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Connecticut Transit (CTTRANSIT) Fuel Cell Transit Bus: Second Evaluation Report – Appendices

Technical Report
NREL/TP-560-45670-2
May 2009

Kevin Chandler, Battelle
Leslie Eudy, National Renewable Energy Laboratory

Link to Report

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Introduction to the Appendices

The National Renewable Energy Laboratory (NREL) has reported evaluation results for fuel cell buses since 2003. These reports include a broad range of background on the transit property, the buses, infrastructure, and overall experience operating fuel cell buses. Several reports are planned for each evaluation site. The first data report typically includes extensive background material plus an analysis of the first round of data. Update reports follow the initial publication, focusing on the newest data analysis and lessons learned since the previous report. The authors would like to provide more focus on the new data without depriving new readers of the background and context on the transit property and the technology. These appendices, referenced in the main report, are designed to provide the full background for the evaluation. They will be updated as new information is collected but will contain the original background material from the first report. Both parts can be downloaded separately. A Web link is provided on the cover to allow the reader to download the main report.

All NREL publications on hydrogen and fuel cell buses are available at:
http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html

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Appendix A: NREL Transit Bus Evaluation Activities

Under funding from the Department of Energy (DOE) and in coordination with the Federal Transit Administration (FTA), the National Renewable Energy Laboratory (NREL) has been evaluating alternative fuel transit buses since the early 1990s. In 1996, DOE and NREL completed an evaluation of transit buses at eight transit agencies that included six different alternative fuels. As part of this alternative fuel transit bus evaluation, NREL and Battelle (NREL's contractor for this effort) developed a customized data-collection and evaluation protocol. This protocol has evolved over time but is still based on the original effort.

NREL first began evaluating hydrogen-fueled transit buses in 2000 with SunLine Transit Agency. Since that time, NREL has published reports on fuel cell bus (FCB) performance and fleet experience for several transit agencies in the United States. These evaluations were funded under the Technology Validation activity within DOE's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program[1], which is focused on addressing the technical challenges and accelerating the development and successful market introduction of hydrogen technologies. Beginning with fiscal year 2009, Technology Validation was moved from HFCIT into the Vehicle Technology Program. NREL supports DOE's Technology Validation activity by evaluating hydrogen and fuel cell vehicles in parallel with hydrogen infrastructure to determine the current status of the technology and to assess the progress toward technology readiness.

While DOE has not funded the direct development of fuel cell buses, it has provided funding to NREL to conduct data collection, analysis, and reporting of existing FCB project evaluation results under its Technology Validation activity. The current hydrogen transit bus evaluations include four active projects and four that were completed in the last few years.

In 2006, FTA initiated its newest development program, the National Fuel Cell Bus Program (NFCBP)[2]. The NFCBP was established as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: a Legacy for Users (SAFETEA-LU) transportation authorization. The NFCBP program designates $49 million in funding for 2006 through 2009 to help develop commercially viable fuel cell buses and technologies. The FTA competitively selected three nonprofit organizations—the Center for Transportation and the Environment (CTE), the Northeast Advanced Vehicle Consortium (NAVC), and CALSTART—to administer projects under the program. The FTA selected 14 separate projects in all, including eight planned demonstration projects.

The FTA is collaborating with DOE and NREL to ensure that data are collected on all fuel cell bus demonstrations under the program. FTA has tasked NREL with evaluating the fuel cell bus demonstrations for the NFCBP. NREL uses the standard data collection and analysis protocol established for DOE heavy-duty vehicle evaluations as described in this plan. In May 2008, NREL published *Hydrogen and Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration*, which outlines the methodology for these evaluations[3]. Table A-1 provides an overview of all the FCB evaluation

[1] DOE HFCIT Web site: www1.eere.energy.gov/hydrogenandfuelcells/
[2] FTA Bus Research and Testing Web site: www.fta.dot.gov/assistance/technology/research_4578.html
[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, www.nrel.gov/hydrogen/pdfs/42781-1.pdf

projects planned under both DOE and FTA funding. This overview is the estimated timing for NREL's data collection and evaluation and does not reflect the early design, development, and construction phase for the buses. The plans for upcoming evaluations are subject to change as each project progresses. The projects are separated by funding agency; however, for the NFCBP evaluation sites, any detailed data collection and analysis of the fuel cell system or infrastructure will be funded by DOE. Table A-2 provides more details and status for the evaluation sites funded solely by DOE. Additional details on the eight NFCBP demonstration sites funded by FTA are listed in Table A-3. FTA is also considering additional funding for one or two sites beyond the NFCBP sites, but this funding has not been determined.

