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Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Third Report

Leslie Eudy and Matthew Post
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NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-5400-60527
May 2014

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Acronyms and Abbreviations

Ah	amp-hours
CARB	California Air Resources Board
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
FCEB	fuel cell electric bus
FCEV	fuel cell electric vehicle
FCPP	fuel cell power plant
ft	feet
FTA	Federal Transit Administration
GGT	Golden Gate Transit
GVWR	gross vehicle weight rating
hp	horsepower
HVAC	heating, ventilation, and air conditioning
in.	inches
kg	kilograms
kW	kilowatts
kWh	kilowatt hours
lb	pounds
MBRC	miles between roadcalls
mpDGE	miles per diesel gallon equivalent
mpg	miles per gallon
mph	miles per hour
NREL	National Renewable Energy Laboratory
PMI	preventive maintenance inspection
PRD	pressure relief device
psi	pounds per square inch
RC	roadcall
SamTrans	San Mateo County Transit District
SFMTA	San Francisco Municipal Transportation Agency
SI	International System of Units
SOFC	solid oxide fuel cell
VTA	Santa Clara Valley Transportation Authority
ZBus	zero emission bus
ZEBA	Zero Emission Bay Area

Executive Summary

This report presents results of a demonstration of 12 fuel cell electric buses (FCEB) operating in Oakland, California. The FCEBs have a fuel cell dominant hybrid electric propulsion system in a series configuration. The bus manufacturer—Van Hool— fully integrated the hybrid design using a Siemens ELFA 2 hybrid system; ClearEdge Power's newest-design fuel cell power system; and an advanced lithium-based energy storage system by EnerDel. NREL has published two previous reports, in August 2011[1] and July 2012,[2] describing operation of these buses. New results in this report provide an update covering eight months through October 2013.

The 12 FCEBs operate as a part of the Zero Emission Bay Area (ZEBA) demonstration, which also includes two new hydrogen fueling stations. This effort is the largest FCEB demonstration in the United States and involves five participating transit agencies. The ZEBA partners are collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. NREL has been evaluating FCEBs under funding from DOE and the U.S. Department of Transportation's Federal Transit Administration (FTA). NREL uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations.[3]

The development process for commercializing advanced technology buses, such as FCEBs, begins at technology readiness level (TRL) 1—basic research/concept—and ends at TRL 9—commercial deployment. FCEB development is currently in the technology demonstration/ commissioning phase that includes TRLs 6 through 8. NREL considers the ZEBA buses to be at TRL 7. At this point of development, the manufacturers' goals for the demonstration are to verify that the FCEB performance meets the technical targets and identify any issues that need to be resolved. NREL's goal in evaluating FCEBs is to document the performance and track progress over time toward meeting the technical targets. NREL collects data on conventional buses at each demonstration site for a baseline comparison. This report includes baseline data from two different bus types: Van Hool diesel buses that are the same model as the FCEBs and newer Gillig buses that have mileage similar to that of the FCEBs.

The focus of this evaluation is to compare performance of the FCEBs to that of conventional technology, although a cost analysis and comparison is also provided. The current costs for FCEB technology—both capital and operating costs—are still much higher than the costs of conventional diesel technology. This is expected when comparing a very mature technology, like diesel, to new technologies in the development stage.

Since the last report, there have been multiple accomplishments.

- The Emeryville hydrogen station was repaired and upgraded after an incident in May 2012 and was re-commissioned and fueling buses by the end of January 2013.

[1] Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: First Results Report, NREL/TP-5600-52015, August 2011, http://www.nrel.gov/hydrogen/pdfs/52015.pdf.
[2] Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: Second Results Report, NREL/TP-5600-55367, July 2012, http://www.nrel.gov/hydrogen/pdfs/55367.pdf.
[3] Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-560-49342-1, November 2010, www.nrel.gov/hydrogen/pdfs/49342-1.pdf.

- AC Transit successfully reintroduced the FCEB fleet back into service after the extended downtime for the station. The agency reports that there were no major issues with the process to restart the fuel cells and that the buses are operating well.
- The FCEBs have operated 551,494 miles and 61,411 hours on the fuel cell power systems and have used 78,940 kg of hydrogen.
- Availability for the FCEBs has increased dramatically from 56% (in the last report) to 82% for the data period in this report.
- Three of the twelve fuel cell power systems continue to accumulate high hours of service without fuel cell stack maintenance or major power degradation (more than 15,000 hours; 11,000 hours; and 9,700 hours). This is the highest number of hours documented to date on a fuel cell in a transit application.
- AC Transit and its transit agency and manufacturer partners continue to ramp up service of the FCEBs, including troubleshooting, maintenance, and training for all involved. The buses will begin operation on more routes and will operate on weekends.

This third results report provides data analysis summaries of FCEB operations beginning in March 2013, when the station was back online and all the buses were back in service, through October 2013. During this time period, several issues have been resolved, and the agency is increasing the service toward full operation. Table ES-1 provides a summary of the evaluation results presented in this report.

Table ES-1. Summary of Evaluation Results

Data Item	Fuel Cell	Diesel VH[a]	Diesel Gillig
Number of buses	12	3	10
Data period	3/13–10/13	3/13–10/13	6/13–10/13
Number of months	8	8	5
Total mileage in period	259,171	97,773	229,318
Average monthly mileage per bus	2,700	4,074	4,586
Total fuel cell operating hours	30,192	N/A	N/A
Average bus operating speed (mph)	8.6	N/A	N/A
Availability (85% is target)	82	76	84[b]
Fuel economy (miles/kg)	6.43	N/A	N/A
Fuel economy (miles/DGE[c])	7.26	3.78	4.04
Miles between roadcalls (MBRC) – bus	5,634	2,573	4,247
MBRC – propulsion only	9,256	5,751	12,740
MBRC – fuel cell system only	21,598	N/A	N/A
Total maintenance ($/mile)[d]	0.67	1.03	0.21
Maintenance – propulsion only ($/mile)	0.35	0.44	0.05

[a] The Van Hool (VH) buses are out of the warranty period.
[b] Availability for the Gillig buses is from July through October.
[c] Diesel gallon equivalent.
[d] Work order maintenance cost.

Overall, the FCEBs averaged 6.43 miles per kilogram of hydrogen, which equates to 7.26 miles per diesel gallon equivalent. These results indicate that the FCEBs have an average fuel economy that is 87% higher than that of the Van Hool diesel buses and 80% higher than that of the Gillig diesel buses. Fuel cost for hydrogen remains much higher than the cost of diesel—$9.08 per kilogram of hydrogen compared to $3.05 per gallon for diesel. Fuel cost calculates to $1.41 per mile for the FCEBs compared to $0.79 per mile for the Van Hool diesel buses and $0.75 per mile for the Gillig buses.

In April 2013, Golden Gate Transit (GGT) began operating one of the ZEBA buses in its service area. During this time, GGT accumulated 14,516 miles for a daily average of 141 miles. Because of the high average operating speed, the fuel economy for GGT operations was higher than for AC Transit at 7.94 miles per kilogram hydrogen or 8.97 miles per diesel gallon equivalent.

Total maintenance costs per mile for the FCEBs were 35% lower when compared to the Van Hool diesel buses. This is expected, considering the Van Hool buses are out of warranty and have reached a mileage level where mid-life rebuilds are needed. The FCEB maintenance costs were three times higher than that of the new Gillig diesel buses.

Although the performance of FCEBs has improved over time, there are still challenges that must be addressed before the technology can be considered commercial. Challenges include the following:

- Increasing durability and reliability of components
- Improving systems integration and optimization
- Providing for adequate parts supply
- Transitioning of all maintenance to transit staff
- Lowering cost—both capital and operating.

In September 2012, DOE and FTA published performance, cost, and durability targets for FCEBs. These targets, established with industry input, include interim targets for 2016 and ultimate targets for commercialization. Table ES-2 summarizes the current performance results of the ZEBA buses compared to these targets.

Table ES-2. Summary of FCEB Performance Compared to DOE/FTA Targets[4]

	Units	This Report[a]	2012 Status	2016 Target	Ultimate Target
Bus lifetime	years/miles	3/ 35,800–66,000[b]	5/100,000	12/500,000	12/500,000
Power plant lifetime[c]	hours	3,800–15,000[d]	12,000	18,000	25,000
Bus availability	%	82	60	85	90
Fuel fills[e]	per day	1	1	1 (<10 min)	1 (<10 min)
Bus cost[f]	$	2,500,000[g]	2,000,000	1,000,000	600,000
Power plant cost[c,f]	$	N/A[h]	700,000	450,000	200,000
Hydrogen storage cost	$	N/A[h]	100,000	75,000	50,000
Roadcall frequency (bus/fuel cell system)	miles between roadcalls	5,600/ 21,500	2,500/ 10,000	3,500/ 15,000	4,000/ 20,000
Operation time	hours per day/days per week	7–14/ 5–7	19/7	20/7	20/7
Scheduled and unscheduled maintenance cost[i]	$/mile	0.67	1.20	0.75	0.40
Range	miles	260[j]	270	300	300
Fuel economy	miles per diesel gallon equivalent	7.26	7	8	8

[a] Summary of the results for the ZEBA buses in this report: data from March 2013–October 2013.
[b] Accumulated totals for the ZEBA buses through October 2013; these buses have not reached end of life; targets are for lifetime.
[c] For the DOE/FTA targets, the power plant is defined as the fuel cell system and the battery system. The fuel cell system includes supporting subsystems such as the air, fuel, coolant, and control subsystems. Power electronics, electric drive, and hydrogen storage tanks are excluded.
[d] The status for power plant hours is for the fuel cell system only; battery lifetime hours were not available.
[e] Multiple sequential fuel fills should be possible without an increase in fill time.
[f] Cost targets are projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only and does not represent an anticipated level of sales.
[g] AC Transit's per-bus purchase price for the ZEBA buses.
[h] Capital costs for subsystems are not currently reported by the manufacturers.
[i] Excludes mid-life overhaul of the power plant.
[j] Based on fuel economy and useful fuel tank capacity. AC Transit reports lower real-world range.

[4] Fuel Cell Technologies Program Record # 12012, September 12, 2012, http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf.

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Introduction

A group of transit agencies in the San Francisco Bay Area have been participating in a demonstration of a fleet of second-generation[5] fuel cell electric buses (FCEB) since May 2010. The Zero Emission Bay Area (ZEBA) demonstration includes 12 advanced-design fuel cell buses and two new hydrogen fueling stations. This is the largest FCEB demonstration in the United States. Five transit agencies are participating in the demonstration:

- Alameda-Contra Costa Transit District (AC Transit)—lead transit agency for ZEBA
- Santa Clara Valley Transportation Authority (VTA)
- Golden Gate Transit (GGT)
- San Mateo County Transit District (SamTrans)
- San Francisco Municipal Transportation Agency (SFMTA).

AC Transit has been the primary operator of the buses; however, GGT recently began operating one bus in its service area.

The ZEBA partners are collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. NREL has been evaluating FCEBs under funding from DOE and the U.S. Department of Transportation's Federal Transit Administration (FTA). NREL uses a standard data-collection and analysis protocol originally developed for DOE heavy-duty vehicle evaluations. This protocol was documented in a joint evaluation plan for transit bus evaluations.[6] The objectives of these evaluations are to provide comprehensive, unbiased evaluation results of fuel cell bus development and performance compared to conventional baseline vehicles. NREL published two earlier reports on this demonstration in August 2011[7] and July 2012.[8] This report is an update to the previous reports and focuses on data from March 2013 through October 2013.

Fuel Cell Buses in California

The California Air Resources Board's (CARB) 2000 "Fleet Rule for Transit Agencies"[9] has been the primary reason for demonstrations of FCEBs in the state of California. This rule set more stringent emission standards for new urban bus engines and promoted advances in the cleanest technologies, specifically zero-emission buses (ZBus). Under the rule, agencies with more than 200 buses must include ZBuses as 15% of new bus purchases. The effective date of this purchase requirement is currently under consideration by CARB and the decision will take into account cost and performance data from this and other FCEB demonstrations.

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[5] The FCEBs described in this report are considered a second-generation Van Hool fuel cell electric bus design.
[6] Fuel Cell Transit Bus Evaluations: Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration, NREL/MP-560-49342-1, November 2010, www.nrel.gov/hydrogen/pdfs/49342-1.pdf.
[7] Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: First Results Report, NREL/TP-5600-52015, August 2011, http://www.nrel.gov/hydrogen/pdfs/52015.pdf.
[8] Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration: Second Results Report, NREL/TP-5600-55367, July 2012, http://www.nrel.gov/hydrogen/pdfs/55367.pdf.
[9] Fact Sheet: Fleet Rule for Transit Agencies: Urban Bus Requirements, California Air Resources Board, http://www.arb.ca.gov/msprog/bus/ub/ubfactsheet.pdf.

There were two early-generation ZBus demonstrations that began in the mid-2000s and paved the way for the more advanced-design buses that are in service today. In the first project, VTA and SamTrans teamed up to operate three Gillig 40-foot buses with Ballard fuel cells based at VTA in San Jose, California. The buses were operated from 2004 through 2009.[10] The bus design was not a hybrid system and did not have an energy storage system. The resulting fuel economy was lower than expected. In the second early-generation FCEB project, AC Transit and GGT teamed up to demonstrate three Van Hool 40-foot buses with ClearEdge Power (formerly UTC Power) fuel cells at AC Transit in Oakland, California. This demonstration began in 2006 and operated into 2010.[11] This bus design was a hybrid system and was able to take advantage of regenerative braking. The resulting fuel economy was approximately 50% higher than that of the diesel baseline buses. These two demonstrations provided valuable information to the industry and helped develop next-generation FCEBs on a clear path to commercialization.

ZEBA Fuel Cell Bus Demonstration

In 2006, CARB updated the transit rule and added a requirement for an advanced zero-emission bus demonstration for the larger California agencies. As a result, the five largest transit agencies in the San Francisco Bay Area formed the ZEBA demonstration group. Of that group, SFMTA is a voluntary participant because the agency already owns and operates a large fleet of zero-emission electric trolley buses. The ZEBA partners' operating areas are shown in Figure 1.

The ZEBA demonstration group is supported through funding and planning by the Metropolitan Transportation Commission, the Bay Area Air Quality Management District, CARB, the California Energy Commission, and the FTA (including early funding under the National Fuel Cell Bus Program). Besides AC Transit, four of the five transit agencies (excluding SFMTA) in the ZEBA demonstration group are providing funding, participating in training activities, and plan to periodically operate buses as part of the demonstration.

