for the maintenance technicians assigned to the fuel cell bus. Instruction included preventative maintenance procedures, an overview of the drive system and electronic controls, and battery change-out procedures.
- **Fuel-Cell System Training**—UTC Power provided training on the fuel-cell power system in two phases. Phase I included a general overview of the fuel-cell power system and safety; Phase II focused on detailed system descriptions and preventive maintenance.
- **ZEBRA Battery Training**—UTC Power and MES-DEA (the battery manufacturer) provided training on the ZEBRA batteries. This training included detailed operating instruction, troubleshooting, and component and whole-battery replacement procedures.

- **Fuel Cell Bus Operator Training**—The fuel cell bus has operated almost exclusively on CTTRANSIT’s Star Shuttle route. Drivers for this high-profile route are hand-picked by the agency, because they act as ambassadors for the city and must be the best and most personable drivers. Because of these factors, the drivers also are considered the best for the FCB. In addition to the above-listed training classes, the fuel cell bus operators were taught start-up and shut-down procedures.

Public Awareness – CTTRANSIT has experienced a high level of interest in the fuel cell bus demonstration from the local community and the larger New England region. Concerns about air quality and reducing petroleum use in the area have resulted in an increasing awareness of hydrogen and fuel cell technologies as a potential to address these issues. The agency is the first in the area to actually operate a fuel cell bus, so there have been many requests for hands-on demonstrations. CTTRANSIT understands the need to educate local officials and the general public on this promising technology and has accommodated as many requests as possible. During the evaluation period for this report, the agency participated in 23 events to showcase the fuel cell bus, including hydrogen fueling demonstrations at the UTC Power hydrogen fueling station, shuttle service for conventions in downtown Hartford, and demonstrations at neighboring transit agencies and environmental themed conferences. One particular conference, the Green Build Conference held in Chicago, took the bus out of transit service for 14 days.

Evaluation Results

The evaluation period presented in this report includes operation of the fuel cell and diesel baseline buses from April 2007 through June 2008. This includes 15 months of operation for the fuel cell bus. The diesel buses are new and began operation toward the end of August 2007. To remove some of the start-up issues for the new diesel buses, September 2007 was selected as the start date for the evaluation period. Because of this, the evaluation period for the diesel buses includes only 10 months of data.

In this evaluation, the fuel cell bus is considered to be prototype technology that is in the process of being commercialized. The analysis and comparisons with standard diesel buses help create a baseline for measuring the progress of the fuel cell bus technology. There is no intent to consider this implementation of fuel cell buses as commercial (or full revenue transit service). This evaluation focuses on documenting progress and opportunities for improving the vehicles, infrastructure, and procedures.

Bus Use and Availability

Bus use and availability are indicators of reliability. Lower bus usage could indicate downtime for maintenance or an intentional reduction of planned work for the buses. This section provides a summary of bus usage and availability for the two groups studied.

Table 5 summarizes the average monthly mileage accumulation by the fuel cell bus and the diesel study group for the evaluation period. During this period, the fuel cell bus accumulated 12,115 miles, and the fuel cell systems accumulated 2,049 hours. These numbers indicate an overall average speed of 5.9 mph, which is significantly slower than the average CTTRANSIT speed of 12 mph and the 10-mph Star route average.

The diesel buses operated a monthly average of 3,248 miles each as compared to the fuel cell bus, which had a monthly average of 808 miles. This indicates that the fuel cell buses traveled only 25% of the miles that the diesel buses did during the same period. The fuel cell bus was limited to one 8-hour shift per weekday for most of the evaluation period. The diesel buses were used in typical service—up to 7 days per week and 16 to 20 hours per day.

Another measure of reliability is availability—the percent of days that a bus is actually available compared to the days the bus is planned for operation. Figure 11 shows monthly availability for the fuel cell bus during the evaluation period. As discussed in the section describing bus experience (above), most of the availability issues were due to problems with the traction batteries and the fuel cell CSAs. The most recently installed UTC Power CSAs in the fuel cell bus are a newer upgraded version of the power system. UTC Power expects this newer power system to be much more durable than the previous versions.

Table 5. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average Mileage	Fuel Cell System Hours
FCB/701	N/A	12,046	12,115	15	808	2,049
725	2,112	35,544	33,432	10	3,343	N/A
726	2,201	34,297	32,096	10	3,430	N/A
727	1,745	33,664	31,919	10	3,192	N/A
Diesel			97,447	30	3,248	N/A