Table A-1. Summary of NREL Hydrogen Evaluations for DOE and FTA[4]

NREL Hydrogen Bus Evaluations for DOE and FTA

Site/Location	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 Technology Validation								CA ZEB Advanced Demo								
SunLine/ Thousand Palms	CA		FCB Extended Testing															
SunLine/ Thousand Palms	CA									Advanced FCB Project								
CTTRANSIT/ Hartford	CT		CTTRANSIT FCB Demo															
City of Burbank/ Burbank	CA									Burbank FCB								
AC Transit/ Oakland	CA	FTA National Fuel Cell Bus Program	Accelerated Testing															
SunLine/ Thousand Palms	CA										American FCB Demo							
CTTRANSIT/ Hartford	CT									Nutmeg Hybrid FCB Demo								
Columbia / Site 2	SC								Dual Variable Output Hybrid FCB									
Logan Airport / Boston	MA										MA H2 FCB Demo							
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: Northern California; Southern California; New England; New York; Southeast; South

[4] For a current version of the summary table, see link: www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

Table A-2. DOE/NREL Heavy Vehicle Fuel Cell/Hydrogen Evaluations

Fleet	Vehicle/Technology	Number	Evaluation Status
SunLine Transit Agency (Thousand Palms, CA)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	Extended testing with updated fuel cell system; in process
Connecticut Transit (Hartford, CT)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	Bus in operation; in process
City of Burbank, CA	Proterra battery-dominant, plug-in hybrid bus using two Hydrogenics fuel cells	1	Evaluation to begin in 3rd Quarter 2009
Bay Area Transit Consortia led by AC Transit (Oakland, CA)	Van Hool/UTC Power fuel cell hybrid	12	Evaluation to begin in 3rd Quarter 2009
Completed Evaluations			
SunLine Transit Agency (Thousand Palms, CA)	New Flyer/ISE Corp. hydrogen internal combustion engine transit bus	1	Complete; results reported in Feb. 2007, Sep. 2007, and June 2008
	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	
Alameda-Contra Costa Transit District (Oakland, CA)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	3	Complete; results reported in Mar. 2007, Oct. 2007, and July 2008
Santa Clara VTA, (San Jose, CA) and San Mateo (San Carlos, CA)	Gillig/Ballard fuel cell transit bus	3	Complete and reported in 2006
SunLine Transit Agency (Thousand Palms, CA)	ThunderPower hybrid fuel cell transit bus; ISE Corp./ UTC Power	1	Complete and reported in 2003

Overall Evaluation Objectives

The objectives of the DOE and FTA evaluations are to provide comprehensive, unbiased evaluation results of fuel cell and hydrogen bus development and performance compared with conventional baseline vehicles when available and appropriate. Baseline vehicles are typically diesel buses or occasionally compressed natural gas (CNG). These evaluations also include information on the development and performance of hydrogen infrastructure and descriptions of the facility modifications required for safe operation of hydrogen-fueled vehicles.

The DOE and FTA demonstration and evaluation programs have two major goals:

- Provide credible data analysis results to the transit bus and fuel cell industries that go beyond “proof of concept” for fuel cell transit buses and infrastructure.
- Provide results focused on performance and use, including progress over time and experience from integrating vehicle systems, operations, and facilities for the fuel cell transit buses and supporting infrastructure.

DOE and FTA have both cited the lack of data and analysis results in real-world service as a challenge to move the technology forward. These evaluations have proved useful for a variety of groups, including transit operators considering the technology for future procurements, manufacturers needing to understand the status of the technology for transit applications, and government agencies making policy decisions or determining future research needs.

Table A-3. Summary of FTA NFCBP Demonstration Projects

Project	Description
Dual Variable Output Fuel Cell Hybrid Bus Validation and Testing (CTE)	Proterra will develop a battery-dominant 35-ft. plug-in hybrid fuel cell bus (Hydrogenics) that will first be demonstrated in Columbia, SC.
Nutmeg/Connecticut Fuel Cell Bus Program (NAVC)	UTC Power and NAVC are leading a team to develop and demonstrate advanced version hybrid 40-ft. fuel cell buses; enhanced UTC Power 120-kW PEM fuel cell with upgraded seals, catalysts, bipolar plates, balance of plant
Lightweight Fuel Cell Hybrid Bus (NAVC)	GE-led team to develop an advanced propulsion system integrated with a lightweight bus platform for field evaluation focused on advanced battery technologies for lower cost
Massachusetts Hydrogen Fuel Cell Powered Bus Fleet (NAVC)	Advanced bus development and in-service demonstration; integrate Nuvera 82-kW fuel cell with drive system from ISE Corp. and advanced energy storage; demonstration effort includes Nuvera's PowerTap fueling infrastructure
NY Hydrogen Powered FCB Program (NAVC)	The project team led by the New York Power Authority will develop and demonstrate a 40-ft. bus for operation in upstate New York for up to two years.
American Advanced Fuel Cell Bus Program (CALSTART)	A team led by SunLine will design and demonstrate a 40-ft. fuel cell bus, with design improvements, that meets FTA "Buy America" requirements; revenue service evaluation in hot desert climate
Compound Fuel Cell Hybrid Bus for 2010 (CALSTART)	A team led by BAE will develop a 40-ft. hybrid bus with a fuel cell auxiliary power unit (Hydrogenics, 16kW PEM) coupled with a diesel engine; demonstrate for one year at San Francisco MTA; BAE Systems drive, electrically driven accessories, advanced energy storage (Lithium Ion)
AC Transit HyRoad: Commercialization of Fuel Cells for Public Transit (CALSTART)	Accelerated testing of existing fuel cell buses; team includes Van Hool (bus chassis), ISE (hybrid drive system), and UTC Power (fuel cell system)

Appendix B: CTTRANSIT Description

CTTRANSIT Profile

CTTRANSIT[5] 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 B-1 shows the service area for this Division.