The goals for the ZEBA demonstration include the following:

- **Operating performance:** Demonstrate that FCEBs can fulfill or exceed the operating requirements and standards of baseline diesel buses from the perspective of drivers and passengers (i.e., schedule adherence, vehicle handling, and passenger acceptance).
- **Fleet availability:** Match the "A.M. Pullout" fleet availability percentages of baseline diesel buses with a minimum fleet size of 12 buses.
- **Fleet reliability:** Match the miles between roadcalls (MBRC) of diesel buses for the bus as a whole and for the propulsion system category with a minimum fleet size of 12 buses.
- **Fuel economy:** Exceed the fuel economy of baseline diesel buses.
- **Infrastructure support:** Develop renewable sources of hydrogen, and demonstrate safe fueling systems and throughput (fueling speeds) equivalent to diesel fueling.

[10] NREL evaluation results reported in Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Evaluation Results, 2006, NREL/TP-560-40615, http://www.nrel.gov/hydrogen/pdfs/40615.pdf.

[11] Last results report for this demonstration—National Fuel Cell Bus Program: Accelerated Testing Evaluation Report #2 and Appendices, FTA-CO-26-7004-2010.1, http://www.nrel.gov/hydrogen/pdfs/48106-1.pdf.

- **Maintenance costs:** Track labor and material costs to compare with baseline diesel buses across applicable expense categories.

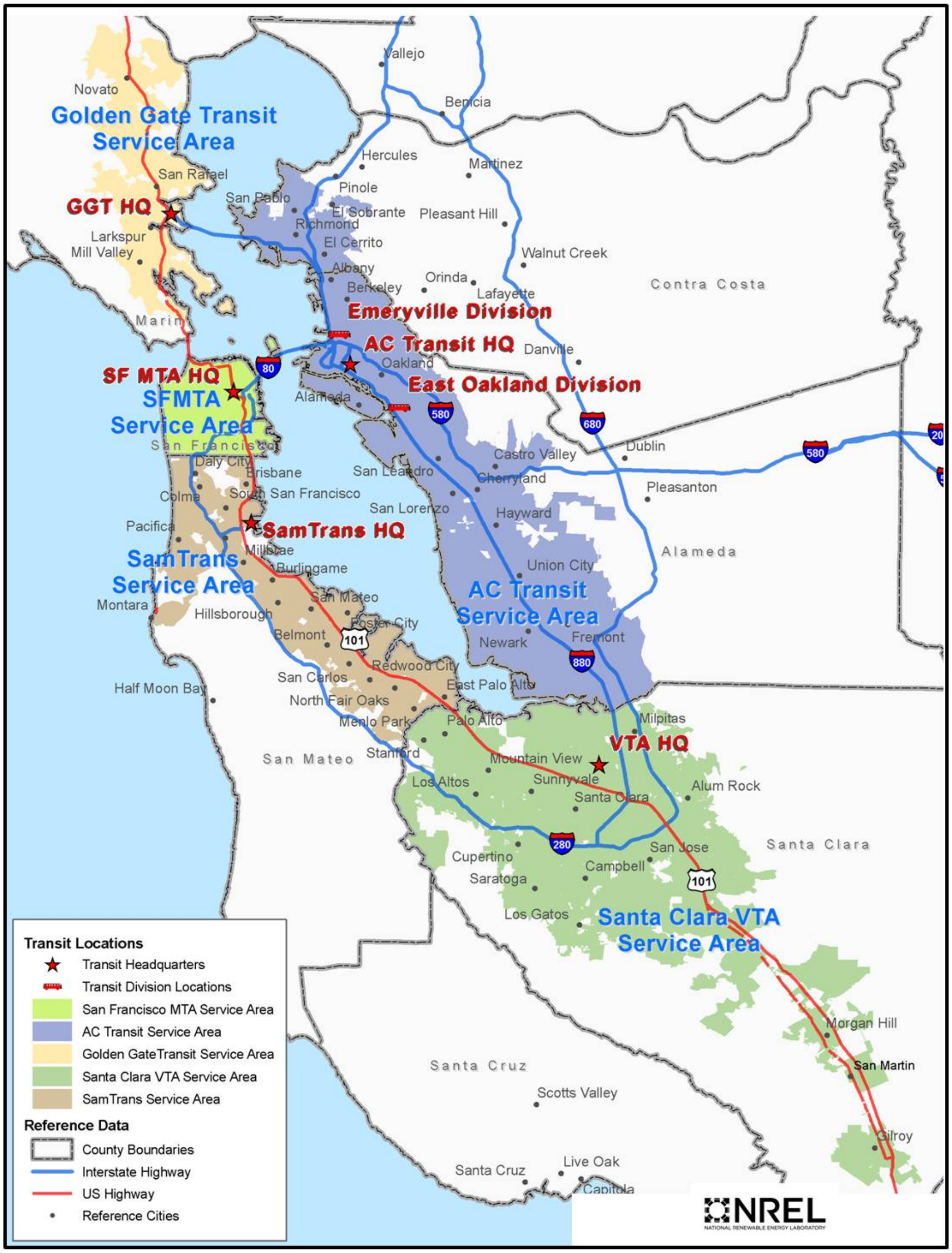

Figure 1. Map of ZEBA transit partner operating locations

FCEB Development Process—Technology Readiness Levels

In its 2012 annual FCEB status report,[12] NREL introduced a guideline for assessing the technology readiness level (TRL) for FCEBs. This guideline was developed using a Technology Readiness Assessment Guide[13] published by DOE in September 2011. Table 1 provides a TRL guide tailored for the commercialization of FCEBs. Figure 2 provides a graphic representation of this process.

Table 1. Technology Readiness Levels for FCEB Commercialization

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Deployment	TRL 9	Actual system operated over the full range of expected conditions	The technology is in its final form. Deployment, marketing, and support begin for the first fully commercial products.
Technology Demonstration/ Commissioning	TRL 8	Actual system completed and qualified through test and demonstration	The last step in true system development. Demonstration of a limited production of 50 to 100 buses at a small number of locations. Beginning the transition of all maintenance to transit staff.
	TRL 7	Full-scale validation in relevant environment	A major step up from TRL 6 by adding larger numbers of buses and increasing the hours of service. Full-scale demonstration and reliability testing of 5 to 10 buses at several locations. Manufacturers begin to train larger numbers of transit staff in operation and maintenance.
	TRL 6	Engineering/pilot-scale validation in relevant environment	First tests of prototype buses in actual transit service. Field testing and design shakedown of one to two prototypes. Manufacturers assist in operation and typically handle all maintenance. Begin to introduce transit staff to technology.
Technology Development	TRL 5	Laboratory scale, similar system validation in relevant environment	Integrated system is tested in a laboratory under simulated conditions based on early modeling. System is integrated into an early prototype or mule platform for some on-road testing.
	TRL 4	Component and system validation in laboratory environment	Basic technological components are integrated into the system and begin laboratory testing and modeling of potential duty cycles.
Research to Prove Feasibility	TRL 3	Analytical and experimental critical function and/or proof of concept	Active research into components and system integration needs. Investigate what requirements might be met with existing commercial components.
	TRL 2	Technology concept and/or application formulated	Research technology needed to meet market requirements. Define strategy for moving through development stages.
Basic Technology Research	TRL 1	Basic principles observed and reported	Scientific research and early development of FCEB concepts.

[12] Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012, NREL/TP-5600-56406.
[13] DOE Technology Readiness Assessment Guide, G 143.3-4a, https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view.

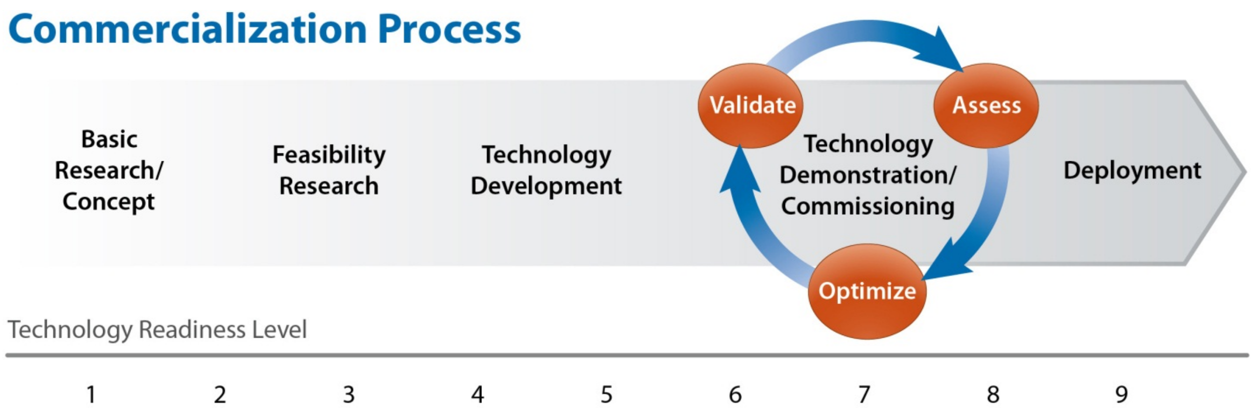

Figure 2. Graphic representation of the commercialization process developed for FCEBs

FCEB development is currently in the technology demonstration/commissioning phase that includes TRLs 6 through 8. This phase begins the iterative process to validate the design, analyze the results, and reconfigure or optimize the design as needed. The manufacturer typically works with a transit agency partner to conduct in-service tests on the bus. Updates to the design are made based on the performance results, and the buses go back into demonstration and through the cycle until the design meets the performance requirements. This can be a time-consuming process as manufacturers work through technical difficulties.

NREL considers the ZEBA buses to be at TRL 7 because the design of the bus was led by manufacturers experienced with FCEB development and the deployment includes the 12-bus ZEBA fleet. These buses represent a full-scale validation in a relevant environment. At this point in the development, FCEBs are not commercial products. The manufacturers' goals for the demonstration are to verify that the FCEB performance meets the technical targets and identify any issues that need to be resolved. The current costs for FCEB technology—both capital and operating costs—are still much higher than that of conventional diesel technology. This is expected considering diesel is a very mature technology (TRL 9) and FCEBs are still in the development stage. Once an advanced technology, such as FCEBs, meets the performance targets, the industry can work to reduce costs. This was the case with both compressed natural gas and diesel-hybrid bus technologies when they were first developed.

NREL's goal in evaluating FCEBs is to document the performance and track progress over time toward meeting the technical targets. NREL collects data on conventional buses at each demonstration site for a baseline comparison. This is important primarily because fuel economy is highly dependent on duty-cycle, but also because maintenance practices can be different from site to site. The best comparisons need to include buses operated in similar service at the same operating division. The most accurate comparison would be between buses of the same manufacturer, model, production year, and mileage. In that case, the only difference between the FCEB and baseline buses would be the propulsion system. This type of baseline comparison is not always possible.

Since the ZEBA demonstration began, NREL has collected data on three Van Hool diesel buses that are the same model as the FCEBs. These buses are the best physical match for the FCEBs; however, they are slightly older, have accumulated four times more miles than the FCEBs, and are no longer under warranty. These buses have reached mid-life, and maintenance records have begun to show increased cost typical of this period. AC Transit recently purchased a fleet of 40-foot Gillig buses. To allow comparison to the newest diesel bus design, NREL is collecting data on ten of these buses. These buses were delivered beginning in spring 2013. While these Gillig buses provide a comparison of the newest diesel technology to the FCEBs, they are not the best physical match because they were produced by another manufacturer. Because of this, the chassis is different from that of the FCEBs. The Gillig buses are younger; however, the mileage of each bus is much closer to that of the FCEBs. NREL has collected five months of data on the Gillig buses.

Bus Technology Descriptions

Table 2 provides bus system descriptions for the fuel cell and diesel buses that were studied in this evaluation. The FCEBs in service primarily at AC Transit (Figure 3) are 40-foot, low-floor buses built by Van Hool with a hybrid electric propulsion system that includes a ClearEdge Power fuel cell power system. The Van Hool diesel buses have Cummins engines with a diesel oxidation catalyst. The Gillig buses have Cummins engines that meet 2010 EPA emissions standards using a diesel particulate filter and selective catalytic reduction. Figure 4 shows one of AC Transit's Van Hool diesel buses and Figure 5 shows one of the new Gillig buses.

Table 2. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	FCEB	Diesel Van Hool	Diesel Gillig
Number of buses	12	3	10
Bus manufacturer/model	Van Hool A300L FC low floor	Van Hool A300L low floor	Gillig low floor
Model year	2010	2009	2013
Length/width/height	40 ft/102 in./136 in.	40 ft/102 in./121 in.	40 ft/102 in./122 in.
GVWR/curb weight	39,350 lb/31,400 lb	40,800 lb/27,800 lb	39,600 lb
Wheelbase	269 in.	278 in.	279 in.
Passenger capacity	33 seated or 29 seated plus 2 wheelchairs	31 seated or 28 seated plus 2 wheelchairs	37 seated or 29 seated plus 2 wheelchairs
Engine manufacturer/model	ClearEdge Power fuel cell power system	Cummins ISL	Cummins ISL, 8.9L
Rated power	Fuel cell power system: 120 kW	280 hp @ 2,200 rpm	280 hp @ 2,200 rpm
Accessories	Electrical	Mechanical	Mechanical
Emissions equipment	None	Diesel oxidation catalyst	Diesel particulate filter and selective catalytic reduction
Transmission/retarder	Seico brake resistors regenerative braking	Voith integrated retarder	Allison
Fuel capacity	40 kg hydrogen	92 gal	120 gal
Bus purchase cost	$2.5 million	$323,000	$413,826

Figure 3. AC Transit fuel cell bus

Figure 4. AC Transit Van Hool diesel bus at Emeryville Division

Figure 5. A new Gillig diesel bus at AC Transit. ***Photo courtesy of AC Transit***

Table 3 provides a description of some of the electric propulsion systems for the fuel cell buses. The diesel baseline buses are not hybrids and do not have regenerative braking or energy storage for the drive system. The FCEBs have a fuel cell dominant hybrid electric propulsion system in a series configuration. Van Hool fully integrated the hybrid design using a Siemens ELFA 2 hybrid system; Clear Edge Power's newest-design fuel cell power system that includes lessons learned from previous operation; and an advanced lithium-based energy storage system by EnerDel.

Table 3. Additional Electric Propulsion System Descriptions

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

Fueling and Maintenance Facilities

As part of the ZEBA demonstration, AC Transit planned construction of two hydrogen stations: one at the Emeryville Division and another to replace the decommissioned station at the Oakland Division. In addition, the agency plans to modify one maintenance bay in the garage at Emeryville to allow safe maintenance of hydrogen-fueled buses. One maintenance bay at the Oakland Division garage has already been modified. This section describes the station at Emeryville, outlines the status of construction, and provides a summary of fueling data from September 2011 through October 2013.

Emeryville Hydrogen Station

AC Transit's Emeryville hydrogen station, built by Linde LLC, was completed in July 2011 and fully commissioned by the end of August 2011. This station, shown in Figure 6, is a combined facility for light-duty fuel cell electric vehicles (FCEV) and FCEBs. AC Transit reports that engineering and construction costs for the station were $10 million. Funding from the state of California made the light-duty FCEV fueling access possible. Dispensers are available to fuel at 350 and 700 bar pressure.

