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

Leslie Eudy, Matthew Post, and Matthew Jeffers
National Renewable Energy Laboratory

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Technical Report
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Acronyms and Abbreviations

AC Transit	Alameda-Contra Costa Transit District
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
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
mpg	miles per gallon
mph	miles per hour
NREL	National Renewable Energy Laboratory
PM	preventive maintenance
psi	pounds per square inch
RC	roadcall
SI	International System of Units
ZBus	zero emission bus
ZEBA	Zero Emission Bay Area

Definition of Terms

Availability: The number of days the buses are actually available compared to the days that the buses are planned for operation expressed as percent availability.

Clean point: For each evaluation, NREL works with the project partners to determine a starting point—or clean point—for the data analysis period. The clean point is chosen to avoid some of the early and expected operations problems with a new vehicle going into service, such as early maintenance campaigns. In some cases, reaching the clean point may require 3 to 6 months of operation before the evaluation can start.

Deadhead: The miles and hours that a vehicle travels when out of revenue service with no expectation of carrying revenue passengers. Deadhead includes leaving or returning to the garage or yard facility and changing routes.

Miles between roadcalls (MBRC): A measure of reliability calculated by dividing the number of miles traveled by the number of roadcalls. (Also known as mean distance between failures.) MBRC results in the report are categorized as follows:

- Bus MBRC: Includes all chargeable roadcalls. Includes propulsion-related issues as well as problems with bus-related systems such as brakes, suspension, steering, windows, doors, and tires.
- Propulsion-related MBRC: Includes roadcalls that are attributed to the propulsion system. Propulsion-related roadcalls can be caused by issues with the fuel cell, batteries, and electric drive.
- Fuel cell-related MBRC: Includes roadcalls attributed to the fuel cell system and balance of plant only.

Revenue service: The time when a vehicle is available to the general public with an expectation of carrying fare-paying passengers. Vehicles operated in a fare-free service are also considered revenue service.

Roadcall: A failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. The analysis includes chargeable roadcalls that affect the operation of the bus or may cause a safety hazard. Non-chargeable roadcalls can be passenger incidents that require the bus to be cleaned before going back into service, or problems with an accessory such as a farebox or radio.

Executive Summary

This report presents results of a demonstration of fuel cell electric buses (FCEBs) operating in Oakland, California. Alameda-Contra Costa Transit District (AC Transit) leads the Zero Emission Bay Area (ZEBA) demonstration, which includes 13 advanced-design fuel cell buses and two hydrogen fueling stations. The FCEBs in service at AC Transit are 40-foot, low-floor buses built by Van Hool with a hybrid electric propulsion system that includes a UTC Power-designed PC40 fuel cell power system and EnerDel lithium-based energy storage system. The buses began revenue service in May 2010.

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.[1] NREL has published four previous reports describing operation of these buses. This report presents new and updated results covering data from January 2015 through December 2015.

The focus of this evaluation is to compare the performance of the FCEBs to that of conventional technology buses and to track progress over time toward meeting the technical targets set by DOE and FTA. In the commercialization process that begins at technology readiness level (TRL) 1—basic research/concept—and ends at TRL 9—commercial deployment, 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 collects data on 10 Gillig conventional diesel buses for a baseline comparison at AC Transit.

Since the last report, there have been multiple accomplishments.

- The FCEBs have surpassed a million miles (1,335,412 miles) and 152,061 hours on the fuel cell power systems and have used 200,149 kg of hydrogen.
- AC Transit added a 13th bus to the fleet. This bus was part of the original order of Van Hool FCEBs and was first operated by Connecticut Transit in Hartford with funding through FTA's National Fuel Cell Bus Program. The bus was placed into service at AC Transit in October 2015.
- The FCEBs were operated out of two divisions during the evaluation period: four buses operated from the Emeryville Division, and the remaining nine buses operated from the Oakland Division.
- The 13 fuel cell power plants (FCPP) continue to accumulate high hours of service. One FCPP has surpassed the DOE/FTA 2016 target of 18,000 hours, accumulating 21,422 hours by the end of the data period for the report (22,394 as of April 30, 2016). This is a record number of hours documented to date on a fuel cell in a transit application. In all, 77% of these FCPPs (10 out of 13) have surpassed 12,000 hours of operation.