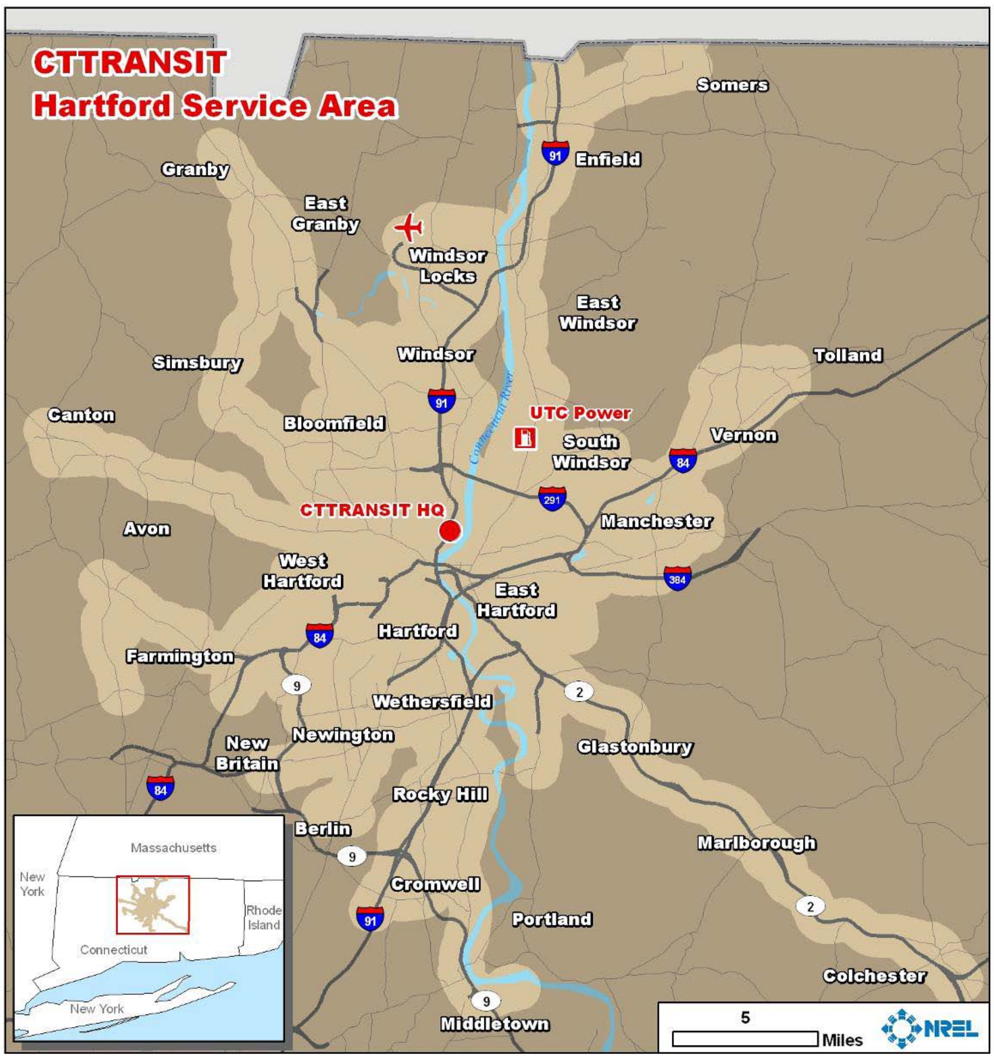

Figure B-1. Service area for CTTRANSIT's Hartford Division

[5] CTTRANSIT Web site: www.cttransit.com.

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, **CT**TRANSIT has a retrofit program in progress to install DPFs on most of its existing bus fleet with completion expected in May 2009.

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 2005[6].

CTTRANSIT's Fuel Cell Demonstration Project

CTTRANSIT unveiled its new fuel cell bus in April 2007. This was not only 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. **CT**TRANSIT'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 B-2 lists the partners involved in the project and their respective roles.

Table B-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, **CT**TRANSIT 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 other related issues, such as problems with 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.

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[6] Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses, Connecticut Academy of Science and Engineering, Oct. 2005, www.ctcase.org/reports/diesel-hybrid.pdf.

CTTRANSIT management and staff understand the need to work with the manufacturers to optimize and develop a product further.

One of the most significant reasons for its selection has been **CT**TRANSIT'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 enriched its fuel cell bus development program further by periodically collecting additional diagnostic data and evaluating possible design enhancements on the **CT**TRANSIT 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 **CT**TRANSIT 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 issues[7].
- In December 2004, the state adopted California LEV-II vehicle emissions regulations, set to begin with the 2008 model year.
- In 2005, 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 06-187[8]: *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, the Fuel Cell Economic Development Plan—Hydrogen Roadmap[9] was submitted to the Department of Economic and Community Development by the Connecticut Center for Advanced Technologies. The plan includes recommendations to increase the number of fuel cell buses in operation in the state. **CT**TRANSIT expects to participate in the activities from this plan.

[7] Connecticut Climate Change Action Plan, http://ctclimatechange.com/StateActionPlan.html.
[8] Public Act 06-187, *The Roadmap to Connecticut's Economic Future*, www.cga.ct.gov/2006/ACT/PA/2006PA-00187-R00HB-05846-PA.htm.
[9] Roadmap, www.ct.gov/ecd/cwp/view.asp?Q=410448&A=1105.