Figure 6. The Linde hydrogen station at AC Transit's Emeryville Division

Figure 7 provides a simple block diagram of the station and primary components. Hydrogen is provided from two sources: liquid hydrogen delivery and a solar-powered electrolyzer. Hydrogen from both sources feeds into high-pressure gaseous storage tubes for fueling buses and autos. The electrolyzer is capable of producing 65 kg of hydrogen per day. When combined with the delivered liquid hydrogen, the station has the capacity to dispense up to 600 kg of hydrogen per day.

The station uses two compressors: one is a high-pressure mechanical compressor and the other is an ionic compressor. The mechanical compressor (MF-90) handles the FCEV side of the station and is capable of filling at both 350 and 700 bar. The MF-90 boosts the pressure to 700 bar for the FCEVs that operate at the higher pressure. The station can fully fuel a light-duty vehicle in 3 to 5 minutes depending on vehicle tank capacity.

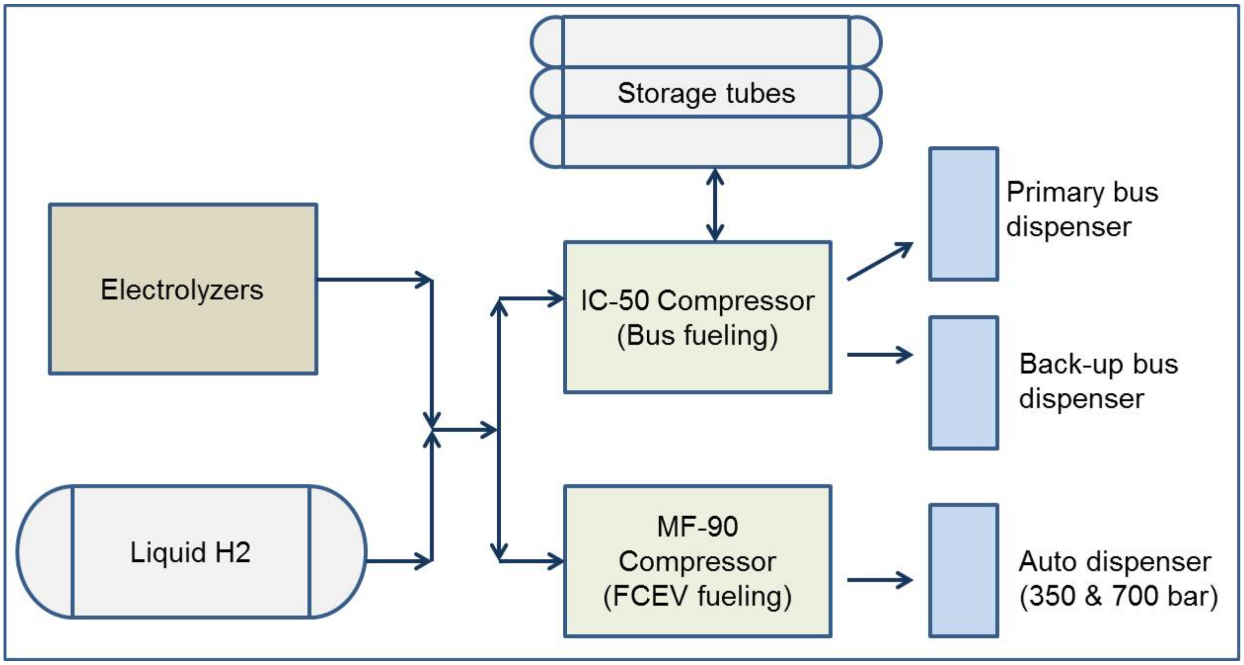

Figure 7. Block diagram of the Emeryville station

The bus fueling side of the station is handled by Linde's ionic compressor (IC-50). The IC-50 uses a proprietary ionic liquid in place of a mechanical piston. The buses can be fueled quickly—30 kg in about 6 minutes. Figure 8 shows the bus fueling area and a picture of the primary bus dispenser. The station also has a back-up dispenser for the buses in case there are issues with the primary fueling dispenser. AC Transit has a maintenance contract with Linde for 3 years with options for extension. The annual cost for this maintenance and service agreement is approximately $142,000.

Figure 8. Bus fueling at the Emeryville hydrogen station: fueling area (left) and close-up of the bus dispenser (right)

Oakland Seminary Division Hydrogen Fueling

AC Transit also contracted with Linde for the new station planned for the Seminary Division in Oakland. This station will be similar in design to the one at Emeryville. The primary differences are:

- The bus dispensers will be installed in-line with the diesel fueling island.
- There will be no public access for light-duty FCEV fueling because the station is at the back of the property.
- Hydrogen will be available at 350 bar pressure only.
- The on-site electrolyzer will be powered by a solid oxide fuel cell (SOFC) fueled with directed biogas.[14]

At the time of this report, the station is in the final design phase. The SOFC system has been installed and is operational. The power from this fuel cell system is being fed back into the grid while the rest of the station is being built. AC Transit's goal is to complete the second station in early 2014. This station location will be more convenient for use by ZEBA partner agencies VTA and SamTrans.

Maintenance Facilities

AC Transit converted one of the maintenance bays at the Oakland Seminary Division to accommodate hydrogen-fueled buses for the earlier demonstration. This bay is available for the FCEBs; however, the fleet is currently operated out of the Emeryville Division. To use this bay for maintenance requires shuttling the buses between the divisions and results in additional labor charges. The agency has plans to upgrade a bay at the Emeryville Division to make maintenance more convenient. AC Transit reports that the estimated cost to upgrade a maintenance bay is between $300,000 and $350,000.

Summary of Fueling Data

The Linde Emeryville station began fueling buses in mid-August 2011 and was fully commissioned by the end of that month. Figure 9 shows the average daily hydrogen dispensed (for days when hydrogen was dispensed; zero-use days were excluded) by month for the data period beginning in September 2011 through October 2013. During this period, the buses were fueled 3,210 times for a total of 60,197 kg. The average amount per fueling was 18.8 kg. The station downtime is noted on the graph—no fuel was dispensed during this timeframe. This downtime is explained in the next section.

Figure 10 tracks the total hydrogen dispensed into the buses from September 2010 through October 2013. More than 79,000 kg of hydrogen has been dispensed into the buses since they first began service.

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[14] Directed biogas implies a process of injecting purified biomethane (methane/natural gas developed from decaying organic matter) into the natural gas pipeline. Designated customers of the biomethane do not use the identical biomethane but can take credit for using the biomethane when using natural gas from the pipeline.

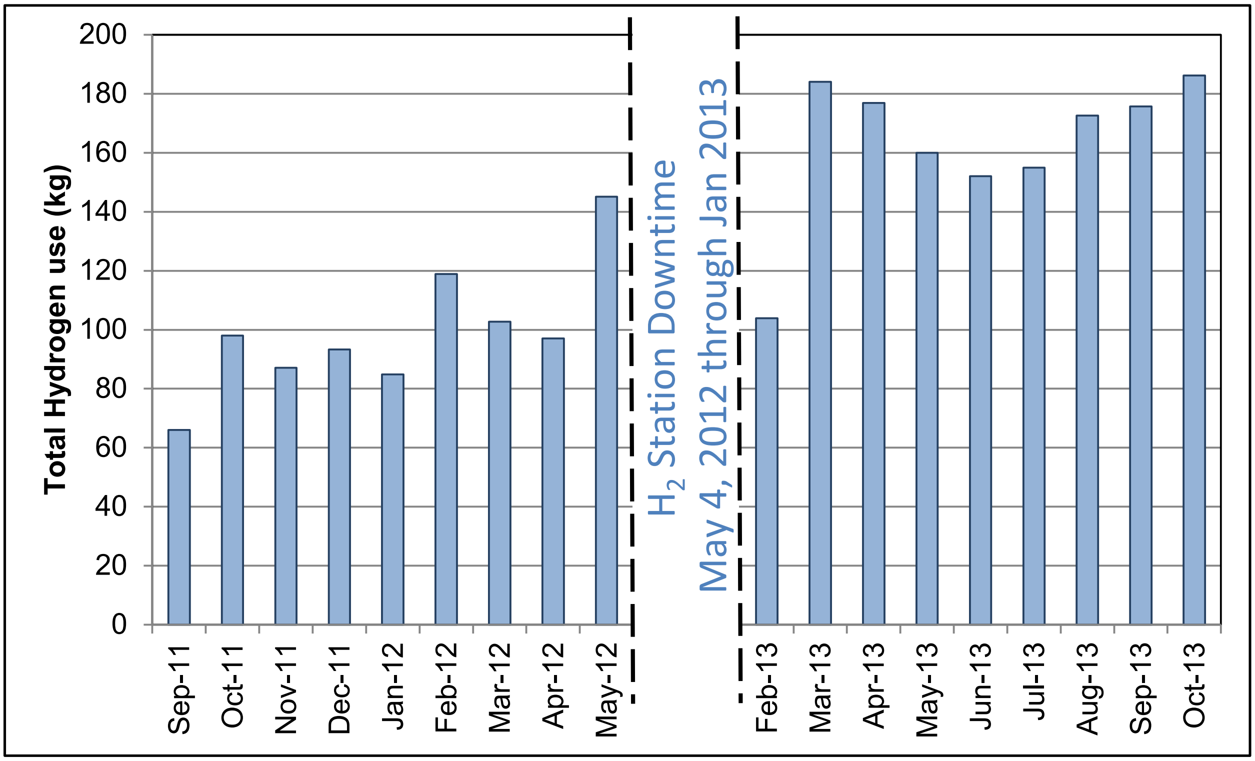

Figure 9. Average hydrogen dispensed per day at the Emeryville station (excluding 0 kg days)

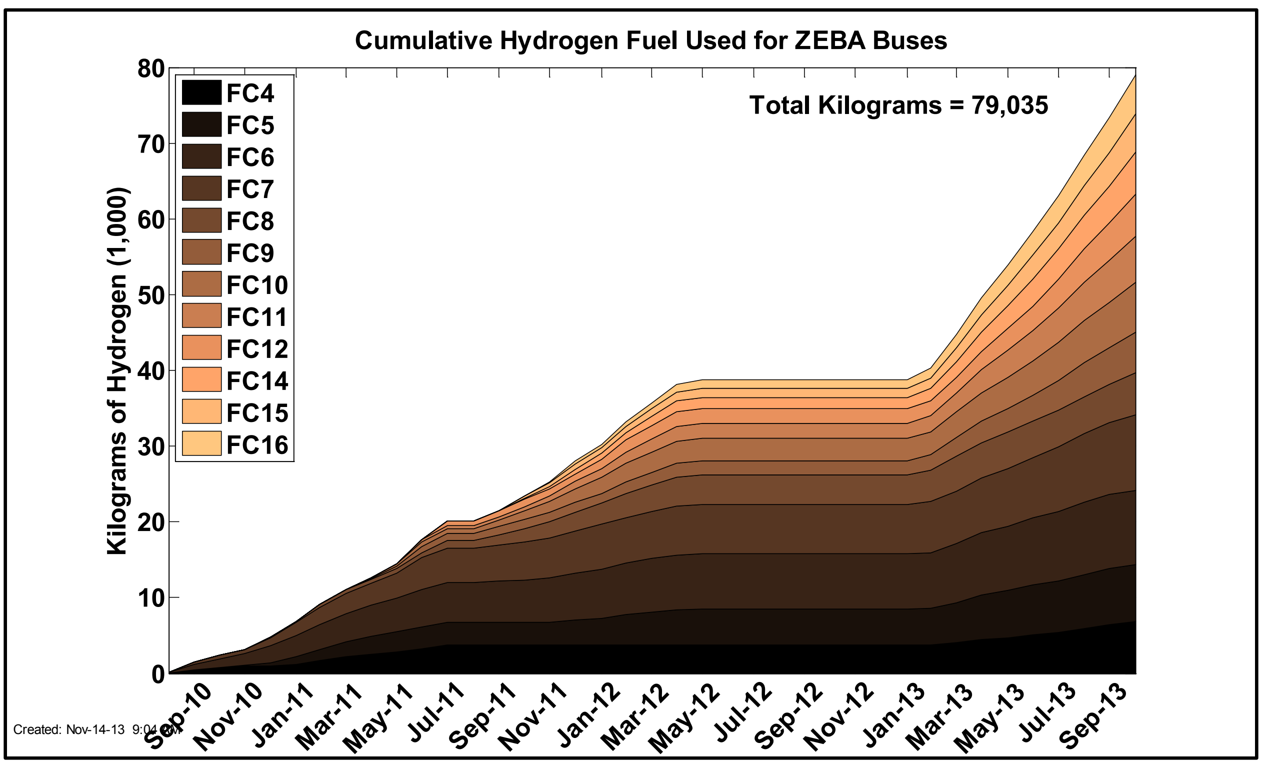

Figure 10. Cumulative hydrogen dispensed into the buses through October 2013

Implementation Experience

This section focuses on the project partners' experiences in implementing FCEBs into the fleet including the achievements and challenges encountered since the last report. Project partners include the five ZEBA transit agencies and the manufacturers, although AC Transit is the lead agency with the most experience operating the buses. All of the buses have been operating out of the Emeryville Division since August 2011 when the Linde station went online. Once the new hydrogen station is completed at the Oakland Division, the fleet will be split—six buses operating out of Oakland and six out of Emeryville. At that time, SamTrans and VTA will explore the potential of operating FCEBs in their fleets. GGT is closer to the Emeryville Division and has already begun operating one of the FCEBs.

Successful Reintroduction of FCEB Fleet

In the last report, NREL noted that there had been a safety incident at the Emeryville station. In early May 2012, a mechanical failure of a pressure relief device (PRD) valve on one of the high pressure storage tubes resulted in venting and ignition of pressurized hydrogen through the vent stacks. The emergency systems worked as designed. There were no injuries or threats of injuries, and no damage occurred, except for minor singeing on a corrugated canopy roof on one side of the station. The local authorities evacuated the area for several hours as a precaution. AC Transit's FCEB operations were suspended while this incident was fully investigated.

The investigation team was composed of representatives from AC Transit, Linde, CARB, Sandia National Laboratories (funded by CARB), and the Alameda County Fire Department.[15] The root cause of the incident was the failed PRD. Analysis showed the nozzle sub-assembly was made of a material that was a poor choice for use with hydrogen. This choice of material as well as deviations in process during production of the valve led to the failure. Other factors, such as the lack of timely communication, contributed to the escalation of the event. Although there were no injuries or major damage, several lessons were learned from the event that should be considered when planning a hydrogen station for FCEBs or other application, including:

- Evaluate the components, sub-components, and other parts of the station to ensure all materials used are appropriate for hydrogen.
- Plan for isolation of different sub-systems within the station in the case of a hydrogen release, and ensure vent outlets are sufficiently above and oriented away from other equipment.
- Define and update communications plans to establish responsibility for specific processes, such as assigning which staff members are responsible for contacting first responders in an emergency. Ensure that critical information is accessible by emergency responders.
- Educate staff early on and provide refresher training on a regular basis. Performing mock drills can be particularly effective to ensure employee response to an event is appropriate.