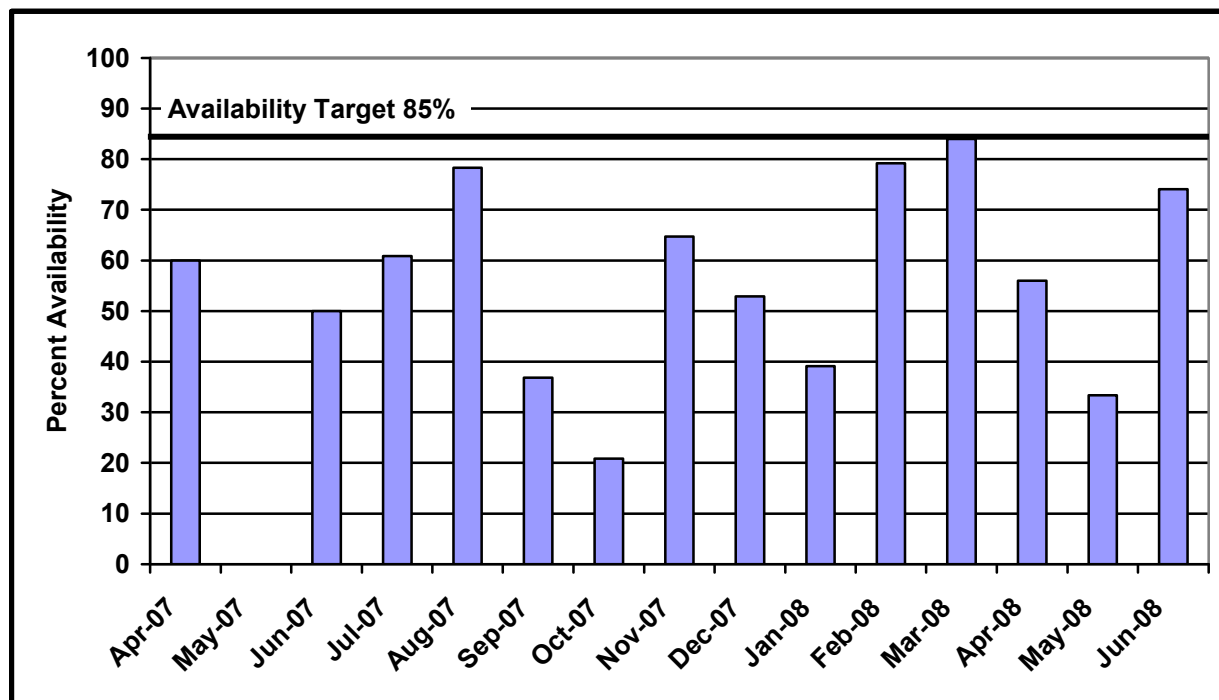


Figure 11. Availability for the fuel cell bus

Figure 12 shows the uses of the fuel cell bus when it was available for service during the evaluation period. This bus was used 82% of the time on route in service and 13% in support of event activities. Figure 13 shows the reasons that the bus was unavailable for service. The primary reasons for unavailability are for the UTC Power fuel cell system at 38%, problems with

the ZEBRA/traction batteries at 32%, and the ISE hybrid propulsion system and fuel system responsibilities at 23%.