- In June 2008, Public Act 08-98: *An Act Concerning Connecticut Global Warming Solutions* was signed into law. This Act requires the state to create a program and schedule to reduce greenhouse gas emissions in the state.

Appendix C: Evaluation Bus Technology Descriptions

Fuel Cell and Diesel Buses

Table C-1 provides bus system descriptions for the fuel cell and diesel buses included in the **CT**TRANSIT evaluation. Three diesel buses (one shown in Figure C-1) from the most recent bus order were selected for baseline comparison data. The fuel cell bus (shown in Figure C-2) went into revenue service in April 2007.

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 **CT**TRANSIT, 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 C-2 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.

Figure C-1. One of CTTRANSIT's newest diesel buses

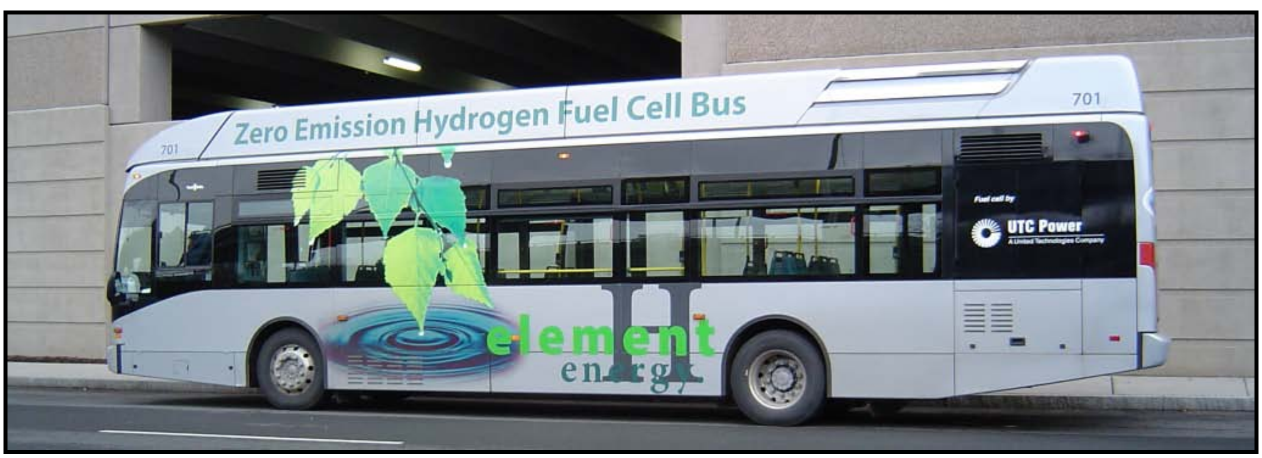

Figure C-2. CTTRANSIT's fuel cell bus

Table C-1. 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[1] 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 C-2. 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 **CT**TRANSIT 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 C-3) is a series configuration, meaning 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.

[1] 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[2].

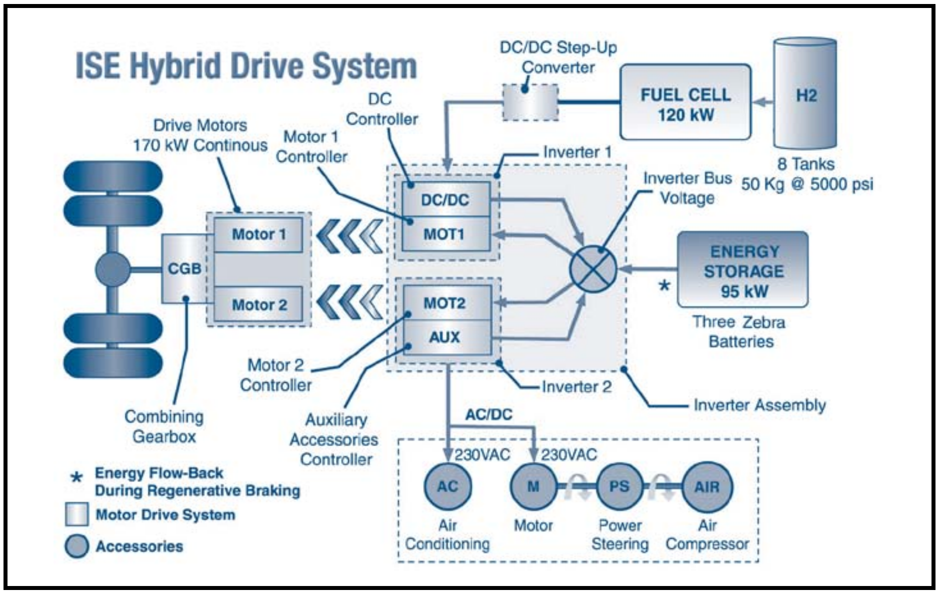

Figure C-3. Hybrid propulsion system diagram

[2] Web site: www.betard.co.uk/

Appendix D: Evaluation Infrastructure Description

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, **CT**TRANSIT 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. **CT**TRANSIT'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, **CT**TRANSIT 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. **CT**TRANSIT 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 **CT**TRANSIT 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 D-1 shows the maintenance bay at the **CT**TRANSIT facility.

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 **CT**TRANSIT technicians. The agency reports excellent and responsive support from both UTC Power and ISE (located in San Diego, California). The biggest challenge has been troubleshooting issues from opposite sides of the country (and sometimes across the world).