[15] Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility (Revised), SANDIA2012-8642, October 2012, http://www.osti.gov/scitech/servlets/purl/1055884.

The station was repaired, upgraded, and re-commissioned by the end of January 2013. Linde made the changes necessary to address the issues and made additional enhancements during this time. These changes included:

- Replacing faulty valves with new valves made from hydrogen-appropriate materials from a different manufacturer
- Raising the vent stacks (see Figure 11)
- Adding isolations to prevent all of the tanks from venting in a similar situation
- Changing the safety response process for AC Transit
- Installing a remote emergency shutoff in the Emeryville Operation Center (see Figure 12).

Figure 11. The vent stacks were raised above the level of the canopy

Figure 12. An emergency stop control was added to the Emeryville Division Control Center

During the 9-month period that the station was down, the FCEBs were parked at the depot. AC Transit staff moved some of the buses around the yard for maintenance as long as they had fuel; however, AC Transit had no way to fill the buses once the hydrogen in the tanks was depleted. Once the station was back online, the agency began the start-up procedure to get the FCEBs operational. This situation had never been experienced during a demonstration and the partners did not know how well the buses would operate after a long period of inactivity. AC Transit reports that the start-up procedure for the fuel cells went extremely well and that anticipated problems did not occur. The primary result of the buses sitting idle was that the 12-volt batteries on the buses were all depleted and had to be replaced. Once the batteries were replaced, maintenance staff conducted a re-wet procedure to force water up into the fuel cells and conducted a thorough inspection of all the bus systems. The buses were then started, fueled, and run through a series of operational tests. There have been no apparent problems with the buses as a result of the downtime. The process to bring the entire fleet back into operation was limited by the manpower available to inspect and test all 12 buses prior to service start.

AC Transit took advantage of the downtime to complete several upgrades on the buses and to repair one bus (FC4) that had been out of service for an extended period waiting for parts. This bus was removed from service in August 2011 for a drive system issue that caused the bus to stall. The problem proved difficult to diagnose, and during this time maintenance staff removed several parts to more quickly repair other buses. Once the original issue was repaired, the bus was down until the removed parts could be replaced. These parts were not typically stocked and had a long lead time for delivery.

Golden Gate Transit Service

In April 2013, GGT began operating one of the ZEBA buses in its service area. GGT is one of three divisions operated by the Golden Gate Bridge, Highway & Transportation District. GGT operates 179 buses in various types of bus service, including inter-county, commuter express, and local. GGT operates primarily in Marin and Sonoma counties across the Bay northward from San Francisco. The service area covers 256 square miles. The agency has previous experience operating FCEBs through its partnership with AC Transit on the early-generation ZBus demonstration. During that time, the two agencies worked through the logistics for GGT to operate a bus. Preparations included:

- Training operators and maintenance staff
- Selecting routes
- Coordinating plans in case of an issue with a bus
- Programming GGT routes into the headsign
- Training of local firefighters and emergency responders
- Alerting GGT riders to the demonstration plans.

Because of this past experience, GGT was well prepared to participate in the ZEBA demonstration. As with the previous demonstration, GGT worked with AC Transit staff to train drivers on how to operate the buses. Most training occurred at the Emeryville Division, with GGT personnel participating in regularly scheduled training for AC Transit staff.

GGT's service profile is very different from most transit agencies in the San Francisco Bay area. Because GGT primarily serves regional riders and commuters, the average bus speed is relatively high at 16.5 mph. GGT defined several routes for the FCEB to maximize the public exposure to the technology. The agency is beginning its demonstration with one bus. Once GGT staff becomes familiar with the daily operation, the agency will consider adding a second bus. This demonstration is planned for an indefinite time period.

Because the two agencies use different equipment on their buses, the use of existing fareboxes was an issue. GGT has a complicated fare structure that could not be easily programmed into the AC Transit fareboxes. AC Transit agreed to provide a bus for GGT to operate each day; however, it might not be the same bus. In the previous demonstration, GGT elected to provide free service with the FCEB instead of changing out the farebox. For a longer-term demonstration, GGT needed to find another solution. GGT inspected the buses and determined that its fareboxes would not fit into the existing mount. The agency built an adapter that would match the GGT farebox mount to the bus. Once a bus is outfitted, swapping out a farebox takes about 15 minutes. Similarly, GGT staff developed a solution to install GGT-specific onboard equipment for the Bay Area regional smart card (Clipper) fare collection system. In this configuration, the FCEB collects fares and passenger trip data the same way a GGT bus does. GGT collaborated with VTA and SamTrans to ensure that these data and fare collection solutions would work similarly for those agencies once they are ready to begin operating the buses.

GGT Operation Summary

The in-service demonstration of the FCEB began on April 16, 2013. The agency operated a bus through October for a total of 101 days out of a possible 154 weekdays. During this time, GGT accumulated 14,516 miles for a daily average of 141 miles. Because of the high average operating speed, the fuel economy for GGT operations was higher than for AC Transit at 7.94 miles per kilogram hydrogen (mi/kg) or 8.97 miles per diesel gallon equivalent (mpDGE). At the end of each day, a GGT mechanic would drive the bus to Emeryville for fueling and then return the bus to the GGT facility to be prepped and parked for the next day's service. There were several days when the bus was available but not used because of a lack of trained drivers. To address this issue, GGT has worked with AC Transit to train more drivers. There were no roadcalls during this period.

GGT needed to inform its riders about the demonstration project to avoid causing confusion, especially with boarding a bus that looked very different from the rest of its fleet. To prepare its customer base for the demonstration, GGT did some outreach on its website. GGT reports that the demonstration is going well and the riders like the buses. The main complaint has been about the seats. Because much of its service is longer-distance commutes into the city, GGT equips its buses with motor coach-type seating. The ZEBA buses have less-padded seats typical of most transit buses. The GGT drivers are receptive of the new technology, but they have noted decreased hill climbing power compared to the diesel buses and the comparatively stiff riding suspension of the FCEBs. Figure 13 shows one of the FCEBs in GGT service on the Golden Gate Bridge.

Figure 13. ZEBA bus in GGT service travels over the Golden Gate Bridge. ***Photo courtesy of GGT***

Progress Toward Meeting Technical Targets for Fuel Cell Systems

Increasing the durability and reliability of the fuel cell system to meet transit requirements continues to be a key challenge. FTA life cycle requirements for a full size bus are 12 years or 500,000 miles. Because transit agencies typically rebuild the diesel engines at approximately mid-life, a fuel cell power plant (FCPP) should be able to operate for at least half the life of the bus. FTA has set an early performance target of 4–6 years (or 20,000–30,000 hours) durability for the fuel cell propulsion system. The ZEBA buses continue to demonstrate some of the highest hours for FCEBs in service. As mentioned in the previous report, three of the FCPPs in the ZEBA buses had accumulated hours in service prior to being installed in the new buses. Those three FCPPs continue to operate and accumulate hours in service.

Figure 14 shows the cumulative hours on each FCPP through October 2013. The top FCPP has now achieved more than 15,000 hours of operation without major repair or cell replacements. This is the highest number of FCPP hours documented for a FCEB and moves the technology further toward meeting the target of 25,000 hours. Another FCPP has surpassed 11,000 hours and a third has surpassed 9,700 hours. Table 4 provides the total hours accumulated on each of the FCPPs since they were installed.

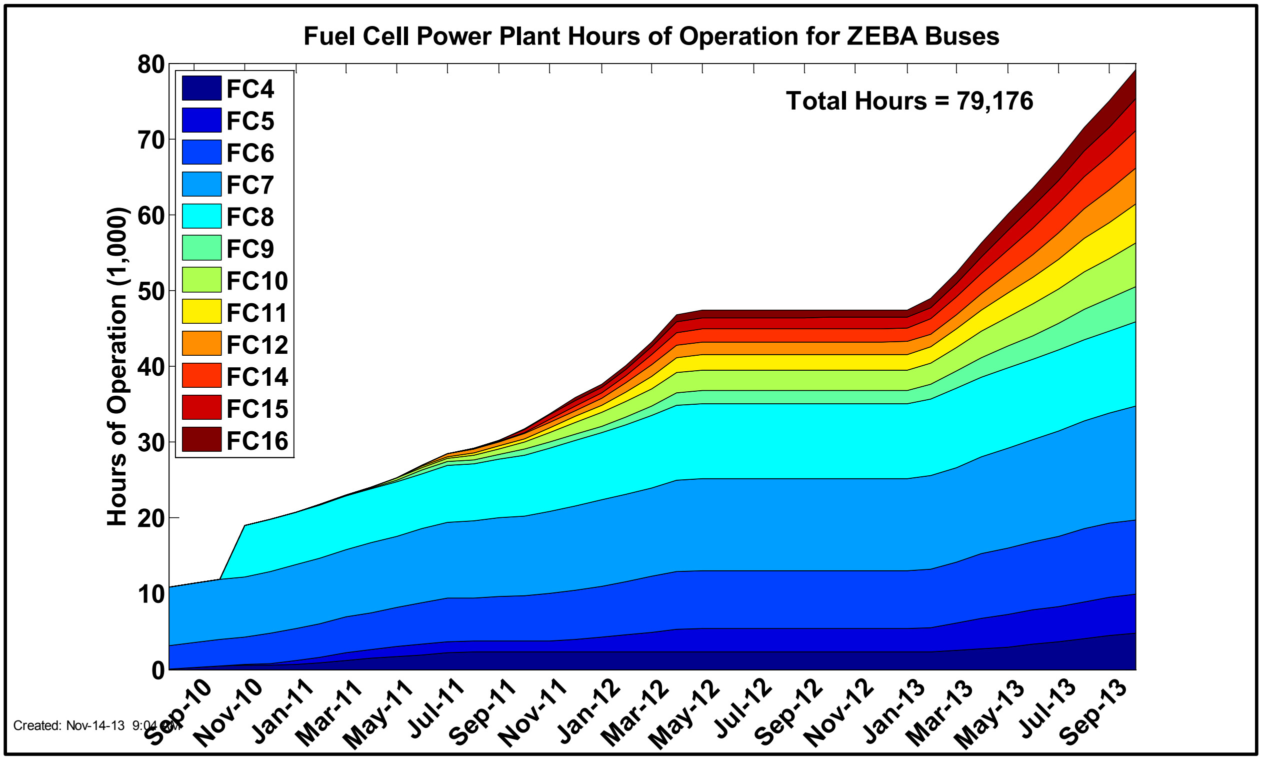

Figure 14. Cumulative FCPP hours on the ZEBA buses

Table 4. Total Hours Accumulated on the FCPPs

Bus Number	Date of FCPP Installation	FCPP Hours at Installation	Total Hours Through October 2013
FC4	8/22/10	59	4,744
FC5	8/20/10	20	5,143
FC6	8/1/10	2,915	9,789
FC7	8/29/10	7,727	15,029
FC8	11/15/10	6,806	11,201
FC9	2/22/11	34	4,647
FC10	3/1/11	20	5,696
FC11	5/5/11	0	5,119
FC12	5/12/11	0	4,785
FC14	8/17/11	0	4,981
FC15	8/15/11	0	3,590
FC16	9/30/11	0	3,866

Challenges

Advanced technology demonstrations typically experience challenges and issues that need to be resolved. A few of the issues and status of resolution are provided here.

- **Parts supply**—AC Transit has had issues with bus components that have a long lead time for delivery, in some cases because they come from outside the United States. These components were not typically stocked and were only ordered when needed. This has changed over time as the project partners have learned what should be kept on hand. While convenient, stocking these components can also be challenging. In part this is because the cost for advanced technologies can be high, but also because warranties on a component often begin when it is shipped, and the warranty can run out before it is installed. Although the parts supply issues have improved, they have not yet been completely resolved.
- **Changing project partners**—The current economic climate has resulted in changing players within the FCEB market. Over the years, several companies have left the market through restructuring or bankruptcy. This makes conducting long-term demonstrations a challenge when the partners no longer provide technical support or produce parts needed for repair. During the last year, United Technologies made a business decision to sell its fuel cell division, UTC Power. Because UTC Power was one of the major players in the bus market, this had ramifications for several FCEB demonstrations, especially the ZEBA project. ClearEdge Power, a relatively small company in the fuel cell market, purchased UTC Power, which included the production capability for transit bus power plants as well as the stationary power business. After completing the acquisition, ClearEdge Power announced its intent to focus on the stationary power business and to sell the transit bus power plant portion of the company. This has resulted in some uncertainty for the project. A California technology company, US Hybrid, has stepped in to take on the UTC Power projects that were awarded under the National Fuel Cell Bus Program, including support to the ZEBA demonstration. US Hybrid was founded in 1999 and specializes in design and manufacture of integrated power conversion components for electric propulsion systems in medium- and heavy-duty vehicles.
- **Increasing service**—AC Transit plans to increase service of the FCEBs to cover additional routes and weekends. The agency has trained all operators at the Emeryville division on the FCEBs. At the beginning of the demonstration, AC Transit defined specific route blocks for the FCEBs. The agency selected routes that were sufficient in length to test the buses but did not go over the expected range. AC Transit also selected routes that had higher passenger loads and could provide maximum public exposure to the technology. There was also a concern about the height of the buses and potential issues with low tree branches on some routes. As the buses are rolled out to more routes, the agency will need to address these potential issues.
- **Software and controls—**Systems integration and optimization is still one of the major challenges for commercializing FCEBs. AC Transit continues to work with its manufacturer partners to optimize and update the hybrid system to eliminate issues and increase performance. The buses have had several software changes to address issues with the hybrid system and energy storage. Some of the early issues were intermittent,

which made troubleshooting difficult. The battery manufacturer, EnerDel, has updated all the electronics for the energy storage system.

- **Costs—**At this point in the development of FCEB technology, costs are still high. Capital costs of the buses have dropped, but they are still an order of magnitude higher than conventional diesel costs. Operating costs for the FCEBs are also higher, due to several factors. Maintenance staff is still learning the new technology and spends more time troubleshooting advanced systems. AC Transit has purchased extended warranty agreements with the manufacturers that add to the cost.

Evaluation Results

The results presented in this section cover data from September 2011 through October 2013, with a focus on the most recent data beginning in March 2013. The time period when the hydrogen station was out of service is highlighted in the graphs. The station was fully operational in January 2013, but the buses were placed back in service over a several-week period during February. Because March was the first full month of service for the entire fleet, the data period for the report begins with this month. From March through October 2013, the FCEBs have operated 259,171 miles over 30,192 hours of fuel cell operation. This indicates an overall operational speed of 8.6 mph.

The diesel baseline buses include three Van Hool buses that were planned to operate on similar route blocks as the 12 FCEBs. As mentioned previously, NREL has begun collecting data on a new fleet of Gillig buses at AC Transit. These buses were placed into service in mid-May. The report data period begins with June because it was the first full month of service for the buses.