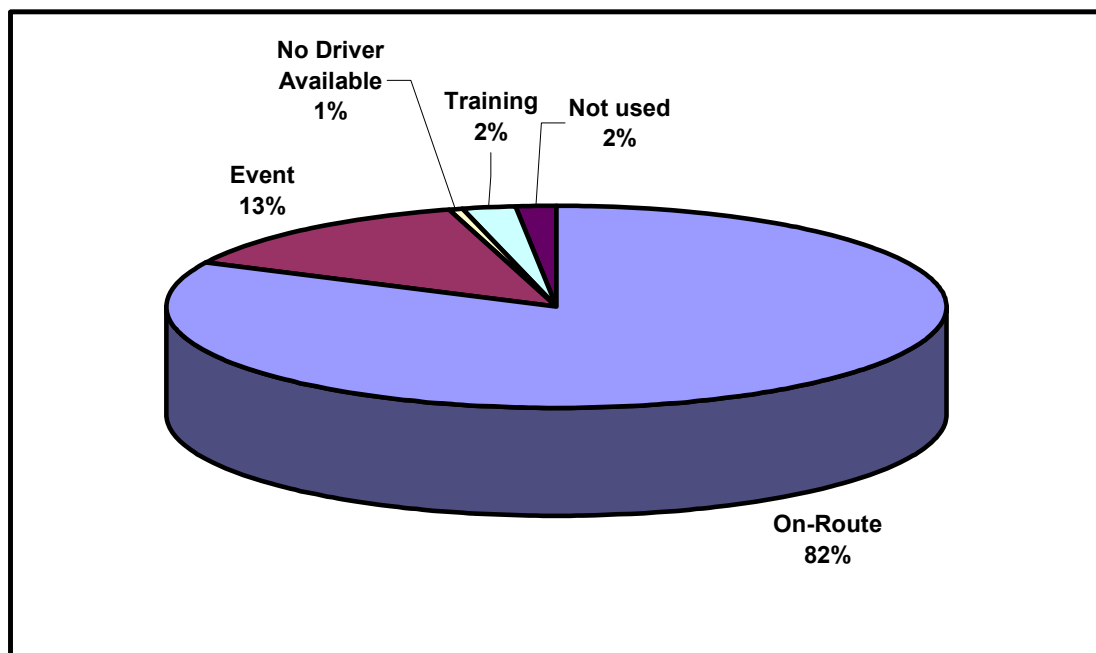


Figure 12. Use of the fuel cell bus when available for service

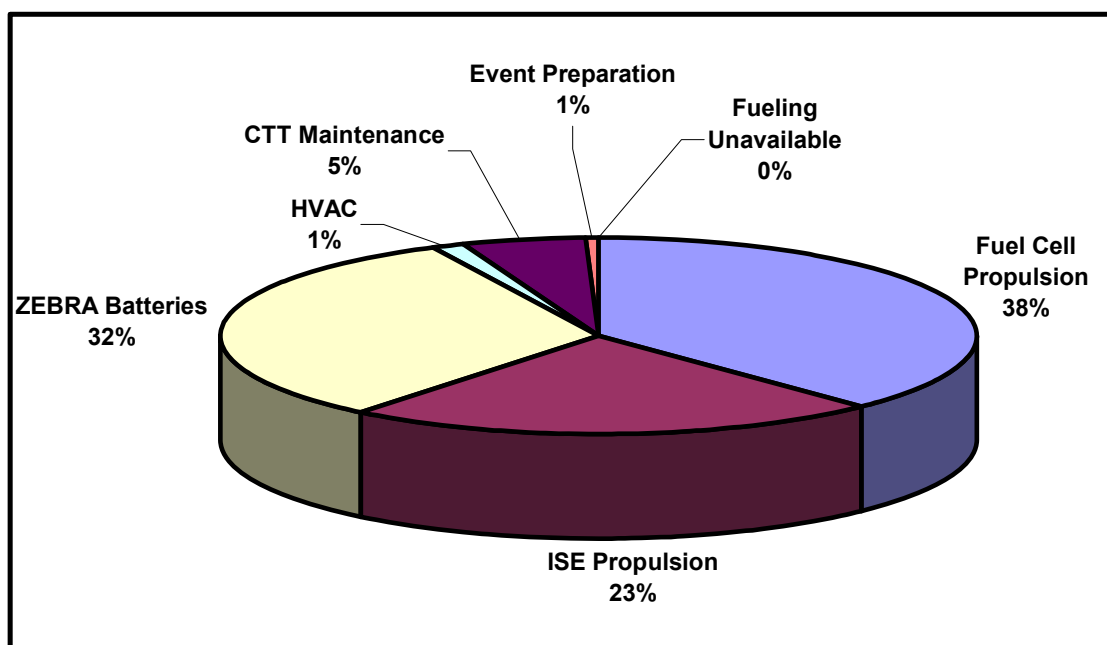


Figure 13. Reasons that the fuel cell bus was unavailable

Fuel Economy and Cost

Hydrogen fuel is supplied by the UTC Power fueling station (discussed above). The hydrogen is dispensed at up to 5,000 psi for the fuel cell transit bus. During the evaluation period, UTC Power employees provided all fueling services, and fueling data was recorded by CTTRANSIT.

Table 6 shows hydrogen and diesel fuel consumption and fuel economy for the study buses during the evaluation period. Overall, the fuel cell bus averaged 4.79 miles per kg of hydrogen, which equates to 5.41 miles per diesel gallon equivalent (DGE). The energy conversion from kg of hydrogen to DGE is provided at the end of Appendix A. As noted above, the buses are plugged in each night to recharge the batteries. The electric energy added to the fuel cell buses each night currently is not accounted for in the fuel economy calculation¹⁰.

Table 6. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (Fuel Base)	Hydrogen (kg)	Miles per kg	Diesel Equivalent Amount (Gallon)	Miles per Gallon (mpg)
FCB 701 Total	11,719	2,446.9	4.79	2,165	5.41
725	33,432			9,018	3.71
726	32,047			9,009	3.56
727	31,742			8,951	3.55
Diesel Total	97,221			26,979	3.60

The diesel fuel consumption data for the evaluation period are available for September 2007 through June 2008. For this 10-month period, the 3 diesel baseline buses averaged 3.60 mpg, which indicates the fuel economy for the fuel cell bus is an overall 50% higher than that of the diesel buses. Note that the diesel buses operate at an average speed of approximately 12 mph and the fuel cell bus had a measured average speed of approximately 6 mph during the evaluation period.

Figure 14 shows the average monthly fuel economy in both miles per kg and miles per DGE for the fuel cell bus, and in miles per gallon for the diesel buses. For reference, the chart also shows the average monthly high and low temperatures. The fuel cell bus fuel economy drops to its lowest point in November 2007, right before the fuel cell power system was replaced. Starting in January 2008, the fuel economy rose to an expected level.