[1] 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, http://www.nrel.gov/docs/fy11osti/49342-1.pdf.

- AC Transit and its manufacturer partners continue to ramp up service of the FCEBs, including troubleshooting, maintenance, and training for all involved. The buses are now being operated on any routes out of the two depots that are serviced by 40-foot buses (with the exception of commuter routes).
- All maintenance has been fully transitioned to in-house staff, and AC Transit has begun building a program to integrate the FCEB maintenance training into its standard training program.
- The Oakland hydrogen station was completed by adding an electrolyzer and gaseous hydrogen buffer tank. The electrolyzer is powered by a stationary fuel cell that uses directed biogas.

This fifth results report provides data analysis summaries of FCEB operations from January 2015 through December 2015. Table ES-1 provides a summary of the evaluation results presented in this report.

Table ES-1. Summary of Evaluation Results[a]

Data Item	Fuel Cell	Diesel Gillig
Number of buses	13	10
Data period	1/15–12/15	1/15–12/15
Number of months	12	12
Total mileage in period	366,267	518,245
Average monthly mileage per bus	2,492	4,319
Total fuel cell operating hours	49,421	N/A
Average bus operating speed (mph)	8.5	N/A
Availability (85% is target)	74	89
Fuel economy (miles/kg)	5.47	N/A
Fuel economy (miles/DGE[b])	6.18	4.25
Miles between roadcalls (MBRC) – bus	4,513	6,954
MBRC – propulsion only[c]	7,512	15,453
MBRC – fuel cell system only[c]	23,260	N/A
Fuel cost ($/mile)	1.58	0.44
Total maintenance cost ($/mile)[d]	1.15	0.47
Maintenance cost – propulsion only ($/mile)	0.65	0.14
Total maintenance cost including extended support and extra labor costs ($/mile)[e]	2.11	—

[a] Issues with two FCEBs during the data period resulted in lower numbers for some performance metrics.
[b] Diesel gallon equivalent.
[c] Cumulative data from September 2010.
[d] Work order maintenance cost.
[e] Extended support from US Hybrid and EnerDel for the fuel cell buses began in April 2014.

Overall, the FCEBs had an average fuel economy of 5.47 miles per kilogram of hydrogen, which equates to 6.18 miles per diesel gallon equivalent. These results indicate that the FCEBs have an average fuel economy that is 43% higher than that of the Gillig diesel buses. The fuel economy for the FCEBs has dropped over time. This decrease could be due to a variety of factors that include the following:

- Duty cycle—Although the average speeds for the two divisions are essentially the same, other characteristics of the routes, such as terrain, number of stops, and passenger loading, have an effect on efficiency.
- Operators—Differences in driving styles of the operators could influence efficiency.
- Temperature—Higher ambient temperatures result in increased auxiliary loads for air conditioning.
- FCPP degradation—As fuel cells age, the ability to provide the same power decreases.
- Hydrogen station metering differences between stations—Accurately measuring the amount of hydrogen dispensed has been a challenge for the industry.

Fuel cost for hydrogen remains much higher than the cost of diesel—$8.62 per kilogram of hydrogen compared to $1.86 per gallon for diesel for the evaluation period. The cost of hydrogen has decreased slightly since the previous report. The average cost of diesel fuel has also dropped. Fuel cost calculates to $1.58 per mile for the FCEBs compared to $0.44 per mile for the Gillig diesel buses.

The overall availability for the FCEBs has increased compared to what was documented in the last report—74% compared to 72% from the previous data period. The Gillig diesel buses had an availability of 89% during the period.

Reliability, measured as miles between roadcall (MBRC), continues to show improvement. When evaluating cumulative totals since the buses first went into service, the overall bus MBRC for the ZEBA buses is showing a slow increase over time and has surpassed the DOE/FTA ultimate target of 4,000 miles. The fuel cell MBRC shows a steady increase and has passed the DOE/FTA ultimate target of 20,000 miles.