In the last report, NREL noted that fuel cell bus FC4 had been out of service for an extended period of time. This bus was fully repaired during the station downtime period and has been operating since the fleet was placed back into service. Fuel cell bus FC8 has experienced drive system issues that have proved difficult to diagnose. As the data indicate, this bus has been out of service for about half the data period.

Route Assignments

The FCEBs have been operating from AC Transit's Emeryville Division for the entire evaluation period presented here. AC Transit operates the fuel cell and Van Hool diesel study buses on a set of route blocks on the 18 and 51B local routes, which include weekday and weekend service. The average operating speed for the buses is around 10.6 mph for Route 18 and around 8.7 mph for Route 51B. The overall average speed is 9.6 mph for the route blocks assigned as part of this demonstration. Based on availability, the buses are randomly dispatched on these assigned route blocks. AC Transit has recently increased service of the FCEBs to include most routes out of Emeryville, but the FCEBs will not be operated on any commuter routes such as Transbay service. During the data period the FCEBs' operation time was roughly split between the 18 and 51B routes. Although the buses were made available to other routes beginning in the June/July timeframe, the operators have run the buses primarily on the original designated routes.

The three Van Hool baseline buses were originally limited to the same route blocks as the FCEBs, but over time they have been operated on a wider selection of routes. During the data period, these buses were used on Route 76 for 45% of the time and Route 72 for 18% of the time. The Gillig baseline buses have been operated primarily on Route 72 (45%), Route 18 (15%), and Route 10 (14%). The overall average speed for the depot is 12.45 mph, including the higher speed Transbay routes. The average speed for the diesel baseline buses based on their actual use is 12 mph.

Bus Use and Availability

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

Table 5 summarizes average monthly mileage for the study buses for the data period. Overall the FCEBs have achieved 34% of the usage of the Van Hool diesel buses and 41% of the usage of the Gillig diesel buses. AC Transit is ramping up service of the FCEBs; the average monthly mileage has increased over what was documented in the last report when the buses had achieved a monthly average of 1,598 miles. Figure 15 shows the average monthly mileage for the FCEBs and diesel buses since September 2011. The monthly mileage for the FCEBs shows a general upward trend and is approaching the performance target of 3,000 miles per month.

Table 5. Average Monthly Mileage (Evaluation Period)

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Average Monthly Mileage
FC4	28,631	47,948	19,317	8	2,415
FC5	31,596	52,899	21,303	8	2,663
FC6	47,729	63,846	16,117	8	2,015
FC7	45,590	66,128	20,538	8	2,567
FC8	29,528	37,669	8,141	8	1,018
FC9	16,845	40,544	23,699	8	2,962
FC10	25,449	48,343	22,894	8	2,862
FC11	18,469	43,189	24,720	8	3,090
FC12	14,891	39,841	24,950	8	3,119
FC14	17,364	45,331	27,967	8	3,496
FC15	12,601	37,538	24,937	8	3,117
FC16	11,293	35,881	24,588	8	3,074
Total Fuel Cell			***259,171***	***96***	***2,700***
1208	184,237	217,599	33,362	8	4,170
1209	192,147	220,257	28,109	8	3,514
1210	165,518	201,820	36,302	8	4,538
Total VH Diesel			***97,773***	***24***	***4,074***
1338	1,638	25,555	23,917	5	4,783
1339	1,693	26,604	24,911	5	4,982
1340	922	26,178	25,256	5	5,051
1341	1,749	27,435	25,686	5	5,137
1342	1,941	27,597	25,656	5	5,131
1343	1,970	26,920	24,950	5	4,990
1344	1,889	27,105	25,216	5	5,043
1345	1,710	23,736	22,026	5	4,405
1346	530	20,200	19,670	5	3,934
1347	1,545	13,575	12,030	5	2,406
Total Gillig Diesel			***229,318***	***50***	***4,586***

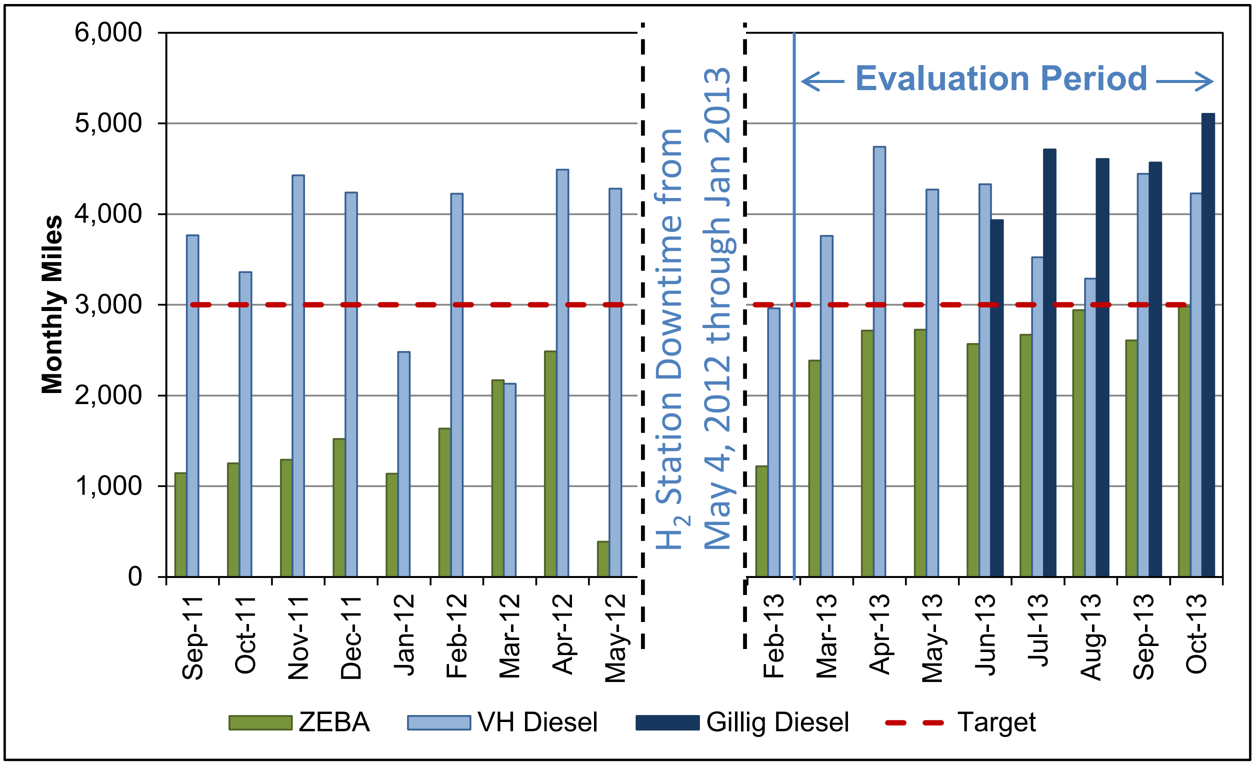

Figure 15. Monthly average miles for the ZEBA FCEB and diesel buses

Another measure of reliability is availability—the percentage of days the buses are actually available out of days that the buses are planned for operation. Figure 16 shows availability for the FCEBs (green line) and diesel buses (medium blue line for the Van Hool buses, dark blue line for the Gillig buses) from September 2011 through October 2013. The availability for the FCEBs shows a general upward trend over time with an average of 82%. This is an increase over what was reported in the second data report, when the buses were averaging 56% availability. The figure also provides an indication of the reasons for unavailability. The stacked bars for each month show the number of days the FCEBs were not available by five categories.

Table 6 summarizes the reasons for availability and unavailability for the fuel cell and diesel buses. During this reporting period, the average availability was 82% for the FCEBs, 76% for the the Van Hool diesel buses, and 84% for the Gillig buses. Bus-related maintenance (separate from the fuel cell, hybrid, and traction battery systems) is the reason for the highest percentage of unavailability for all three groups of buses.

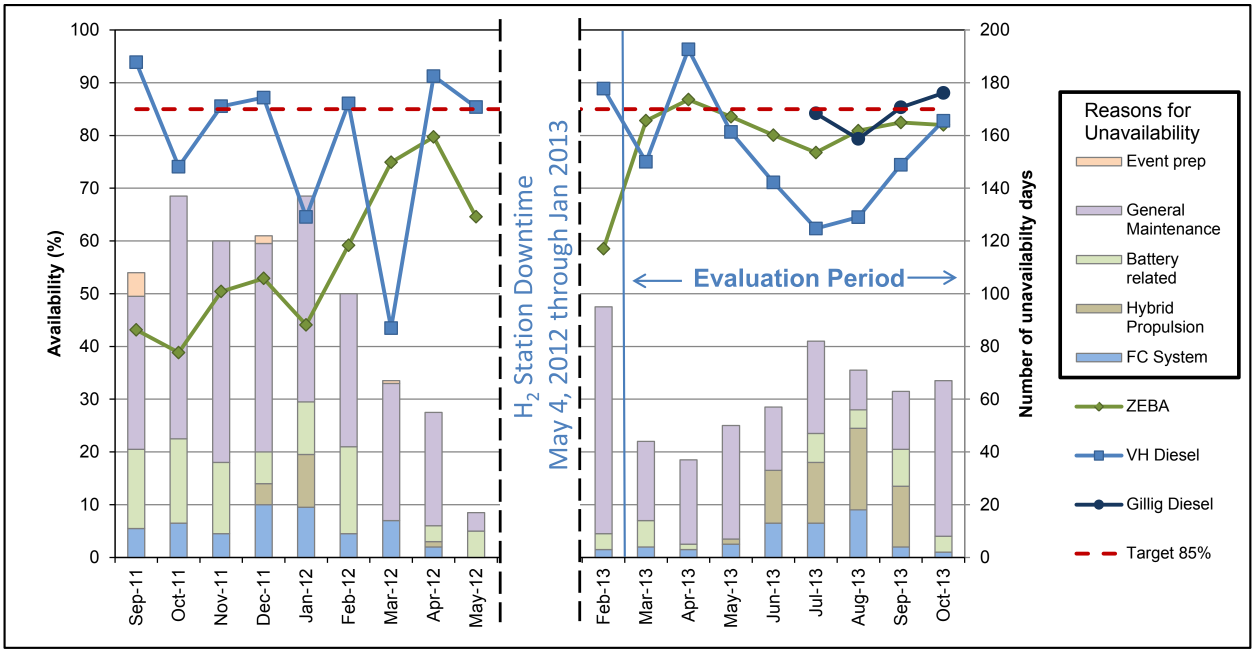

Figure 16. Availability for the ZEBA FCEB and diesel buses

Table 6. Summary of Reasons for Availability and Unavailability of Buses for Service

Category	FCEB # Days	FCEB %	VH Diesel # Days	VH Diesel %	Gillig Diesel # Days	Gillig Diesel %
Planned work days	2,582		718		1,230	
Days available	2,111	82	543	76	1,036	84
Available	**2,111**	**100**	**543**	**100**	**1,036**	**100**
On route	1,903	90	543	100	1,036	100
Event/demonstration	2	<1				
Training	18	1				
Not used	176	8				
Fueling unavailable	12	1				
Unavailable	**471**	**100**	**175**	**100**	**193**	**100**
Fuel cell propulsion	62	13				
Hybrid propulsion	99	21				
Traction battery issues	50	11				
Bus maintenance	260	55	175	100	193	100

Fuel Economy and Cost

As discussed above, hydrogen fuel is provided by a fueling station designed and constructed by Linde at AC Transit's Emeryville Division. The hydrogen is dispensed at up to 350 bar (5,000 psi). AC Transit employees perform nearly all fueling services for the hydrogen-fueled vehicles. NREL collects fueling records from two sources: electronic fueling records from Linde and manual logs from AC Transit. These records are merged for the analysis. There have been a few issues with the mass flow meter at the station that resulted in missing or inaccurate measurements. During March and April 2012, AC Transit and Linde were working to increase the hydrogen flow rate into the buses, which caused some issues with the ability to accurately record the mass amounts. During this time period, the calculated fuel economy was higher than in previous months. Because of this issue, NREL has removed the three affected months (April 2012, May 2012, and February 2013) from the overall average fuel economy calculations.

Table 7 shows hydrogen and diesel fuel consumption and fuel economy for the study buses during the reporting period. Overall, the FCEBs averaged 6.43 mi/kg of hydrogen, which equates to 7.26 mpDGE. The energy conversion from kilograms of hydrogen to DGE appears at the end of Appendix A. (Appendix B contains the summary statistics in SI units.) These results indicate that the FCEBs have an average fuel economy that is 87% higher than that of the Van Hool diesel buses and 80% higher than that of the Gillig diesel buses.

Figure 17 shows monthly average fuel economy for the FCEBs and diesel buses in miles per DGE. The average monthly high temperature is included in the graph to track any seasonal variations in the fuel economy due to heating or cooling of the bus, which might require additional energy use. As mentioned previously, GGT began operating one of the buses in its service area in April 2013. The fuel economy for the GGT service is shown separately on the graph (orange line). The average operating speed for GGT is higher than that of AC Transit. The FCEB has averaged 7.94 mi/kg (8.97 mpDGE) during the 7-month period at GGT.

The cost of hydrogen production as dispensed during the data period was $9.08 per kg, not including the capital cost of the station. The hydrogen fuel cost per mile is $1.41. Diesel fuel cost during the reporting period was $3.04 per gallon, which calculates to $0.79 per mile for the Van Hool diesel buses and $0.75 per mile for the Gillig diesel buses.