The operating cost for the UTC Power hydrogen production and dispensing is currently unknown; however, the current cost of fuel charged by UTC Power is \$4.18/kg. This amount does not include all of the costs of purchasing, transporting, and dispensing the fuel. During the evaluation period, CTTRANSIT spent 175 hours of mechanic time driving the fuel cell bus to and from UTC Power for fueling. This cost is not included in the price of fuel, but it would add another \$0.72 per mile based on a \$50-per-hour labor rate. Using the \$4.16 per kg cost for hydrogen fuel indicates that the cost per mile for the fuel cell bus is \$0.87, and adding the labor brings it to \$1.59 per mile. The average diesel fuel cost per gallon during the evaluation period is \$2.51. Although diesel prices increased tremendously during the evaluation period, CTTRANSIT locked into a fixed cost for 12 months, which included the evaluation period. The diesel fuel cost per mile was \$0.70, or less than half of the fuel cell bus fueling cost per mile.

¹⁰ Additional study is underway at AC Transit to estimate the amount of energy consumed in the recharging process and the impact to the fuel economy calculation. Results from that effort will be included in the next report.

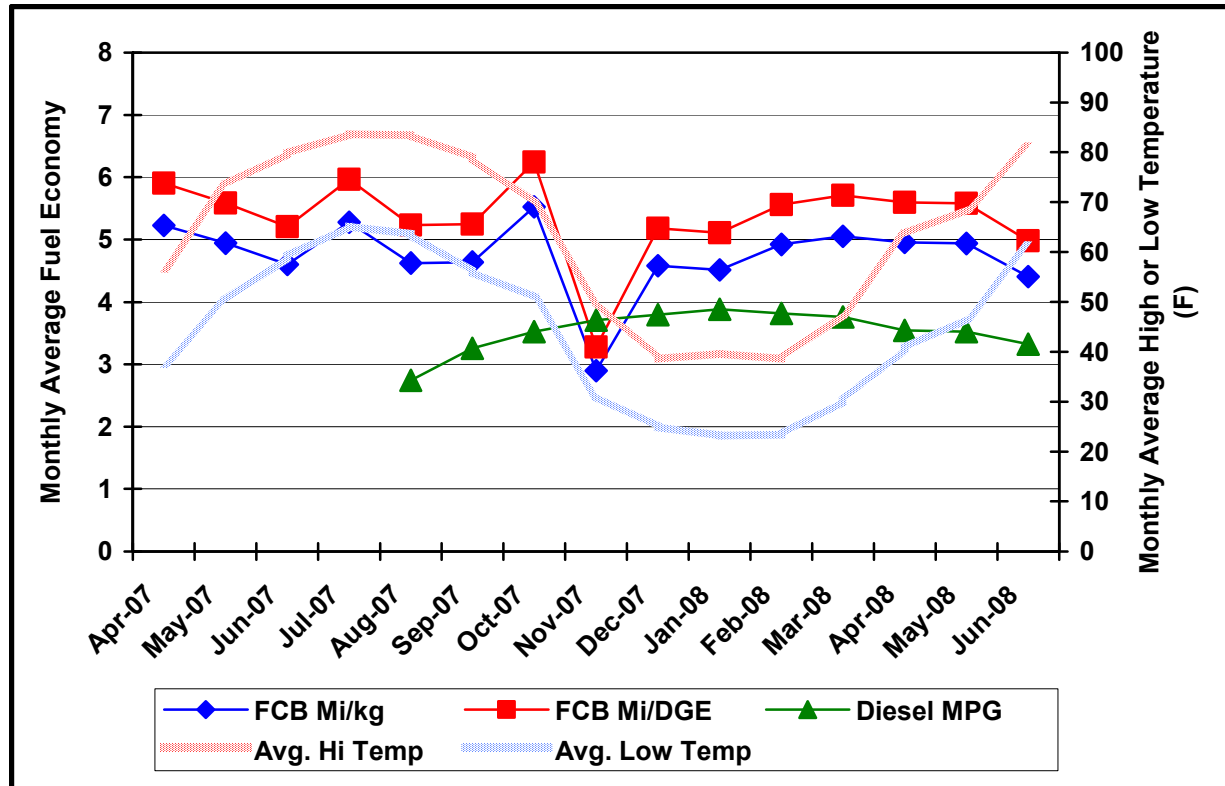


Figure 14. Average monthly fuel economy (evaluation period)

Maintenance Analysis

The maintenance cost analysis presented here includes only the evaluation period (April 2007 through June 2008). Warranty costs are not included in the cost-per-mile calculations. All work orders for the study buses were collected and analyzed for this evaluation. For consistency, the maintenance labor rate was kept at a constant \$50 per hour; this does not reflect an average rate for CTTRANSIT. This section first covers total maintenance costs, and then provides maintenance costs separated by bus system.

Total Maintenance Costs – Total maintenance costs include the price of parts and labor rates of \$50 per hour; this total does not include warranty costs. Cost per mile is calculated as follows.

$$\text{Cost per mile} = ((\text{labor hours} * 50) + \text{parts cost}) / \text{mileage}$$

Table 7 shows total maintenance costs for the fuel cell and diesel buses. Note that the fuel cell bus maintenance costs shown in the table are significantly greater because of the on-site warranty work done by the CTTRANSIT mechanics, and because these were not charged back as warranty claims. The mechanic labor costs for taking the fuel cell bus to and from fueling at UTC Power also are not included here.