In addition to analyzing the FCEB performance, NREL provides a cost analysis and comparison. 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. The FCEBs are now out of the original warranty period resulting in an increase in operating costs. AC Transit has negotiated agreements with US Hybrid and EnerDel for extended support.

The FCEB maintenance costs were more than 2 times higher than that of the Gillig diesel buses. Throughout the demonstration, the ZEBA buses have incurred some costs that fall outside of the typical maintenance costs. These costs include labor for shuttling buses between depots for maintenance, research/training activities, and fueling the buses. Over the last year, the added labor costs were primarily for shuttling the buses between depots for maintenance. These are considered non-recurring costs for the FCEBs attributed primarily to the learning curve for maintenance staff. The non-recurring costs for the ZEBA fleet have dropped dramatically over the last year and add only $0.04 per mile to the operating cost of the buses for the evaluation period in this report. Once the Emeryville maintenance bay is completed, shuttling the buses between depots will not be necessary and the costs for all non-recurring activities should be completely eliminated. When factoring in the costs for the extended warranties and other costs, the current cost to operate the FCEBs comes to $2.11 per mile.

AC Transit has experienced issues with specific buses that resulted in extended downtime. During this evaluation period, two buses were out of service for long periods for maintenance activities that are considered to be atypical.

- FC8 had an issue with the fuel cell system that resulted in several failed inductors and caused extended downtime. The issue developed in February 2015 and kept the bus out of service for 7 months. The agency worked with US Hybrid to troubleshoot the problem. The FCPP was shipped to Connecticut for testing, which showed no issues with the FCPP; however, the team discovered that a valve in the fuel cell system had been disabled. After the valve was enabled, the problem has not occurred.
- FC9 was out of service from February 2015 through the remainder of that year. The bus system would shut down, but no error codes were generated. The lack of codes made troubleshooting a challenge. The issue was eventually traced to a failed thermal switch that caused the FCPP to shut down. The switch was not one of the components that are actively monitored by the FCPP controller. The switch was replaced and is now part of the active monitoring for the system.

During the data period, FC8 accumulated 7,811 miles and FC9 only accumulated 2,592 miles, resulting in performance that was not representative of the overall fleet. The performance indicators of monthly miles, availability, and costs were significantly affected by the downtime of these buses. If these buses are removed from the analysis results, the average monthly mileage increases from 2,492 to 2,893, the availability increases from 74% to 86%, and the maintenance cost decreases from $1.15 per mile to $1.06 per mile. Throughout this report, many analyses are presented with and without these two buses for comparison.

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
- Addressing the bus range/low fuel road service calls by increasing the learning curve for operators and fueling staff
- Providing for adequate parts supply
- Lowering cost—both capital and operating.

DOE and FTA published performance and cost 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[2]

	Units	This Report[a]	2016 Target	Ultimate Target
Bus lifetime	years/miles	5.3/ 8,300–131,900[b]	12/500,000	12/500,000
Power plant lifetime[c]	hours	4,000–21,400[d]	18,000	25,000
Bus availability	%	74	85	90
Fuel fills[e]	per day	1	1 (<10 min)	1 (<10 min)
Bus cost[f]	$	2,500,000[g]	1,000,000	600,000
Power plant cost[c,f]	$	N/A[h]	450,000	200,000
Hydrogen storage cost	$	N/A[h]	75,000	50,000
Roadcall frequency (bus/fuel cell system)	miles between roadcalls	4,500/ 23,200	3,500/ 15,000	4,000/ 20,000
Operation time	hours per day/days per week	7–14/ 5–7	20/7	20/7
Scheduled and unscheduled maintenance cost[i]	$/mile	1.15	0.75	0.40
Range	miles	235[j]	300	300
Fuel economy	miles per diesel gallon equivalent	6.18	8	8

[a] Summary of the results for the ZEBA buses in this report: data from January 2015 to December 2015.
[b] Accumulated totals for the ZEBA buses through December 2015; 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] This represents AC Transit's per-bus purchase price for the ZEBA buses in 2010. More recent orders for FCEBs show a cost of $1.8 million.
[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.