Table 7. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (fuel base)	Hydrogen (kg)	Miles per kg	Diesel Gallon Equivalent (DGE)	Miles per DGE
FC4	18,591	3,024	6.15	2,676	6.95
FC5	20,616	2,703	7.63	2,392	8.62
FC6	15,227	2,434	6.26	2,154	7.07
FC7	19,985	3,343	5.98	2,959	6.75
FC8	7,608	1,419	5.36	1,256	6.06
FC9	22,289	3,306	6.74	2,926	7.62
FC10	21,658	3,527	6.14	3,121	6.94
FC11	23,597	3,856	6.12	3,413	6.91
FC12	23,709	3,640	6.51	3,221	7.36
FC14	27,167	3,841	7.07	3,399	7.99
FC15	23,966	3,704	6.47	3,278	7.31
FC16	23,971	3,849	6.23	3,406	7.04
FCEB Total	***248,384***	***38,647***	***6.43***	***34,201***	***7.26***
1208	32,859			8,348	3.94
1209	26,193			7,298	3.59
1210	34,619			9,147	3.78
VH Diesel Total	***93,670***			***24,793***	***3.78***
1338	15,447			4,055	3.81
1339	18,376			4,408	4.17
1340	16,222			4,116	3.94
1341	16,081			4,052	3.97
1342	18,442			4,533	4.07
1343	17,753			4,404	4.03
1344	19,045			4,523	4.21
1345	15,548			3,747	4.15
1346	14,367			3,525	4.08
1347	4,696			1,284	3.66
Gillig Diesel Total	***155,977***			***38,647***	***4.04***

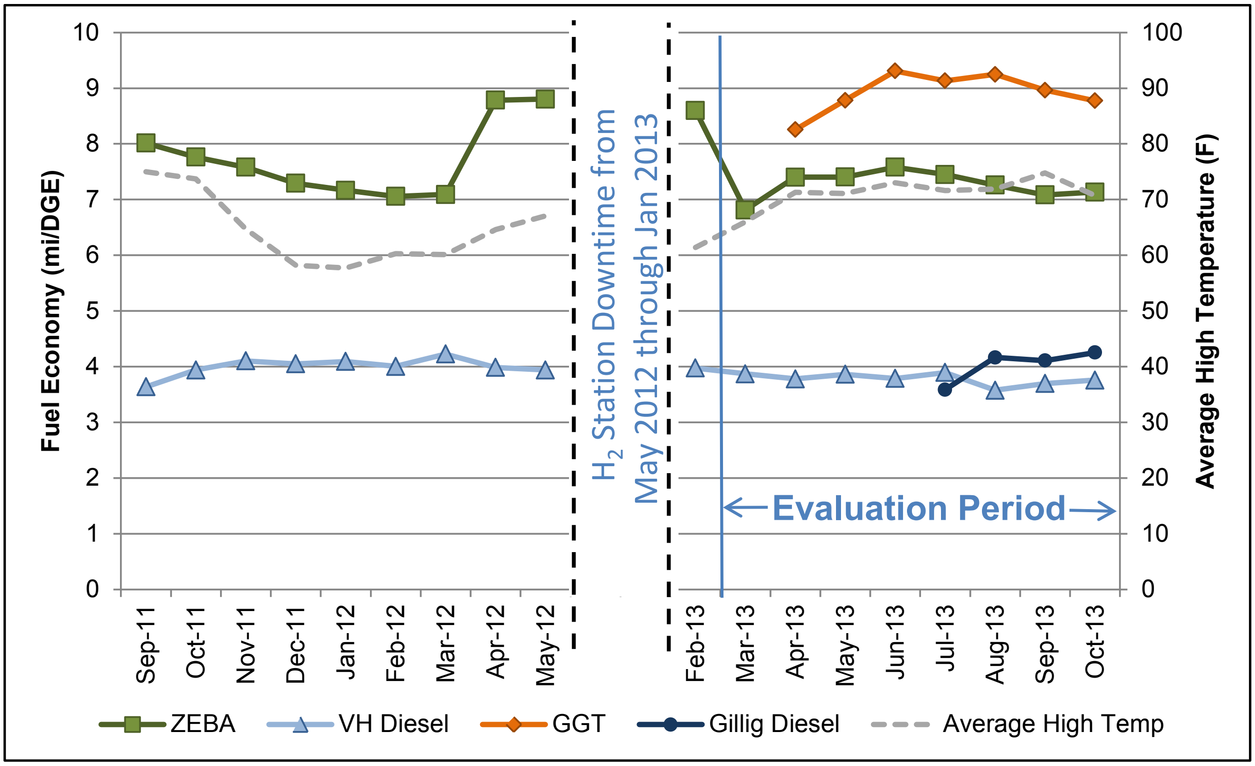

Figure 17. Average fuel economy for the fuel cell and diesel buses (evaluation period)

Bus Range

NREL calculates the effective bus range based on the useful fuel (95% of capacity) and the average fuel economy. Using the current fuel economy, the maximum range is calculated to be 260 miles. AC Transit reports that the real-world range is lower than this maximum. The buses are equipped with a low fuel indicator light that will occasionally illuminate late in the day. This indicator is the same as the low fuel light on many cars and doesn't necessarily mean the bus is out of fuel. Some drivers have expressed that they are uncomfortable when the low fuel light comes on. This could be addressed with more training to familiarize the operators with the way the system operates and how much range is left when the light illuminates. To show how the buses are actually being used, NREL calculated the miles between each fueling. Because transit agencies fuel buses each night, regardless of how low the fuel level is, this does not necessarily represent the limit of the total range. Figure 18 presents a histogram of the miles between fuelings for the ZEBA buses. This shows that AC Transit typically schedules the buses to operate from 100 to 200 miles between fuelings—66% of the records fall within those bins.

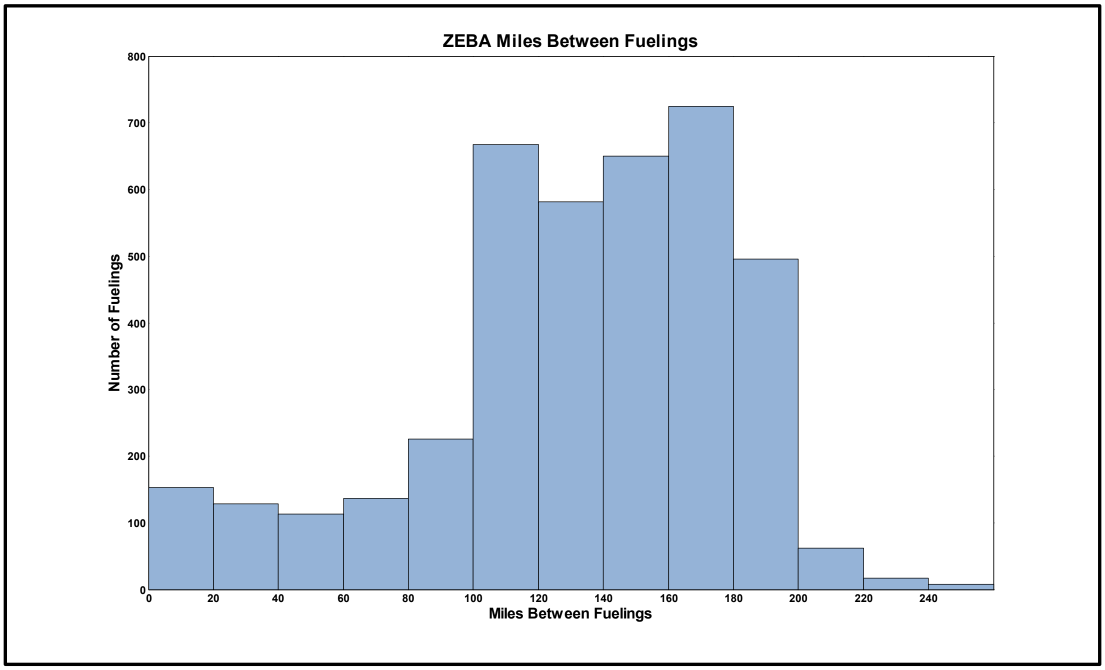

Figure 18. Miles between fuelings histogram

Maintenance Analysis

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 AC Transit. This section first covers total maintenance costs and then maintenance costs by bus system. Warranty costs are not included in the cost-per-mile calculations. As mentioned previously, the Van Hool buses are no longer under warranty, which has resulted in increased maintenance costs since the last report.

Total Maintenance Costs

Total maintenance costs include the price of parts and labor rates at $50 per hour. Cost per mile is calculated as follows:

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

Table 8 shows total maintenance costs for the fuel cell and diesel buses. Scheduled and unscheduled maintenance cost per mile is provided for each bus and study group of buses. Note that the fuel cell bus maintenance is supported by one of ClearEdge Power's engineers at AC Transit. The labor hours for this engineer are not included in the data set. AC Transit has two mechanics/trainers assigned to maintain the FCEBs and provide training and a supervisor for the program (from a maintenance perspective). In addition, AC Transit has resources from this program for cleaning, fueling, and performing body work and painting for the FCEB fleet.

During the reporting period, the FCEBs had a 35% lower cost per mile for maintenance when compared to the Van Hool diesel buses. The Van Hool buses have accumulated more than 4 times the miles of the FCEBs and are beginning to see increased costs typical of buses during the mid-life period. The FCEB maintenance costs were three times higher than the maintenance costs of the new Gillig diesel buses.

Table 8. Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Total Cost per Mile ($)	Scheduled Cost per Mile ($)	Unscheduled Cost per Mile ($)
FC4	19,317	21,047.81	263.2	1.77	0.14	1.63
FC5	21,303	686.63	150.2	0.38	0.17	0.22
FC6	16,117	1,452.33	200.2	0.71	0.14	0.58
FC7	20,538	7,363.19	296.3	1.08	0.16	0.92
FC8	8,141	1,884.26	265.9	1.86	0.14	1.72
FC9	23,699	741.48	206.7	0.47	0.16	0.31
FC10	22,894	1,105.81	215.2	0.52	0.14	0.38
FC11	24,720	5,457.60	175.0	0.57	0.17	0.41
FC12	24,950	1,084.89	191.2	0.43	0.12	0.30
FC14	27,967	1,771.98	207.3	0.43	0.20	0.24
FC15	24,937	2,676.28	178.2	0.46	0.14	0.32
FC16	24,588	1,371.33	185.1	0.43	0.15	0.28
Total Fuel Cell	***259,171***	***46,643.60***	***2,534.4***	***0.67***	***0.15***	***0.52***
1208	33,362	13,817.56	579.9	1.28	0.22	1.06
1209	28,109	13,454.57	354.8	1.11	0.18	0.93
1210	36,302	11,440.01	310.0	0.74	0.11	0.64
Total VH Diesel	***97,773***	***38,712.14***	***1,244.7***	***1.03***	***0.16***	***0.87***
1338	23,917	770.85	86.2	0.21	0.10	0.11
1339	24,911	701.58	85.7	0.20	0.11	0.10
1340	25,256	640.76	80.2	0.19	0.10	0.09
1341	25,686	667.66	67.4	0.16	0.10	0.06
1342	25,656	1,141.18	81.1	0.21	0.10	0.10
1343	24,950	826.56	80.4	0.20	0.10	0.09
1344	25,216	809.35	62.2	0.16	0.10	0.06
1345	22,026	537.97	84.9	0.22	0.15	0.08
1346	19,670	2,526.85	83.5	0.35	0.11	0.23
1347	12,030	243.33	94.2	0.41	0.13	0.28
Total Gillig Diesel	***229,318***	***8,866.09***	***805.8***	***0.21***	***0.11***	***0.11***

Maintenance Costs Categorized by System

Table 9 shows maintenance costs by vehicle system and bus study group (without warranty costs). The vehicle systems shown in the table are as follows:

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

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

Table 9. Maintenance Cost per Mile by System (Evaluation Period)

System	FCEB		Van Hool Diesel		Gillig Diesel	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Propulsion-related	0.35	52	0.44	43	0.05	*23*
Cab, body, and accessories	0.14	21	0.22	21	0.09	*43*
PMI	0.09	13	0.08	7	0.07	*30*
Brakes	0.01	2	0.15	14	0.00	*0*
Frame, steering, and suspension	0.02	3	0.02	2	0.00	*2*
HVAC	0.02	3	0.07	7	0.00	*1*
Lighting	0.01	1	0.01	1	0.00	*0*
Air, general	0.03	4	0.05	5	0.00	*0*
Axles, wheels, and drive shaft	0.00	0	0.00	0	0.00	*0*
Tires	0.00	0	0.00	0	0.00	*0*
Total	***0.67***	*100*	***1.03***	*100*	***0.21***	*100*

The systems with the highest percentage of maintenance costs for the fuel cell buses were propulsion-related; cab, body, and accessories; and PMI. For the Van Hool diesel buses the systems with the highest percentage of maintenance costs were cab, body, and accessories; propulsion-related; and brakes. The Gillig diesel bus systems with the highest percentage of maintenance costs were cab, body, and accessories; PMI; and propulsion-related.

Propulsion-Related Maintenance Costs

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

Table 10 shows the propulsion-related system repairs by category for the three study groups during the reporting period. During the data period, the propulsion-related maintenance costs for the FCEBs were 21% lower than that of the Van Hool diesel buses. When compared to the new Gillig buses, the FCEBs' propulsion-related maintenance costs were 7 times higher.

Electric propulsion system maintenance costs accounted for 42% of the total propulsion cost for the FCEBs. Power plant system repairs accounted for nearly 32% of the total propulsion system costs. This is a clear indication of the increased amount of FCEB maintenance being handled by the AC Transit mechanics. As mentioned above, ClearEdge Power has an engineer on site to supervise and complete maintenance of the fuel cell power system and related systems; however, the AC Transit mechanics have taken on more of the work. The majority of the propulsion costs for the Van Hool diesel buses were for the fuel system and power plant. The majority of the propulsion costs for the Gillig diesel buses were for the power plant.

Table 10. Propulsion-Related Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	Fuel Cell	Van Hool Diesel	Gillig Diesel
Mileage	259,171	97,773	229,318
Total Propulsion-Related Systems (Roll-up)			
Parts cost ($)	38,560.60	15,765.75	4,506.53
Labor hours	1,038.6	553.2	136.8
Total cost ($)	90,492.10	43,425.75	11,344.03
Total cost ($) per mile	**0.35**	**0.44**	**0.05**
Exhaust System Repairs			
Parts cost ($)	0.00	2,200.06	0.00
Labor hours	0.0	44.2	0.0
Total cost ($)	0.00	4,410.06	0.00
Total cost ($) per mile	**0.00**	**0.05**	**0.00**
Fuel System Repairs			
Parts cost ($)	26.75	2,241.41	1,028.30
Labor hours	81.8	219.7	19.9
Total cost ($)	4,118.25	13,226.41	2,023.30
Total cost ($) per mile	**0.02**	**0.14**	**0.01**
Power Plant System Repairs			
Parts cost ($)	9,734.34	2,646.97	1,659.84
Labor hours	391.0	125.5	52.2
Total cost ($)	29,282.84	8,921.97	4,269.84
Total cost ($) per mile	**0.11**	**0.09**	**0.02**
Electric Motor and Propulsion Repairs			
Parts cost ($)	19,571.30	0.00	0.00
Labor hours	377.5	0.0	0.0
Total cost ($)	38,443.80	0.00	0.00
Total cost ($) per mile	**0.15**	**0.00**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)			
Parts cost ($)	4,177.86	1,790.55	211.00
Labor hours	98.1	28.5	30.8
Total cost ($)	9,083.36	3,215.55	1,751.00
Total cost ($) per mile	**0.04**	**0.03**	**0.01**
Air Intake System Repairs			
Parts cost ($)	3205.41	1,937.43	816.66
Labor hours	45.0	40.2	3.8
Total cost ($)	5,455.41	3,947.43	1,006.66
Total cost ($) per mile	**0.02**	**0.04**	**0.00**
Cooling System Repairs			
Parts cost ($)	3,933.87	3,740.60	362.16
Labor hours	89.7	53.1	10.05
Total cost ($)	8,416.87	6,395.60	864.66
Total cost ($) per mile	**0.03**	**0.07**	**0.00**
Transmission Repairs			
Parts cost ($)	0.00	0.00	261.27
Labor hours	0.0	2.2	19.8
Total cost ($)	0.00	110.00	1,251.27
Total cost ($) per mile	**0.00**	**0.00**	**0.01**

Additional Project Costs

AC Transit has resources in its project budget to cover FCEB costs that fall outside of the typical maintenance costs reported above. The following three activities are primarily handled by AC Transit's maintenance staff assigned to the FCEBs:

- **Research and training**: In the early stages of implementing a new technology, it takes time for maintenance staff to learn how to maintain and troubleshoot problems with advanced components and systems. AC Transit tracks these costs as "research and training." These costs drop over time as the maintenance staff becomes familiar with the technology.
- **Shuttling FCEBs between depots**: AC Transit is currently operating the buses out of the Emeryville depot; however, the facility does not have a maintenance bay equipped to allow work on a hydrogen-fueled bus. Maintenance that can't be conducted in the yard requires maintenance staff to shuttle the buses to the Oakland depot where there is a maintenance bay outfitted for the FCEBs. This adds to the labor costs for the buses and is tracked separately in the work orders. The agency has funds to retrofit one of the Emeryville maintenance bays similar to what was done at the Oakland depot. Once the retrofit is complete, this activity will no longer be necessary.
- **Fueling and cleaning**: Currently, AC Transit has maintenance staff assigned specifically to the FCEBs for fueling and cleaning the buses. These activities for buses at a depot are typically handled by different staff during the evenings when all buses are prepared for the next morning pullout. Eventually the FCEBs will be worked into the overall process and this cost will not be specifically attributed to the project.