Table 7. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts (\$)	Labor Hours	Cost per Mile (\$)
Total Fuel Cell 701	12,115	2,145.24	1,068.0	4.59
725	33,432	5,091.50	152.2	0.38
726	32,096	1,139.59	97.3	0.19
727	31,919	1,415.23	106.8	0.21
Total Diesel	97,447	7,646.32	356.3	0.26
Avg. per Bus	32,482	2,548.77	118.8	--

Maintenance issues for the fuel cell bus centered on problems with the traction batteries and the replacement of fuel cell system CSAs. Most of the repair costs were to support troubleshooting and repairs for the air conditioning, increasing heat in the winter, a specific cooling issue, battery changeouts, and support to UTC Power for changing the CSAs twice.

Maintenance issues for the diesel buses were mostly for one bus: 725. Bus 725 had specific costly repairs for an alternator change, brakes, and suspension. Other issues for the three buses were for the engine, a minor accident for bus 727, and video and camera equipment repairs.

The total maintenance costs—excluding warranty costs—are much less for the diesel buses. The per-bus results for the fuel cell buses compared to the diesel buses are as follows.

- Usage/Mileage: The fuel cell buses mileage is 63% lower than that of the diesel buses.
- Parts Costs: The fuel cell buses parts are 16% less than those for the diesel buses.
- Labor Hours: The fuel cell buses labor hours are 9 times higher than for the diesel buses.
- Cost per Mile (excluding warranty costs): The fuel cell buses costs are 17.6 times greater than those of diesel buses.

Maintenance Costs Broken Down by System – Table 8 shows maintenance costs by vehicle system and bus study group (excluding warranty costs). The vehicle systems shown in the table include the following.

- **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:** Includes repairs for exhaust, fuel, engine, electric motors, fuel cell modules, propulsion control, non-lighting electrical (charging, cranking, ignition), air intake, cooling, and transmission.
- **Preventive Maintenance Inspections (PMI):** Includes 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

Table 8. Breakdown of Vehicle System Maintenance Cost per Mile (Evaluation Period)

System	Fuel Cell		Diesel	
	Cost per Mile (\$)	Percent of Total (%)	Cost per Mile (\$)	Percent of Total (%)
Cab, Body, and Accessories	0.18	4	0.09	35
Propulsion Related	3.72	81	0.07	27
PMI	0.05	1	0.06	23
Brakes	0.05	1	0.01	4
Frame, Steering, and Suspension	0.07	2	0.02	7
HVAC	0.48	10	0.01	4
Lighting	0.04	1	0.00	0
Air, General	0.00	0	0.00	0
Axles, Wheels, and Drive Shaft	0.00	0	0.00	0
Tires	0.00	0	0.00	0
Total	4.59	100	0.26	100

The systems with the greatest percentage of maintenance costs for the fuel cell bus were propulsion related; HVAC; and cab, body, and accessories. Two of these systems also had the greatest maintenance costs for the diesel buses, with the exception of HVAC being replaced with PMI.

Propulsion-Related Maintenance Costs – Propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. Table 9 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 ISE and UTC Power personnel, which was covered under warranty.

Table 9. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Diesel
Mileage	12,115	97,447
Total Propulsion-Related Systems (Roll-Up)		
Parts cost (\$)	659.98	4,311.90
Labor hours	888.00	44.90
Total cost (\$)	45,059.98	6,557.90
Total cost (\$) per mile	3.72	0.07
Exhaust System Repairs		
Parts cost (\$)	0.00	0.00
Labor hours	0.00	3.00
Total cost (\$)	0.00	150.00
Total cost (\$) per mile	0.00	0.00
Fuel System Repairs		
Parts cost (\$)	0.00	348.55
Labor hours	0.30	1.50
Total cost (\$)	16.50	423.55
Total cost (\$) per mile	0.00	0.00
Powerplant System Repairs		
Parts cost (\$)	0.00	613.38
Labor hours	171.50	18.30
Total cost (\$)	8,575.00	1,529.88
Total cost (\$) per mile	0.71	0.02
Electric Motor and Propulsion Repairs		
Parts cost (\$)	42.85	0.00
Labor hours	656.20	0.00
Total cost (\$)	32,851.35	0.00
Total cost (\$) per mile	2.71	0.00
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost (\$)	7.28	2,804.43
Labor hours	41.00	6.40
Total cost (\$)	2,057.28	3,125.43
Total cost (\$) per mile	0.17	0.03
Air Intake System Repairs		
Parts cost (\$)	10.98	540.54
Labor hours	0.00	0.00
Total cost (\$)	10.98	540.54
Total cost (\$) per mile	0.00	0.01
Cooling System Repairs		
Parts cost (\$)	598.87	5.00
Labor hours	19.00	15.70
Total cost (\$)	1,548.87	788.50
Total cost (\$) per mile	0.13	0.01
Transmission Repairs		
Parts cost (\$)	0.00	0.00
Labor hours	0.00	0.00
Total cost (\$)	0.00	0.00
Total cost (\$) per mile	0.00	0.00

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 which 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 a 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), engine, etc., or things that are deemed to be safety issues if operation of the bus continued. Chargeable RCs do not include roadcalls for things such as problems with radios or destination signs.