Hydrogen Fueling Station – For **CT**TRANSIT, 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 an FTA grant.

Figure D-1. CTTRANSIT fuel cell bus maintenance bay (lower left), operating procedures (upper left), and alarm control system (right)

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 D-2 shows the fueling facility and dispenser at UTC Power headquarters.

Figure D-2. Fueling facility (left) and dispenser (right) at UTC Power headquarters

Appendix E: Survey Results

Passenger Survey Results

On August 27, 2008, the marketing department of **CT**TRANSIT handed out a passenger survey to gather input on acceptance and awareness of the Fuel Cell Bus. The FCB was operated that day on the A-Asylum/Hillside route. There were 79 surveys completed, which is an estimated 80% of the total ridership for the run. The analysis by question is provided below.

Q1: I have ridden in the hydrogen fuel cell bus:

Response	#	%
First time today	65	82%
Occasionally	12	15%
Often	1	1%
No answer	1	1%

Q2: When you boarded the bus were you aware that it was a special hydrogen bus?

Response	#	%
Yes	52	66%
No	24	30%
No answer	3	4%

Q3: Were you aware that the hydrogen fuel cell bus…

a… has zero emissions?

b… gets double the fuel economy when compared to a standard diesel bus?

c… runs on a hybrid electric drive system?

d… converts the electric motors to generators upon braking to charge the batteries?

e… is the only operating transit hydrogen fuel cell bus in the United States outside of California?

Response	Q3 a		Q3 b		Q3 c		Q3 d		Q3 e	
	#	%	#	%	#	%	#	%	#	%
Yes	29	37%	27	34%	38	48%	25	32%	17	22%
No	49	62%	46	58%	37	47%	48	61%	55	70%
No answer	1	1%	6	8%	4	5%	6	8%	7	9%

Q4: How does the hydrogen fuel cell bus overall noise level compare to a standard diesel bus?
Q5: How does the hydrogen fuel cell bus acceleration compare to a standard diesel bus?
Q6: How does the hydrogen fuel cell bus braking compare to a standard diesel bus?
Q7: How does the hydrogen fuel cell bus vibration compare to standard diesel bus?

Response	Q4		Q5		Q6		Q7	
	#	%	#	%	#	%	#	%
Better	71	90%	65	82%	65	82%	70	89%
Worse	1	1%	1	1%	1	1%	1	1%
The same	5	6%	13	16%	13	16%	6	8%
No answer	2	3%	0	0%	0	0%	2	3%

Q8: How does the hydrogen fuel cell bus interior heat compare to a standard diesel bus?
Q9: How does the hydrogen fuel cell bus interior air conditioning compare to a standard diesel bus?

Response	Q8		Q9	
	#	%	#	%
Better	48	61%	53	67%
Worse	1	1%	1	1%
The same	19	24%	22	28%
No answer	11	14%	3	4%

Q10: Do you prefer to ride in a hydrogen fuel cell bus or a standard diesel bus?

Response	#	%
Hydrogen fuel cell bus	66	84%
Standard diesel bus	6	8%
No answer	7	9%

Q11: Has riding in a fuel cell bus changed your opinion of the technology?

Response	#	%
Yes	64	81%
No	11	14%
No answer	4	5%

Q12: Are there other aspects of the fuel cell bus, such as knowing there are zero emissions, that enhance your passenger experience?

Response	#	%
Yes	22	28%
No	28	35%
No answer	29	37%

Operator Survey Results

During fall of 2008, **CT**TRANSIT also conducted a survey to measure awareness and acceptance of its bus operators. A total of 21 operators participated in the survey. The results are summarized below.

Q1: I have driven the hydrogen fuel cell bus?

Response	#	%
First time today	3	14%
Occasionally	10	48%
Often	6	29%
No answer	2	10%

Q2: Was it hard to get used to driving the hydrogen fuel cell bus?

Response	#	%
Yes	0	0%
No	13	62%
A little	8	38%

Q3: How does the hydrogen fuel cell bus overall noise level compare to a standard diesel bus?
Q4: How does the hydrogen fuel cell bus acceleration compare to a standard diesel bus?
Q5: How does the hydrogen fuel cell bus braking compare to a standard diesel bus?
Q6: How does the hydrogen fuel cell bus vibration compare to a standard diesel bus?

Response	Q3		Q4		Q5		Q6	
	#	%	#	%	#	%	#	%
Better	20	95%	9	43%	3	14%	15	71%
Worse	1	5%	7	33%	3	14%	1	5%
The same	0	0%	3	14%	13	62%	4	19%
No answer	0	0%	2	10%	2	10%	1	5%

Q7: In normal driving conditions how does the hydrogen fuel cell bus handling compare to a standard diesel bus?
Q8: In rain/snow conditions how does the hydrogen fuel cell bus handling compare to a standard diesel bus?

Response	Q7		Q8	
	#	%	#	%
Better	4	19%	1	5%
Worse	1	5%	1	5%
The same	14	67%	11	52%
No answer	2	10%	8	38%

Q9: How does the hydrogen fuel cell bus window defroster compare to a standard diesel bus?
Q10: How does the hydrogen fuel cell bus interior heat compare to a standard diesel bus?
Q11: How does the hydrogen fuel cell bus interior AC compare to a standard diesel bus?