These costs are considered non-recurring costs for the FCEBs; however, they add to the current cost per mile of the ZEBA buses.

Table 11 shows the breakdown of these costs and how they affect the total cost per mile of the project. The costs during the station downtime are shown separately because the buses were not operating and therefore not accumulating miles.

Table 11. Maintenance Costs Including Non-Recurring Labor

	Total Miles	Parts ($)	Labor Hours	Total Cost	Cost per Mile
Station downtime period (May 2012 through Feb 2013)					
Maintenance	19,296	10,511	1,022	61,595.02	3.19
Shuttling FCEBs			118.5	5,925.00	0.31
Research/training			1,703	85,169.00	4.41
Fueling and cleaning			908	45,411.50	2.35
Total	***19,296***	***10,511***	***3,752***	***198,100.52***	***10.27***
Evaluation period (Mar 2013 through Oct 2013)					
Maintenance	259,171	46,644	2,534	173,362.60	0.67
Shuttling FCEBs			211	10,536.50	0.04
Research/training			322	16,099.50	0.06
Fueling and cleaning			75	3,740.00	0.01
Total	***259,171***	***46,644***	***3,142***	***203,738.60***	***0.79***

Roadcall Analysis

A roadcall or revenue vehicle system failure (as named in the National Transit Database[16]) is defined as a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule.[17] If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a roadcall. The analysis described here includes only roadcalls that were caused by "chargeable" failures. Chargeable roadcalls include systems that can physically disable the bus from operating on route, such as interlocks (doors, air system), engine, or things that are deemed to be safety issues if operation of the bus continues. They do not include roadcalls for things such as problems with radios or destination signs.

Table 12 provides the miles between roadcall (MBRC) for the FCEBs and diesel buses categorized by bus roadcalls and propulsion-related-only roadcalls. The fuel-cell-related roadcalls and MBRC are included for the FCEBs. The FCEB MBRC for each category has increased since the buses went back into service. Figure 19 presents the cumulative MBRC by category for the FCEBs since September 2011. The MBRC is showing a steady increase over time.

Table 12. Roadcalls and MBRC

	FCEB Total	FCEB Evaluation Period	Van Hool Diesel Total	Van Hool Diesel Evaluation Period	Gillig Diesel Evaluation Period[a]
Dates	9/11–10/13	3/13–10/13	9/11–10/13	3/13–10/13	3/13–10/13
Mileage	425,591	259,171	179,424	97,773	229,318
Bus roadcalls	126	46	71	38	54
Bus MBRC	3,378	5,634	2,527	2,573	4,247
Propulsion roadcalls	80	28	32	17	18
Propulsion MBRC	5,320	9,256	5,607	5,751	12,740
Fuel cell roadcalls	31	12			
Fuel cell MBRC	13,729	21,598			

[a] The Gillig buses were placed into service in May 2013; therefore the total and evaluation period are the same.

[16] National Transit Database website: www.ntdprogram.gov/ntdprogram/.
[17] AC Transit defines a significant delay as 6 or more minutes.

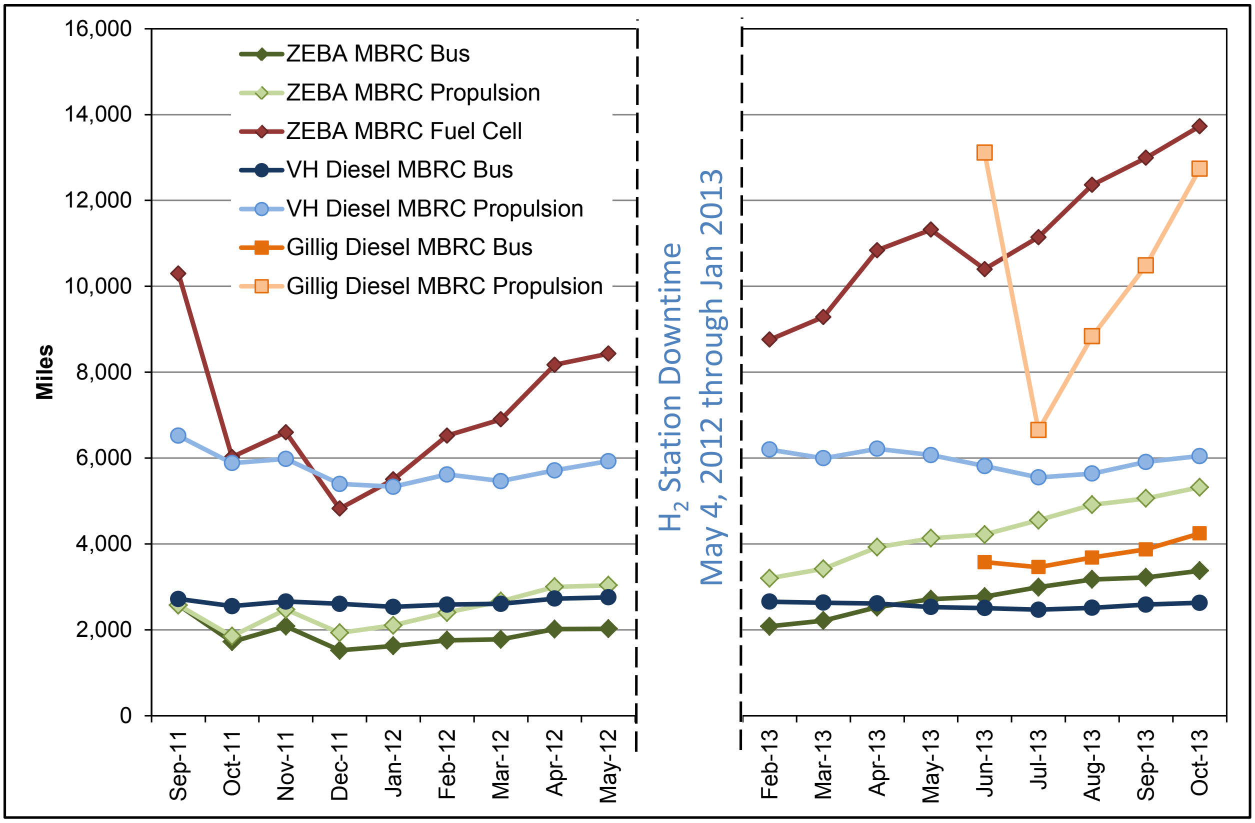

Figure 19. Cumulative MBRC for the FCEBs

What's Next for ZEBA

The plans for the ZEBA demonstration are to continue operating out of the Emeryville Division while the Oakland station is constructed. Once that station is operational, each division is to operate six buses. GGT will continue to operate one or two buses in its service area. SamTrans and VTA will explore the potential to operate an FCEB in their service areas once the Oakland station is fully operational.

AC Transit was awarded a grant in the final round of the National Fuel Cell Bus Program funding. Managed through one of the non-profit consortia—the Center for Transportation and the Environment—the $1.8 million award will provide funds to support the continued operation of the FCEB fleet.

NREL will continue to evaluate the buses at AC Transit and will collect data and experience from the other operators once they put the buses in service. VTA and GGT also operate diesel hybrid-electric buses. NREL is planning to collect data on the hybrid buses to compare the fuel efficiency with that of FCEBs in similar service. The next report is expected in fall 2014.

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References and Related Reports

All NREL hydrogen and fuel cell-related evaluation reports can be downloaded from the following website: www.nrel.gov/hydrogen/proj_fc_bus_eval.html.

AC Transit

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Appendix A: Fleet Summary Statistics

Fleet Summary Statistics: ZEBA FCEB and Diesel Bus Groups and Evaluation Periods

Fleet Operations and Economics

	ZEBA Early Service 9/11-4/12	ZEBA Station Downtime Period 5/12-2/13	ZEBA Evaluation Period 3/13-10/13	Van Hool Diesel Early Service 9/11-4/12	Van Hool Diesel Evaluation Period 3/13-10/13	Gillig Diesel Evaluation Period 7/13-10/13
Number of vehicles	12	12	12	3	3	10
Period used for fuel and oil op analysis	9/11-4/12	5/12-2/13	3/13-10/13	9/11-4/12	3/13-10/13	7/13-10/13
Total number of months in period	8	10	8	8	8	4
Fuel and oil analysis base fleet mileage	120,355	16,281	248,384	82,098	67,787	155,977
Period used for maintenance op analysis	9/11-4/12	5/12-2/13	3/13-10/13	9/11-4/12	3/13-10/13	6/13-10/13
Total number of months in period	8	10	8	8	8	5
Maintenance analysis base fleet mileage	147,007	19,296	259,171	83,599	97,773	229,318
Average monthly mileage per vehicle	1,598	—	2,700	3,635	4,074	4,670
Availability	56%	—	82%	77%	76%	84%
Fleet fuel usage (H_2 in kg, diesel in gallons)	18,016.0	2,125.2	38,646.8	20,509.3	17,594.9	38,646.6
Roadcalls	73	—	28	24	16	54
Overall MBRC	2,014	—	9,256	2,117	6,111	4,247
Propulsion roadcalls	49	—	19	14	9	18
Propulsion MBRC	3,000	—	13,641	3,629	10,864	12,740
Fleet miles/kg hydrogen (1.13 kg H_2)	6.68	7.66	6.43	—	—	—
Representative fleet MPG (energy equiv)	7.55	8.66	7.26	4.00	3.85	4.04
Hydrogen cost per kg	9.34	8.47	9.08	—	—	—
Diesel cost per gallon	—	—	—	3.18	3.04	3.04
Fuel cost per mile	**1.40**	**1.11**	**1.41**	**0.79**	**0.79**	**0.75**
Total scheduled repair cost per mile	0.26	0.08	0.15	0.13	0.16	0.11
Total unscheduled repair cost per mile	1.05	3.11	0.52	0.65	0.87	0.11
Total maintenance cost per mile	**1.31**	**3.19**	**0.67**	**0.79**	**1.03**	**0.21**
Total operating cost per mile	***2.71***	***4.30***	***2.08***	***1.58***	***1.82***	***0.97***

Maintenance Costs

	ZEBA Early Service 9/11-4/12	ZEBA Station Downtime Period 5/12-2/13	ZEBA Evaluation Period 3/13-10/13	Van Hool Diesel Early Service 9/11-4/12	Van Hool Diesel Evaluation Period 3/13-10/13	Gillig Diesel Evaluation Period 7/13-10/13
Fleet mileage	147,007	19,296	259,171	83,599	97,773	229,318
Total parts cost	31,727.9	10,511.0	46,643.6	23,520.4	38,712.1	8,866.1
Total labor hours	3,219.70	1021.7	2534.4	837.8	1244.7	805.8
Average labor cost (@ $50.00 per hour)	160,985.00	51,084.00	126,719.00	41,890.50	62,232.50	40,287.50
Total maintenance cost	192,712.88	61,595.02	173,362.60	65,410.94	100,944.64	49,153.59
Total maintenance cost per bus	16,059.41	5,132.92	14,446.88	5,450.91	33,648.21	16,384.53
Total maintenance cost per mile	***1.31***	***3.19***	***0.67***	***0.78***	***1.03***	***0.21***