Table 10 shows the RCs and miles between the roadcalls (MBRC) for each study bus, categorized by all RCs and propulsion-related-only RCs. The diesel buses have much better MBRC rates for both categories. This is indicative of the low usage and prototype status of the fuel cell bus.

Table 10. Roadcalls and Miles Between Roadcalls (Evaluation Period)

Bus	Mileage	All Roadcalls	All MBRC	Propulsion Roadcalls	Propulsion MBRC	Fuel Cell only MBRC
Total FCB	12,115	24	505	21	577	4,038
725	33,432	5	5,353	3	8,922	—
726	32,096	5	5,109	3	8,515	—
727	31,919	1	25,138	1	25,138	—
Total Diesel	97,447	11	4,582	7	11,064	—

What's Next for CTTRANSIT

This initial evaluation report includes the first 15 months of operation of the fuel cell bus at CTTRANSIT. The next evaluation report will add at least six more months of operation, and most likely will be completed in early 2009. The most important aspect of the evaluation is tracking the progress and desire for CTTRANSIT to maximize the usage of the fuel cell bus and determine if the new version of the UTC Power fuel cell power system makes significant progress to the expected 4,000 hours of operation before it loses too much power. CTTRANSIT also has secured an FTA grant which will be used for several aspects of its fuel cell bus program including;

- Replacement of the fuel cell power system in the existing bus to extend operation and testing
- Purchase of another Van Hool/UTC Power fuel cell bus for delivery in 2009
- Modifications to the agency's chassis dynamometer bay that will allow testing, storage, and maintenance of a fuel cell bus

As noted, CTTRANSIT also is involved with two of the eight evaluation projects in the FTA's NFCBP. Short descriptions of those two projects and plans for facilities expansion and upgrades are provided next.

Connecticut FCB Demonstration Project

Under the FTA's NFCBP, CTTRANSIT will demonstrate up to four next-generation fuel cell buses. UTC Power and the Northeast Advanced Vehicle Consortium are leading a team to develop and demonstrate these advanced version, hybrid-electric, fuel cell buses. The buses will use enhanced UTC Power 120 kW PEM fuel cells with upgraded seals, catalysts, bipolar plates, and balance of plant. Van Hool will design and build the 40-ft bus chassis and hybrid system. The demonstration is expected to begin in fall 2009.

Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing

A team led by Proterra and the Center for Transportation and the Environment is developing a battery-dominant 35-ft plug-in hybrid fuel cell bus for demonstration in three U.S. locations. This project is another demonstration funded under the NFCBP. Proterra, a bus manufacturer in Colorado, will design and build a lightweight composite bus chassis and integrate the hybrid system. The hybrid system includes fuel cells manufactured by Hydrogenics and lithium titanate batteries from Altairnano. The demonstration is scheduled to begin in Columbia, South Carolina, in late 2008, followed by implementation in Austin, Texas. CTTRANSIT is expected demonstrate the bus after the bus completes its demonstrations at the first two sites.

CTTRANSIT Facility Upgrades

The agency must modify its facilities to accommodate the growing fleet of hydrogen-fueled buses. CTTRANSIT already is working with local officials and other partners to determine what modifications are needed and how to accomplish them. The agency has developed a design for a separate building which will provide on-site storage for six buses. Additionally, CTTRANSIT is working with the Connecticut Center for Advanced Technology to potentially site a hydrogen fueling station on its property.



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Related Reports

All NREL Hydrogen and fuel cell–related evaluation reports can be downloaded from the following Web site: www.nrel.gov/hydrogen/proj_fc_bus_eval.html

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Appendix A. Fleet Summary Statistics

Fleet Summary Statistics: Connecticut Transit (CTTRANSIT) Diesel and FCB Study Groups

Fleet Operations and Economics

	Fuel Cell	Diesel
Number of Vehicles	1	3
Period Used for Fuel and Oil Operation Analysis	4/07-6/08	9/07-6/08
Total Number of Months in Period	15	10
Fuel and Oil Analysis Base Fleet Mileage	11,719	97,221
Period Used for Maintenance Operation Analysis	4/07-6/08	9/07-6/08
Total Number of Months in Period	15	10
Maintenance Analysis Base Fleet Mileage	12,115	97,447
Average Monthly Mileage per Vehicle	808	3,248
Availability	54%	N/A
Fleet Fuel Usage in Diesel Gal/H2 kg	2,447	26,980
Roadcalls	24	11
RCs MBRC	505	8,859
Propulsion Roadcalls	21	7
Propulsion MBRC	577	13,921
Fleet Miles/kg Hydrogen	4.17	
(1.13 kg H2/gal Diesel Fuel)		
Representative Fleet MPG (energy equiv.)	5.41	3.60
Hydrogen Cost per kg	4.18	
Diesel Cost per Gallon		2.51
Fuel Cost per Mile	0.87	0.70
Total Scheduled Repair Cost per Mile	0.05	0.09
Total Unscheduled Repair Cost per Mile	4.54	0.17
Total Maintenance Cost per Mile	4.59	0.26
Total Operating Cost per Mile	5.46	0.96