Response	Q9		Q10		Q11	
	#	%	#	%	#	%
Better	3	14%	1	5%	5	24%
Worse	0	0%	5	24%	2	10%
The same	11	52%	1	5%	11	52%
Don't know	-	-	11	52%	0	0%
No answer	7	33%	3	14%	3	14%

Q12: Do you prefer to drive the hydrogen fuel cell bus or a standard diesel bus?

Response	#	%
Hydrogen Fuel Cell	8	38%
Standard diesel	8	38%
No answer	5	24%

Appendix F. Fleet Summary Statistics

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

	Fuel Cell Early Data	Fuel Cell Evaluation	Diesel Early Data	Diesel Evaluation
Number of Vehicles	1	1	3	3
Period Used for Fuel and Oil Operation Analysis	4/07-1/08	1/08-2/09	8/07-12/07	1/08-2/09
Total Number of Months in Period	10	14	5	14
Fuel and Oil Analysis Base Fleet Mileage	4,544	24,104	42,018	136,299
Period Used for Maintenance Operation Analysis	4/07-1/08	1/08-2/09	8/07-12/07	1/08-2/09
Total Number of Months in Period	10	14	5	14
Maintenance Analysis Base Fleet Mileage	5,157	24,127	42,067	137,127
Average Monthly Mileage per Vehicle	516	1,723	2,804	3,265
Availability	45%	77%	N/A	N/A
Fleet Fuel Usage in Diesel Gal/H2 kg	944	5,103	11,928	37,231
Roadcalls	9	21	N/A	18
RCs MBRC	573	1,149	N/A	7,618
Propulsion Roadcalls	7	19	N/A	16
Propulsion MBRC	737	1,270	N/A	8,570
Fleet Miles/kg Hydrogen	4.82	4.72		
(1.13 kg H2/gal Diesel Fuel)				
Representative Fleet MPG (energy equiv.)	5.44	5.34	3.52	3.66
Hydrogen Cost per kg	4.18	5.29		
Diesel Cost per Gallon			2.51	2.70
Fuel Cost per Mile	**0.87**	**1.12**	**0.71**	**0.74**
Total Scheduled Repair Cost per Mile	0.05	0.06	0.07	0.11
Total Unscheduled Repair Cost per Mile	8.40	0.98	0.19	0.31
Total Maintenance Cost per Mile	**8.45**	**1.04**	**0.26**	**0.42**
Total Operating Cost per Mile	**9.32**	**2.16**	**0.97**	**1.16**

Maintenance Costs

	Fuel Cell Early Data	Fuel Cell Evaluation	Diesel Early Data	Diesel Evaluation
Fleet Mileage	5,157	24,127	42,067	137,127
Total Parts Cost	1,471.03	2,723.64	1,643.10	17,136.64
Total Labor Hours	842.8	448.1	185.0	798.2
Average Labor Cost (@ $50.00 per hour)	42,137.50	22,405.00	9,250.00	39,910.00
Total Maintenance Cost	43,608.53	25,128.64	10,893.10	57,046.64
Total Maintenance Cost per Bus	43,608.53	25,128.64	3,631.03	19,015.55
Total Maintenance Cost per Mile	**8.45**	**1.04**	**0.26**	**0.42**