[2] 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

Alameda-Contra Costa Transit District (AC Transit) is leading a demonstration of fuel cell electric buses (FCEBs) in the San Francisco Bay Area of California. The Zero Emission Bay Area (ZEBA) demonstration includes 13 advanced-design fuel cell buses and two hydrogen fueling stations. The buses began revenue service in May 2010. Several Bay Area transit agencies—including Golden Gate Transit, Santa Clara Valley Transportation Authority, and San Mateo County Transit District—participate in the ZEBA demonstration. The agencies provide funding as well as participate in data sharing discussions and training activities.

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.[3] 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 four earlier reports on this demonstration in August 2011, July 2012, May 2014, and July 2015.[4] This report is an update to the previous reports and focuses on data from January 2015 through December 2015.

ZEBA Fuel Cell Bus Demonstration

The California Air Resources Board's (CARB's) 2000 "Fleet Rule for Transit Agencies"[5] 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 (ZBuses). 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. In addition to the four previously mentioned transit agencies, San Francisco Municipal Transit Authority 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.

[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, http://www.nrel.gov/docs/fy11osti/49342-1.pdf.
[4] See the "References and Related Reports" section for links to the four previous reports on the ZEBA Demonstration.
[5] Fact Sheet: Fleet Rule for Transit Agencies: Urban Bus Requirements, California Air Resources Board, http://www.arb.ca.gov/msprog/bus/ub/ubfactsheet.pdf.