Maintenance Costs

	Fuel Cell	Diesel
Fleet Mileage	12,115	97,447
Total Parts Cost	2,145.24	7,646.32
Total Labor Hours	1,068.0	356.3
Average Labor Cost (@ \$50.00 per hour)	53,400.00	17,815.00
Total Maintenance Cost	55,545.24	25,461.32
Total Maintenance Cost per Bus	55,545.24	8,487.11
Total Maintenance Cost per Mile	4.59	0.26

Breakdown of Maintenance Costs by Vehicle System

	Fuel Cell	Diesel
Fleet Mileage	12,115	97,447
Total Propulsion-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)		
Parts Cost	659.98	4,311.90
Labor Hours	888.0	44.9
Average Labor Cost	44,400.00	2,246.00
Total Cost (for system)	45,059.98	6,557.90
Total Cost (for system) per Bus	45,059.98	2,185.97
Total Cost (for system) per Mile	3.72	0.07
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost	0.00	0.00
Labor Hours	0.0	3.0
Average Labor Cost	0.00	150.00
Total Cost (for system)	0.00	150.00
Total Cost (for system) per Bus	0.00	50.00
Total Cost (for system) per Mile	0.00	0.00
Fuel System Repairs (ATA VMRS 44)		
Parts Cost	0.00	348.55
Labor Hours	0.3	1.5
Average Labor Cost	16.50	75.00
Total Cost (for system)	16.50	423.55
Total Cost (for system) per Bus	16.50	141.18
Total Cost (for system) per Mile	0.00	0.00
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost	0.00	613.38
Labor Hours	171.5	18.3
Average Labor Cost	8,575.00	916.50
Total Cost (for system)	8,575.00	1,529.88
Total Cost (for system) per Bus	8,575.00	509.96
Total Cost (for system) per Mile	0.71	0.02
Electric Propulsion Repairs (ATA VMRS 46)		
Parts Cost	42.85	0.00
Labor Hours	656.2	0.0
Average Labor Cost	32,808.50	0.00
Total Cost (for system)	32,851.35	0.00
Total Cost (for system) per Bus	32,851.35	0.00
Total Cost (for system) per Mile	2.71	0.00

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	Diesel
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost	7.28	2,804.43
Labor Hours	41.0	6.4
Average Labor Cost	2,050.00	321.00
Total Cost (for system)	2,057.28	3,125.43
Total Cost (for system) per Bus	2,057.28	1,041.81
Total Cost (for system) per Mile	0.17	0.03
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost	10.98	540.54
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	10.98	540.54
Total Cost (for system) per Bus	10.98	180.18
Total Cost (for system) per Mile	0.00	0.01
Cooling System Repairs (ATA VMRS 42)		
Parts Cost	598.87	5.00
Labor Hours	19.0	15.7
Average Labor Cost	950.00	783.50
Total Cost (for system)	1,548.87	788.50
Total Cost (for system) per Bus	1,548.87	262.83
Total Cost (for system) per Mile	0.13	0.01
Hydraulic System Repairs (ATA VMRS 65)		
Parts Cost	0.00	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00
Total Cost (for system) per Mile	0.00	0.00
General Air System Repairs (ATA VMRS 10)		
Parts Cost	0.00	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00
Total Cost (for system) per Mile	0.00	0.00

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	Diesel
Brake System Repairs (ATA VMRS 13)		
Parts Cost	26.73	228.86
Labor Hours	11.0	14.4
Average Labor Cost	550.00	721.00
Total Cost (for system)	576.73	949.86
Total Cost (for system) per Bus	576.73	316.62
Total Cost (for system) per Mile	0.05	0.01
Transmission Repairs (ATA VMRS 27)		
Parts Cost	0.00	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00
Total Cost (for system) per Mile	0.00	0.00
Inspections Only – No Parts Replacements (101)		
Parts Cost	0.00	0.00
Labor Hours	12.0	120.0
Average Labor Cost	600.00	6,000.00
Total Cost (for system)	600.00	6,000.00
Total Cost (for system) per Bus	600.00	2,000.00
Total Cost (for system) per Mile	0.05	0.06
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost	632.37	2,014.73
Labor Hours	31.8	130.2
Average Labor Cost	1,591.50	6,508.00
Total Cost (for system)	2,223.87	8,522.73
Total Cost (for system) per Bus	2,223.87	2,840.91
Total Cost (for system) per Mile	0.18	0.09
HVAC System Repairs (ATA VMRS 01)		
Parts Cost	0.00	164.46
Labor Hours	116.5	20.0
Average Labor Cost	5,825.00	1,000.00
Total Cost (for system)	5,825.00	1,164.46
Total Cost (for system) per Bus	5,825.00	388.15
Total Cost (for system) per Mile	0.48	0.01