Breakdown of Maintenance Costs by Vehicle System

	Fuel Cell Early Data	Fuel Cell Evaluation	Diesel Early Data	Diesel Evaluation
Fleet Mileage	5,157	24,127	42,067	137,127
Total Propulsion-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts Cost	626.53	1,490.82	536.53	6,666.62
Labor Hours	713.3	335.2	16.7	195.6
Average Labor Cost	35,662.50	16,758.00	833.50	9,779.00
Total Cost (for system)	36,289.03	18,248.82	1,370.03	16,445.62
Total Cost (for system) per Bus	36,289.03	18,248.82	456.68	5,481.87
Total Cost (for system) per Mile	**7.04**	**0.76**	**0.03**	**0.12**
Exhaust System Repairs (ATA VMRS 43)				
Parts Cost	0.00	0.00	0.00	0.00
Labor Hours	0.0	0.0	0.0	6.5
Average Labor Cost	0.00	0.00	0.00	325.00
Total Cost (for system)	0.00	0.00	0.00	325.00
Total Cost (for system) per Bus	0.00	0.00	0.00	108.33
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**	**0.00**
Fuel System Repairs (ATA VMRS 44)				
Parts Cost	0.00	277.30	123.33	658.82
Labor Hours	0.3	8.3	0.0	3.8
Average Labor Cost	16.50	416.50	0.00	187.50
Total Cost (for system)	16.50	693.80	123.33	846.32
Total Cost (for system) per Bus	16.50	693.80	41.11	282.11
Total Cost (for system) per Mile	**0.00**	**0.03**	**0.00**	**0.01**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts Cost	0.00	0.00	243.32	945.52
Labor Hours	162.0	103.4	9.5	29.3
Average Labor Cost	8,100.00	5,171.00	475.00	1,466.50
Total Cost (for system)	8,100.00	5,171.00	718.32	2,412.02
Total Cost (for system) per Bus	8,100.00	5,171.00	239.44	804.01
Total Cost (for system) per Mile	**1.57**	**0.21**	**0.02**	**0.02**
Electric Propulsion Repairs (ATA VMRS 46)				
Parts Cost	16.68	33.45	0.00	0.00
Labor Hours	527.8	216.9	0.0	0.0
Average Labor Cost	26,387.50	10,845.50	0.00	0.00
Total Cost (for system)	26,404.18	10,878.95	0.00	0.00
Total Cost (for system) per Bus	26,404.18	10,878.95	0.00	0.00
Total Cost (for system) per Mile	**5.12**	**0.45**	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell Early Data	Fuel Cell Evaluation	Diesel Early Data	Diesel Evaluation
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts Cost	0.00	467.48	0.00	3,308.31
Labor Hours	4.5	6.5	0.0	18.4
Average Labor Cost	225.00	325.00	0.00	921.00
Total Cost (for system)	225.00	792.48	0.00	4,229.31
Total Cost (for system) per Bus	225.00	792.48	0.00	1,409.77
Total Cost (for system) per Mile	**0.04**	**0.03**	**0.00**	**0.03**
Air Intake System Repairs (ATA VMRS 41)				
Parts Cost	10.98	622.69	166.98	1,318.89
Labor Hours	0.0	0.0	0.0	16.5
Average Labor Cost	0.00	0.00	0.00	825.00
Total Cost (for system)	10.98	622.69	166.98	2,143.89
Total Cost (for system) per Bus	10.98	622.69	55.66	714.63
Total Cost (for system) per Mile	**0.00**	**0.03**	**0.00**	**0.02**
Cooling System Repairs (ATA VMRS 42)				
Parts Cost	598.87	89.90	5.00	337.66
Labor Hours	19.0	0.0	2.9	51.5
Average Labor Cost	950.00	0.00	7.17	2,575.00
Total Cost (for system)	1,548.87	89.90	12.17	2,912.66
Total Cost (for system) per Bus	1,548.87	89.90	4.06	970.89
Total Cost (for system) per Mile	**0.30**	**0.00**	**0.00**	**0.02**
Hydraulic System Repairs (ATA VMRS 65)				
Parts Cost	0.00	0.00	0.00	0.00
Labor Hours	0.0	0.0	0.0	0.0
Average Labor Cost	0.00	0.00	0.00	0.00
Total Cost (for system)	0.00	0.00	0.00	0.00
Total Cost (for system) per Bus	0.00	0.00	0.00	0.00
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)				
Parts Cost	0.00	0.00	0.00	296.86
Labor Hours	0.0	0.0	4.0	5.5
Average Labor Cost	0.00	0.00	200.00	275.00
Total Cost (for system)	0.00	0.00	200.00	571.86
Total Cost (for system) per Bus	0.00	0.00	66.67	190.62
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell Early Data	Fuel Cell Evaluation	Diesel Early Data	Diesel Evaluation
Brake System Repairs (ATA VMRS 13)				
Parts Cost	0.00	54.98	0.00	3,779.15
Labor Hours	3.0	8.0	2.0	70.3
Average Labor Cost	150.00	400.00	100.00	3,517.00
Total Cost (for system)	150.00	454.98	100.00	7,296.15
Total Cost (for system) per Bus	150.00	454.98	33.33	2,432.05
Total Cost (for system) per Mile	**0.03**	**0.02**	**0.00**	**0.05**
Transmission Repairs (ATA VMRS 27)				
Parts Cost	0.00	0.00	0.00	97.42
Labor Hours	0.0	0.0	0.0	69.6
Average Labor Cost	0.00	0.00	0.00	3,479.00
Total Cost (for system)	0.00	0.00	0.00	3,576.42
Total Cost (for system) per Bus	0.00	0.00	0.00	1,192.14
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**	**0.03**
Inspections Only – No Parts Replacements (101)				
Parts Cost	0.00	0.00	0.00	0.00
Labor Hours	5.5	25.0	43.5	191.5
Average Labor Cost	275.00	1,250.00	2,175.00	9,575.00
Total Cost (for system)	275.00	1,250.00	2,175.00	9,575.00
Total Cost (for system) per Bus	275.00	1,250.00	725.00	3,191.67
Total Cost (for system) per Mile	**0.05**	**0.05**	**0.05**	**0.07**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts Cost	610.98	104.63	815.60	5,158.00
Labor Hours	23.5	20.5	103.4	244.1
Average Labor Cost	1,175.00	1,025.50	5,170.50	12,204.50
Total Cost (for system)	1,785.98	1,130.13	5,986.10	17,362.50
Total Cost (for system) per Bus	1,785.98	1,130.13	1,995.37	5,787.50
Total Cost (for system) per Mile	**0.35**	**0.05**	**0.14**	**0.13**
HVAC System Repairs (ATA VMRS 01)				
Parts Cost	0.00	0.00	5.46	485.22
Labor Hours	95.5	23.5	13.0	41.5
Average Labor Cost	4,775.00	1,175.00	650.00	2,075.00
Total Cost (for system)	4,775.00	1,175.00	655.46	2,560.22
Total Cost (for system) per Bus	4,775.00	1,175.00	218.49	853.41
Total Cost (for system) per Mile	**0.93**	**0.05**	**0.02**	**0.02**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Fuel Cell Early Data	Fuel Cell Evaluation	Diesel Early Data	Diesel Evaluation
Lighting System Repairs (ATA VMRS 34)				
Parts Cost	233.52	392.65	6.5	29.16
Labor Hours	2.0	3.7	0.0	6.3
Average Labor Cost	100.00	185.00	0.00	316.50
Total Cost (for system)	333.52	577.65	6.50	345.66
Total Cost (for system) per Bus	333.52	577.65	2.17	115.22
Total Cost (for system) per Mile	**0.06**	**0.02**	**0.00**	**0.00**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts Cost	0.00	680.56	279.01	721.73
Labor Hours	0.0	27.4	2.4	23.6
Average Labor Cost	0.00	1,371.00	121.00	1,179.50
Total Cost (for system)	0.00	2,051.56	400.01	1,901.23
Total Cost (for system) per Bus	0.00	2,051.56	133.34	633.74
Total Cost (for system) per Mile	**0.00**	**0.09**	**0.01**	**0.01**
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	0.00	0.00
Labor Hours	0.0	1.8	0.0	1.2
Average Labor Cost	0.00	91.50	0.00	62.00
Total Cost (for system)	0.00	91.50	0.00	62.00
Total Cost (for system) per Bus	0.00	91.50	0.00	20.67
Total Cost (for system) per Mile	**0.00**	**0.00**	**0.00**	**0.00**
Tire Repairs (ATA VMRS 17)				
Parts Cost	0.00	0.00	0.00	0.00
Labor Hours	0.0	3.0	0.0	18.5
Average Labor Cost	0.00	150.00	0.00	925.00
Total Cost (for system)	0.00	150.00	0.00	925.00
Total Cost (for system) per Bus	0.00	150.00	0.00	308.33
Total Cost (for system) per Mile	**0.00**	**0.01**	**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. The general energy conversions are as follows (actual energy content will vary 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