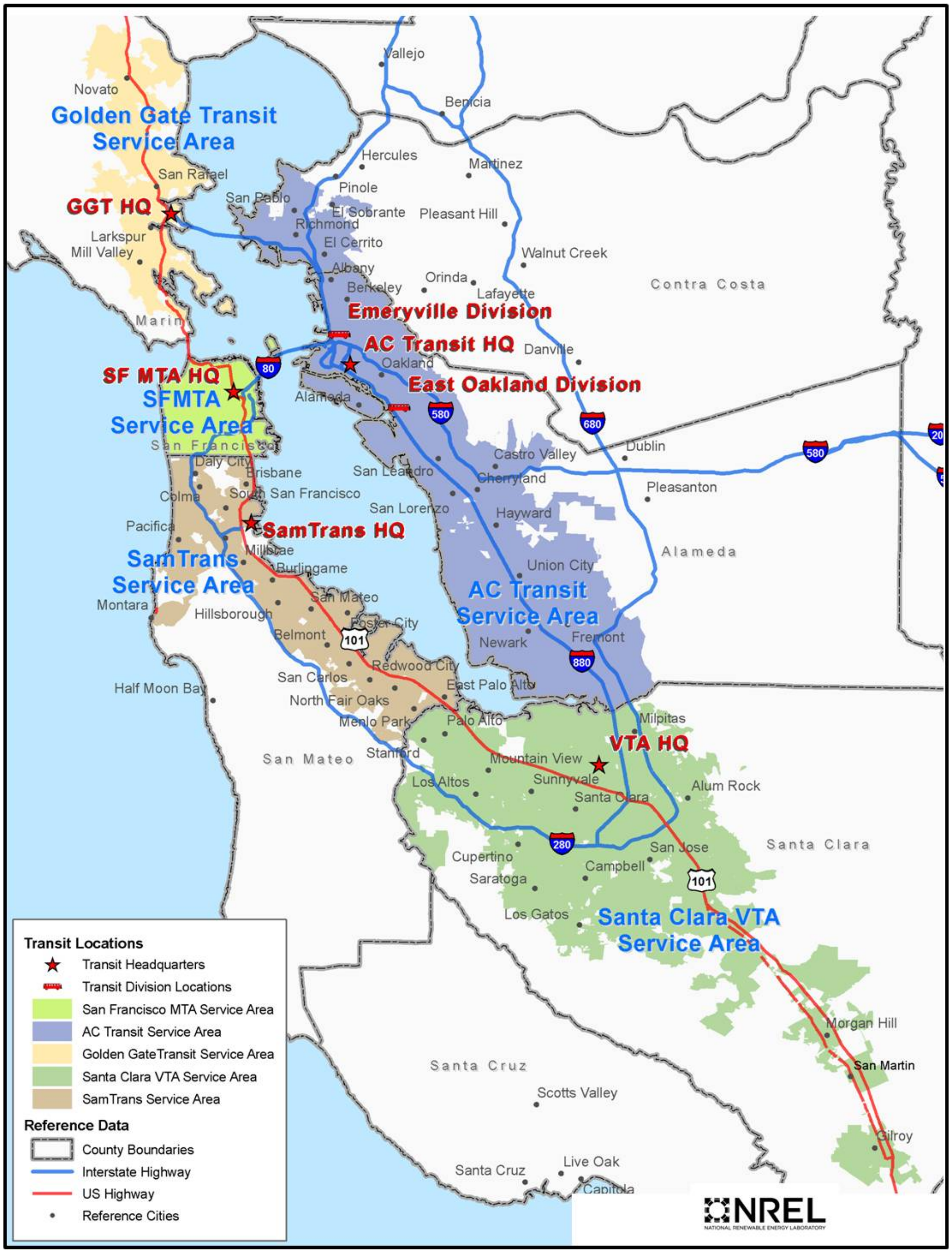

Figure 1. Map of ZEBA transit partner service areas

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). 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 provides funds to support the continued operation of the FCEB fleet.

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

AC Transit's demonstration began in 2010 with 12 FCEBs. A total of 16 buses of this configuration were built by Van Hool: 12 for AC Transit and 4 that were operated by Connecticut Transit in Hartford with funding through the National Fuel Cell Bus Program. At the end of the Connecticut demonstration in 2013, one of the buses was transferred to AC Transit. That bus was put into service in late 2015, bringing the ZEBA fleet to 13 buses.

FCEB Development Process—Technology Readiness Levels

In its 2012 annual FCEB status report,[6] NREL introduced a guideline for assessing the technology readiness level (TRL) for FCEBs. This guideline was developed using a Technology Readiness Assessment Guide[7] published by DOE in September 2011. Figure 2 provides a graphic representation of this process. (Appendix A provides the TRL guideline table tailored for FCEB commercialization.) The guideline considers the FCEB as a whole and does not account for differing TRLs for separate components or sub-systems. Some sub-systems may include off-the-shelf components that are considered commercial, while other sub-systems may feature newly designed components at an earlier TRL.

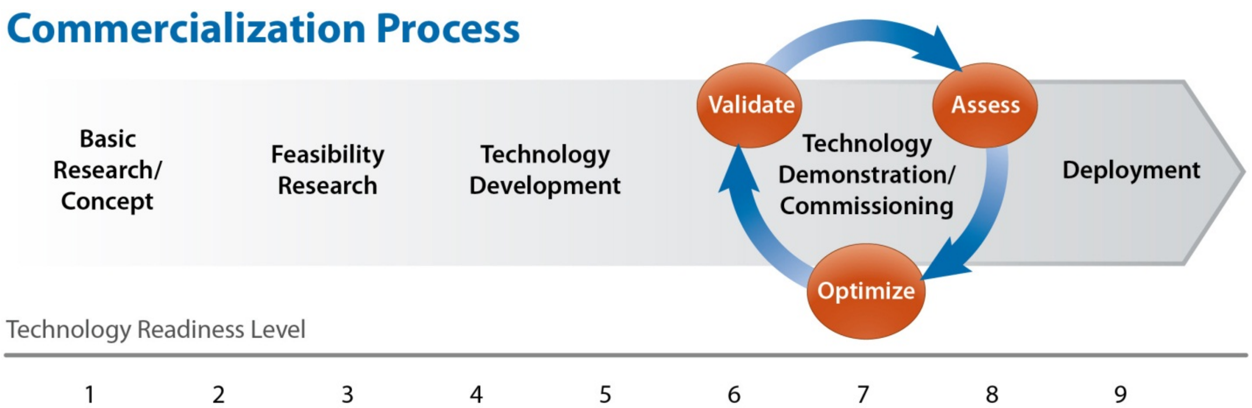

Figure 2. Graphic representation of the commercialization process developed for FCEBs

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 13-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

[6] Fuel Cell Buses in U.S. Transit Fleets: Current Status 2012, NREL/TP-5600-56406, http://www.nrel.gov/docs/fy13osti/56406.pdf.
[7] DOE Technology Readiness Assessment Guide, G 143.3-4a, https://www.directives.doe.gov/directives/0413.3-EGuide-04a/view.