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell	Diesel
Lighting System Repairs (ATA VMRS 34)		
Parts Cost	311.36	18.33
Labor Hours	2.2	2.0
Average Labor Cost	110.00	100.00
Total Cost (for system)	421.36	118.33
Total Cost (for system) per Bus	421.36	39.44
Total Cost (for system) per Mile	0.03	0.00
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost	514.80	908.04
Labor Hours	6.4	20.8
Average Labor Cost	321.00	1,038.00
Total Cost (for system)	835.80	1,946.04
Total Cost (for system) per Bus	835.80	648.68
Total Cost (for system) per Mile	0.07	0.02
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost	0.00	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00
Total Cost (for system) per Mile	0.00	0.00
Tire Repairs (ATA VMRS 17)		
Parts Cost	0.00	0.00
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00
Total Cost (for system) per Mile	0.00	0.00

Notes

1. To compare the hydrogen fuel dispensed and fuel economy to diesel, the hydrogen dispensed was also converted into diesel energy equivalent gallons. The general energy conversions are as follows, actual energy content varies by location.

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/gallon / 113,628 Btu/kg = 1.13 kg/diesel gallon

2. The propulsion-related systems were chosen to include only those systems of the vehicles that could be impacted directly by the selection of a fuel or advanced technology.
3. ATA VMRS coding is based on the parts that were replaced. If no part was replaced in a repair, then the code was based on the system being repaired.
4. In general, inspections (with no part replacements) only were included in the overall totals (not by system). The code "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 fire extinguishers, test kits, etc.; ATA VMRS 71-Body mostly represents windows and windshields.
6. The average labor cost is assumed to be \$50 per hour.
7. Warranty costs are not included.

Appendix B: Fleet Summary Statistics – SI Units

Fleet Summary Statistics: Connecticut Transit (CTTRANSIT) Diesel and FCB Study Groups

Fleet Operations and Economics

	Fuel Cell	Diesel
Number of Vehicles	1	3
Period Used for Fuel and Oil Operation Analysis	4/07-6/08	9/07-6/08
Total Number of Months in Period	15	10
Fuel and Oil Analysis Base Fleet Kilometers	18,859	156,458
Period Used for Maintenance Operation Analysis	4/07-6/08	9/07-6/08
Total Number of Months in Period	15	10
Maintenance Analysis Base Fleet Kilometers	19,497	156,821
Average Monthly Kilometers per Vehicle	1,300	5,227
Availability	54%	N/A
Fleet Fuel Usage in Diesel L/H2 kg	2,447	102,119
Roadcalls	24	11
Kilometers between roadcalls (KBRC)	812	14,256
Propulsion Roadcalls	21	7
Propulsion KBRC	928	22,403
Fleet kg Hydrogen/100 km (1.13 kg H2/gal Diesel fuel)	12.97	
Representative Fleet MPG (L/100 km)	43.46	65.27
Hydrogen Cost per kg	4.18	
Diesel Cost per Liter		0.66
Fuel Cost per Kilometer	0.54	0.43
Total Scheduled Repair Cost per Kilometer	0.03	0.05
Total Unscheduled Repair Cost per Kilometer	2.82	0.11
Total Maintenance Cost per Kilometer	2.85	0.16
Total Operating Cost per Kilometer	3.39	0.60

Maintenance Costs

	Fuel Cell	Diesel
Fleet Kilometers	19,497	156,821
Total Parts Cost	2,145.24	7,646.32
Total Labor Hours	1,068.0	356.3
Average Labor Cost (@ \$50.00 per hour)	53,400.00	17,815.00
Total Maintenance Cost	55,545.24	25,461.32
Total Maintenance Cost per Bus	55,545.24	8,487.11
Total Maintenance Cost per Kilometer	2.85	0.16

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1. REPORT DATE (DD-MM-YYYY) October 2008			2. REPORT TYPE Technical Report		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Connecticut Transit (CTTRANSIT) Fuel Cell Transit Bus: Preliminary Evaluation Results					5a. CONTRACT NUMBER DE-AC36-99-GO10337	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Kevin Chandler and Leslie Eudy					5d. PROJECT NUMBER NREL/TP-560-43847	
					5e. TASK NUMBER H2708200	
					5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393					8. PERFORMING ORGANIZATION REPORT NUMBER NREL/TP-560-43847	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S) NREL	
					11. SPONSORING/MONITORING AGENCY REPORT NUMBER	
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT (Maximum 200 Words) This report provides preliminary results from a National Renewable Energy Laboratory evaluation of a prototype fuel cell transit bus operating at Connecticut Transit in Hartford. Included are descriptions of the planned fuel cell bus demonstration and equipment; early results and agency experience are also provided.						
15. SUBJECT TERMS fuel cell; fuel cell bus; fuel cell evaluation; fuel cell bus demonstration						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)	

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18