Breakdown of Maintenance Costs by Vehicle System

	ZEBA Early Service 9/11-4/12	ZEBA Station Downtime Period 5/12-2/13	ZEBA Evaluation Period 3/13-10/13	Van Hool Diesel Early Service 9/11-4/12	Van Hool Diesel Evaluation Period 3/13-10/13	Gillig Diesel Evaluation Period 7/13-10/13
Fleet mileage	147,007	19,296	259,171	83,599	97,773	229,318
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)						
Parts cost	5,957.71	3414.61	38,560.60	8,142.90	15,765.75	4,506.53
Labor hours	1,012.7	670.3	1,038.6	201.9	553.2	136.8
Average labor cost	50,633.50	33,516.50	51,931.50	10,092.50	27,660.00	6,837.50
Total cost (for system)	56,591.21	36,931.11	90,492.10	18,235.40	43,425.75	11,344.03
Total cost (for system) per bus	4,715.93	3,077.59	7,541.01	6,078.47	14,475.25	1,134.40
Total cost (for system) per mile	**0.38**	**1.91**	**0.35**	**0.22**	**0.44**	**0.05**
Exhaust System Repairs (ATA VMRS 43)						
Parts cost	0.00	0	0.00	217.32	2,200.06	0
Labor hours	0.0	0.0	0.0	3.4	44.2	0
Average labor cost	0.00	0.00	0.00	170.00	2,210.00	0.00
Total cost (for system)	0.00	0.00	0.00	387.32	4,410.06	0.00
Total cost (for system) per bus	0.00	0.00	0.00	129.11	1,470.02	0.00
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**	**0.05**	**0.00**
Fuel System Repairs (ATA VMRS 44)						
Parts cost	15.47	0	26.75	692.04	2,241.41	1,028.30
Labor hours	166.7	30.4	81.8	9.6	219.7	19.9
Average labor cost	8,335.00	1,520.50	4,091.50	480.00	10,985.00	995.00
Total cost (for system)	8,350.47	1,520.50	4,118.25	1,172.04	13,226.41	2,023.30
Total cost (for system) per bus	695.87	126.71	343.19	390.68	4,408.80	202.33
Total cost (for system) per mile	**0.06**	**0.08**	**0.02**	**0.01**	**0.14**	**0.01**
Power Plant (Engine) Repairs (ATA VMRS 45)						
Parts cost	260.89	312.5516	9,734.34	3,767.42	2,646.97	1659.84
Labor hours	204.0	210.2	391.0	100.0	125.5	52.2
Average labor cost	10,200.50	10,510.50	19,548.50	5,000.00	6,275.00	2,610.00
Total cost (for system)	10,461.39	10,823.05	29,282.84	8,767.42	8,921.97	4,269.84
Total cost (for system) per bus	871.78	901.92	2,440.24	2,922.47	2,973.99	426.98
Total cost (for system) per mile	**0.07**	**0.56**	**0.11**	**0.10**	**0.09**	**0.02**
Electric Propulsion Repairs (ATA VMRS 46)						
Parts cost	1,251.77	0	19,571.30	0.00	0.00	0
Labor hours	458.5	329.3	377.5	0.0	0.0	0
Average labor cost	22,924.00	16,463.00	18,872.50	0.00	0.00	0.00
Total cost (for system)	24,175.77	16,463.00	38,443.80	0.00	0.00	0.00
Total cost (for system) per bus	2,014.65	1,371.92	3,203.65	0.00	0.00	0.00
Total cost (for system) per mile	**0.16**	**0.85**	**0.15**	**0.00**	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	ZEBA Early Service 9/11-4/12	ZEBA Station Downtime Period 5/12-2/13	ZEBA Evaluation Period 3/13-10/13	Van Hool Diesel Early Service 9/11-4/12	Van Hool Diesel Evaluation Period 3/13-10/13	Gillig Diesel Evaluation Period 7/13-10/13
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)						
Parts cost	1,747.91	2623.98	2,088.93	51.63	1,790.55	211.00
Labor hours	81.3	46.7	53.7	20.7	28.5	30.8
Average labor cost	4,064.50	2,337.00	2,686.00	1,032.50	1,425.00	1,540.00
Total cost (for system)	5,812.41	4,960.98	4,774.93	1,084.13	3,215.55	1,751.00
Total cost (for system) per bus	484.37	413.42	397.91	361.38	1,071.85	175.10
Total cost (for system) per mile	**0.04**	**0.26**	**0.02**	**0.01**	**0.03**	**0.01**
Air Intake System Repairs (ATA VMRS 41)						
Parts cost	2,152.28	110.55	3,205.41	801.89	1,937.43	816.66
Labor hours	8.7	4.9	45.0	16.9	40.2	3.8
Average labor cost	435.50	245.00	2,250.00	845.00	2,010.00	190.00
Total cost (for system)	2,587.78	355.55	5,455.41	1,646.89	3,947.43	1,006.66
Total cost (for system) per bus	215.65	29.63	454.62	548.96	1,315.81	100.67
Total cost (for system) per mile	**0.02**	**0.02**	**0.02**	**0.02**	**0.04**	**0.00**
Cooling System Repairs (ATA VMRS 42)						
Parts cost	529.39	367.53	3,933.87	1,484.11	3,740.60	362.16
Labor hours	93.5	48.8	89.7	48.0	53.1	10.05
Average labor cost	4,674.00	2,440.50	4,483.00	2,400.00	2,655.00	502.50
Total cost (for system)	5,203.39	2,808.03	8,416.87	3,884.11	6,395.60	864.66
Total cost (for system) per bus	433.62	234.00	701.41	1,294.70	2,131.87	86.47
Total cost (for system) per mile	**0.04**	**0.15**	**0.03**	**0.05**	**0.07**	**0.00**
Hydraulic System Repairs (ATA VMRS 65)						
Parts cost	0.00	0	0.00	0.00	1,208.74	167.3227
Labor hours	0.0	0.0	0.0	0.0	39.8	0.2
Average labor cost	0.00	0.00	0.00	0.00	1,990.00	10.00
Total cost (for system)	0.00	0.00	0.00	0.00	3,198.74	177.32
Total cost (for system) per bus	0.00	0.00	0.00	0.00	1,066.25	17.73
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**	**0.00**
General Air System Repairs (ATA VMRS 10)						
Parts cost	3,875.75	5839.76	1,817.49	723.46	1,996.92	0.00
Labor hours	66.4	12.0	107.5	35.7	59.4	2.0
Average labor cost	3,321.50	599.00	5,375.00	1,785.00	2,970.00	100.00
Total cost (for system)	7,197.25	6,438.76	7,192.49	2,508.46	4,966.92	100.00
Total cost (for system) per bus	599.77	536.56	599.37	836.15	1,655.64	10.00
Total cost (for system) per mile	**0.05**	**0.33**	**0.03**	**0.03**	**0.05**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	ZEBA Early Service 9/11-4/12	ZEBA Station Downtime Period 5/12-2/13	ZEBA Evaluation Period 3/13-10/13	Van Hool Diesel Early Service 9/11-4/12	Van Hool Diesel Evaluation Period 3/13-10/13	Gillig Diesel Evaluation Period 7/13-10/13
Brake System Repairs (ATA VMRS 13)						
Parts cost	321.45	0	334.00	7,301.74	8,400.65	0.00
Labor hours	24.0	0.0	52.0	83.5	124.5	0.0
Average labor cost	1,200.00	0.00	2,600.00	4,172.50	6,225.00	0.00
Total cost (for system)	1,521.45	0.00	2,934.00	11,474.24	14,625.65	0.00
Total cost (for system) per bus	126.79	0.00	244.50	3,824.75	4,875.22	0.00
Total cost (for system) per mile	**0.01**	**0.00**	**0.01**	**0.14**	**0.15**	**0.00**
Transmission Repairs (ATA VMRS 27)						
Parts cost	0.00	0	0.00	1,128.49	0.00	261.27
Labor hours	0.0	0.0	0.0	3.3	2.2	19.8
Average labor cost	0.00	0.00	0.00	165.00	110.00	990.00
Total cost (for system)	0.00	0.00	0.00	1,293.49	110.00	1,251.27
Total cost (for system) per bus	0.00	0.00	0.00	431.16	36.67	125.13
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.02**	**0.00**	**0.01**
Inspections Only - No Parts Replacements (101)						
Parts cost	0.00	0	22.98	0.00	0.00	0.00
Labor hours	669.0	19.5	457.5	140.1	149.3	298.8
Average labor cost	33,449.50	975.00	22,876.50	7,005.00	7,465.00	14,940.00
Total cost (for system)	33,449.50	975.00	22,899.48	7,005.00	7,465.00	14,940.00
Total cost (for system) per bus	2,787.46	81.25	1,908.29	2,335.00	2,488.33	1,494.00
Total cost (for system) per mile	**0.23**	**0.05**	**0.09**	**0.08**	**0.08**	**0.07**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)						
Parts cost	18,550.84	1120.55	2,140.09	4,695.10	7,453.65	4,214.37
Labor hours	1,281.2	259.4	700.1	344.1	272.9	342.3
Average labor cost	64,059.00	12,971.50	35,005.50	17,203.00	13,642.50	17,115.00
Total cost (for system)	82,609.84	14,092.05	37,145.59	21,898.10	21,096.15	21,329.37
Total cost (for system) per bus	6,884.15	1,174.34	3,095.47	7,299.37	7,032.05	2,132.94
Total cost (for system) per mile	**0.56**	**0.73**	**0.14**	**0.26**	**0.22**	**0.09**
HVAC System Repairs (ATA VMRS 01)						
Parts cost	897.40	0	1,786.18	1,914.87	4,615.40	0.00
Labor hours	14.7	5.0	60.8	8.4	45.7	5.9
Average labor cost	735.00	249.00	3,041.50	420.00	2,285.00	295.00
Total cost (for system)	1,632.40	249.00	4,827.68	2,334.87	6,900.40	295.00
Total cost (for system) per bus	136.03	20.75	402.31	778.29	2,300.13	29.50
Total cost (for system) per mile	**0.01**	**0.01**	**0.02**	**0.03**	**0.07**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	ZEBA Early Service 9/11-4/12	ZEBA Station Downtime Period 5/12-2/13	ZEBA Evaluation Period 3/13-10/13	Van Hool Diesel Early Service 9/11-4/12	Van Hool Diesel Evaluation Period 3/13-10/13	Gillig Diesel Evaluation Period 7/13-10/13
Lighting System Repairs (ATA VMRS 34)						
Parts cost	290.00	27.62	1,004.82	71.59	45.06	5.31
Labor hours	24.4	3.3	30.5	1.3	11.3	2.5
Average labor cost	1,220.50	165.50	1,522.50	62.50	565.00	125.00
Total cost (for system)	1,510.50	193.12	2,527.32	134.09	610.06	130.31
Total cost (for system) per bus	125.88	16.09	210.61	44.70	203.35	13.03
Total cost (for system) per mile	**0.01**	**0.01**	**0.01**	**0.00**	**0.01**	**0.00**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)						
Parts cost	1,751.91	108.48	977.43	375.92	434.71	129.19
Labor hours	103.2	52.2	77.3	10.5	24.5	14.0
Average labor cost	5,161.00	2,607.50	3,866.50	525.00	1,225.00	700.00
Total cost (for system)	6,912.91	2,715.98	4,843.93	900.92	1,659.71	829.19
Total cost (for system) per bus	576.08	226.33	403.66	300.31	553.24	82.92
Total cost (for system) per mile	**0.05**	**0.14**	**0.02**	**0.01**	**0.02**	**0.00**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)						
Parts cost	5.48	0	0.00	294.86	0.00	10.69
Labor hours	22.6	0.0	9.0	12.5	1.9	2.5
Average labor cost	1,131.50	0.00	450.00	625.00	95.00	125.00
Total cost (for system)	1,136.98	0.00	450.00	919.86	95.00	135.69
Total cost (for system) per bus	94.75	0.00	37.50	306.62	31.67	13.57
Total cost (for system) per mile	**0.01**	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**
Tire Repairs (ATA VMRS 17)						
Parts cost	0.00	0	0.00	0.00	0.00	0.00
Labor hours	0.00	0	1.0	0.00	2.0	1.0
Average labor cost	0.00	0.00	50.00	0.00	100.00	50.00
Total cost (for system)	0.00	0.00	50.00	0.00	100.00	50.00
Total cost (for system) per bus	0.00	0.00	4.17	0.00	33.33	5.00
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**	**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. Actual energy content will vary by locations, but the general energy conversions are as follows:

> Lower heating value (LHV) for hydrogen = 51,532 Btu/lb
> LHV for diesel = 128,400 Btu/lb
> 1 kg = 2.205 * lb
> 51,532 Btu/lb * 2.205 lb/kg = 113,628 Btu/kg
> Diesel/hydrogen = 128,400 Btu/gal /113,628 Btu/kg = 1.13 kg/diesel gal

2. The propulsion-related systems were chosen to include only those systems of the vehicles that could be affected directly by the selection of a fuel/advanced technology.

3. ATA VMRS coding is based on parts that were replaced. If there was no part replaced in a given repair, then the code was chosen by the system being worked on.

4. In general, inspections (with no part replacements) were included only in the overall totals (not by system). Category 101 was created to track labor costs for PM inspections.

5. ATA VMRS 02-Cab and Sheet Metal represents seats, doors, etc.; ATA VMRS 50-Accessories represents things like fire extinguishers, test kits, etc.; ATA VMRS 71-Body represents mostly windows and windshields.

6. Average labor cost is assumed to be $50 per hour.

7. Warranty costs are not included.

Appendix B: Fleet Summary Statistics—SI Units

Fleet Summary Statistics: ZEBA FCEB and Diesel Bus Groups and Evaluation Periods

Fleet Operations and Economics

	ZEBA Early Service 9/11-4/12	ZEBA Station Downtime Period 5/12-2/13	ZEBA Evaluation Period 3/13-10/13	Van Hool Diesel Early Service 9/11-4/12	Van Hool Diesel Evaluation Period 3/13-10/13	Gillig Diesel Evaluation Period 7/13-10/13
Number of vehicles	12	12	12	3	3	10
Period used for fuel and oil op analysis	9/11-4/12	5/12-2/13	3/13-10/13	9/11-4/12	3/13-10/13	7/13-10/13
Total number of months in period	8	10	8	8	8	4
Fuel and oil analysis base fleet kilometers	193,687	26,201	399,724	132,120	109,090	251,014
Period used for maintenance op analysis	9/11-4/12	5/12-2/13	3/13-10/13	9/11-4/12	3/13-10/13	6/13-10/13
Total number of months in period	8	10	8	8	8	5
Maintenance analysis base fleet kilometers	236,578	31,053	417,084	134,536	157,345	369,041
Average monthly kilometers per vehicle	2,464	259	4,345	5,606	6,556	7,381
Availability	56%	—	82%	77%	76%	84%
Fleet fuel usage (H_2 in kg, diesel in liters)	18,016	2,125	77,636	66,604	146,293	77,636
Roadcalls	73	—	28	24	16	54
Overall KBRC	3,241	—	14,896	5,606	9,834	6,834
Propulsion roadcalls	49	—	19	14	9	18
Propulsion KBRC	4,828	—	21,952	9,610	17,483	20,502
Fleet kg hydrogen/100 km (1.13 kg H_2)	9.30	8.11	9.67	—	—	—
Rep. fleet fuel consumption (L/100 km)	31.16	27.17	32.38	58.76	61.05	58.28
Hydrogen cost per kg	9.34	8.47	9.08	—	—	—
Diesel cost/liter	—	—	—	0.84	0.80	0.80
Fuel cost per kilometer	**0.87**	**0.69**	**0.88**	**0.49**	**0.49**	**0.47**
Total scheduled repair cost per kilometer	0.01	1.28	0.10	0.21	0.10	0.07
Total unscheduled repair cost per kilometer	0.25	4.30	0.44	1.09	0.54	0.07
Total maintenance cost per kilometer	**0.26**	**5.58**	**0.54**	**1.30**	**0.64**	**0.13**
Total operating cost per kilometer	***1.13***	***6.27***	***1.42***	***1.80***	***1.13***	***0.60***

Maintenance Costs

	ZEBA Early Service 9/11-4/12	ZEBA Station Downtime Period 5/12-2/13	ZEBA Evaluation Period 3/13-10/13	Van Hool Diesel Early Service 9/11-4/12	Van Hool Diesel Evaluation Period 3/13-10/13	Gillig Diesel Evaluation Period 7/13-10/13
Fleet mileage	236,578	31,053	417,084	134,536	157,345	369,041
Total parts cost	31,727.9	10,511.0	46,643.6	23,520.4	38,712.1	8,866.1
Total labor hours	3,219.70	1,021.68	2,534.38	837.81	1,244.65	805.75
Average labor cost (@ $50.00 per hour)	160,985.00	51,084.00	126,719.00	41,890.50	62,232.50	40,287.50
Total maintenance cost	192,712.88	61,595.02	173,362.60	65,410.94	100,944.64	49,153.59
Total maintenance cost per bus	16,059.41	5,132.92	14,446.88	21,803.65	33,648.21	16,384.53
Total maintenance cost per kilometer	***0.81***	***1.98***	***0.42***	***0.49***	***0.64***	***0.13***