   The gasoline LHV or GGE is 115,000 Btu/gal, which is approximately 1% higher than 113,628 Btu/kg for hydrogen; these have been called equivalent for this report.

   Gasoline/Diesel = 115,000 Btu/gallon / 128,400 Btu/gallon = 0.896

2. The propulsion-related systems were chosen to include only those vehicle systems that could be directly impacted 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.

4. In general, inspections (with no part replacements) were included only in the overall totals (not by system). 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.

Appendix G: Fleet Summary Statistics—SI Units

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

	Fuel Cell Early Data	Fuel Cell Evaluation	Diesel Early Data	Diesel Evaluation
Number of Vehicles	1	1	3	3
Period Used for Fuel and Oil Operation Analysis	4/07-1/08	1/08-2/09	8/07-12/07	1/08-2/09
Total Number of Months in Period	10	14	5	14
Fuel and Oil Analysis Base Fleet Kilometers	7,313	38,828	67,620	219,346
Period Used for Maintenance Operation Analysis	4/07-1/08	1/08-2/09	8/07-12/07	1/08-2/09
Total Number of Months in Period	10	14	5	14
Maintenance Analysis Base Fleet Kilometers	8,299	38,828	67,698	220,678
Average Monthly Kilometers per Vehicle	830	2,773	4,513	5,254
Availability	45%	77%	N/A	N/A
Fleet Fuel Usage in Diesel L/H2 kg	944	5,103	45,147	140,919
Roadcalls	9	21	N/A	18
Kilometers between roadcalls (KBRC)	922	1,849	N/A	12,260
Propulsion Roadcalls	7	19	N/A	16
Propulsion KBRC	1,186	2,044	N/A	13,792
Fleet kg Hydrogen/100 km (1.13 kg H2/gal Diesel fuel)	12.91	13.14		
Representative Fleet MPG (L/100 km)	43.24	44.02	66.77	64.25
Hydrogen Cost per kg	4.18	5.29		
Diesel Cost per Liter			0.66	0.71
Fuel Cost per Kilometer	**0.54**	**0.70**	**0.44**	**0.46**
Total Scheduled Repair Cost per Kilometer	0.03	0.04	0.04	0.07
Total Unscheduled Repair Cost per Kilometer	5.22	0.61	0.12	0.19
Total Maintenance Cost per Kilometer	**5.25**	**0.65**	**0.16**	**0.26**
Total Operating Cost per Kilometer	**5.79**	**1.34**	**0.60**	**0.72**

Maintenance Costs

	Fuel Cell Early Data	Fuel Cell Evaluation	Diesel Early Data	Diesel Evaluation
Fleet Kilometers	8,299	38,828	67,698	220,678
Total Parts Cost	1,471.03	2,723.64	1,643.10	17,136.64
Total Labor Hours	842.8	448.1	185.0	798.2
Average Labor Cost (@ $50.00 per hour)	42,140.00	22,405.00	9,250.00	39,910.00
Total Maintenance Cost	43,611.03	25,128.64	10,893.10	57,046.64
Total Maintenance Cost per Bus	43,611.03	25,128.64	3,631.03	19,015.55
Total Maintenance Cost per Kilometer	**5.25**	**0.65**	**0.16**	**0.26**

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14. ABSTRACT *(Maximum 200 Words)*
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 evaluation period in this report (January 2008 through February 2009) has been chosen to coincide with a UTC Power propulsion system changeout that occurred on January 15, 2008.

15. SUBJECT TERMS
fuel cell; fuel cell bus; fuel cell evaluation; fuel cell bus demonstration

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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