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 FCEBs and baseline buses would be the propulsion system. This type of baseline comparison is not always possible.

For past reports, NREL included data on two groups of baseline buses at AC Transit. The first group consisted of four Van Hool diesel buses that were the same model as the FCEBs. These buses are the best physical match for the FCEBs; however, they have accumulated 3 times more miles than the FCEBs. These buses have reached mid-life, and maintenance records show increased cost typical of this period. Because of their high mileages (average of 305,000 miles), these buses are no longer a fair comparison to the lower-mileage ZEBA buses (average of 111,000 miles). The second group of diesel baseline buses consists of ten 40-foot Gillig buses purchased in early 2013. These Gillig buses provide a comparison of the newest diesel technology to the FCEBs. The Gillig buses are younger than the FCEBs; however, the mileage of each bus is much less than that of the Van Hool buses and is closer to that of the FCEBs for the evaluation period presented in this report.

Bus Technology Descriptions

Table 1 provides bus system descriptions for the fuel cell and diesel buses that were studied in this evaluation. The FCEBs in service at AC Transit (Figure 3) are 40-foot, low-floor buses built by Van Hool with a hybrid electric propulsion system that includes a fuel cell power system that was originally designed by UTC Power. US Hybrid provides service and support to the fuel cell power systems through a maintenance agreement with AC Transit. 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 the Gillig diesel buses.

Table 1. Fuel Cell and Diesel Bus System Descriptions

Vehicle System	FCEB	Diesel Gillig
Number of buses	13	10
Bus manufacturer/model	Van Hool A300L FC low floor	Gillig low floor
Model year	2010	2013
Length/width/height	40 ft/102 in./136 in.	40 ft/102 in./122 in.
GVWR/curb weight	39,350 lb/31,400 lb	39,600 lb
Wheelbase	269 in.	279 in.
Passenger capacity	33 seated or 29 seated plus 2 wheelchairs	37 seated or 29 seated plus 2 wheelchairs
Engine manufacturer/model	UTC Power PC40	Cummins ISL, 8.9L
Rated power	Fuel cell power system: 120 kW	280 hp @ 2,200 rpm
Accessories	Electrical	Mechanical
Emissions equipment	None	Diesel particulate filter and selective catalytic reduction
Transmission/retarder	Seico brake resistors regenerative braking	Allison
Fuel capacity	40 kg hydrogen	120 gal diesel
Bus purchase cost	$2.5 million[a]	$413,826

[a] This represents AC Transit's per-bus purchase price for the ZEBA buses in 2010. More recent orders for FCEBs show a cost of $1.8 million.

Figure 3. AC Transit fuel cell electric bus

Figure 4. AC Transit Gillig diesel bus. ***Photo courtesy of AC Transit***

Table 2 provides a description of some of the electric propulsion components 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; a fuel cell power system; and an advanced lithium-based energy storage system by EnerDel.

Table 2. 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, Luxfer, type 3 tanks; 5,000 psi rated
Regenerative braking	Yes

Fueling and Maintenance Facilities

AC Transit provides fuel for its ZEBA fleet from two hydrogen stations: one at the Emeryville Division and another at the Oakland Division. AC Transit modified a maintenance bay in the Oakland garage to allow safe maintenance of hydrogen-fueled buses. The agency is in the process of upgrading the garage at Emeryville to include a similar hydrogen-ready bay for maintenance. This section describes the stations at Emeryville and Oakland, outlines plans for the Emeryville maintenance bay upgrade, and provides a summary of fueling data from September 2011 through December 2015.

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 5, is a combined facility for light-duty fuel cell electric vehicles (FCEVs) 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 5. The Linde hydrogen station at AC Transit's Emeryville Division

Figure 6 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.

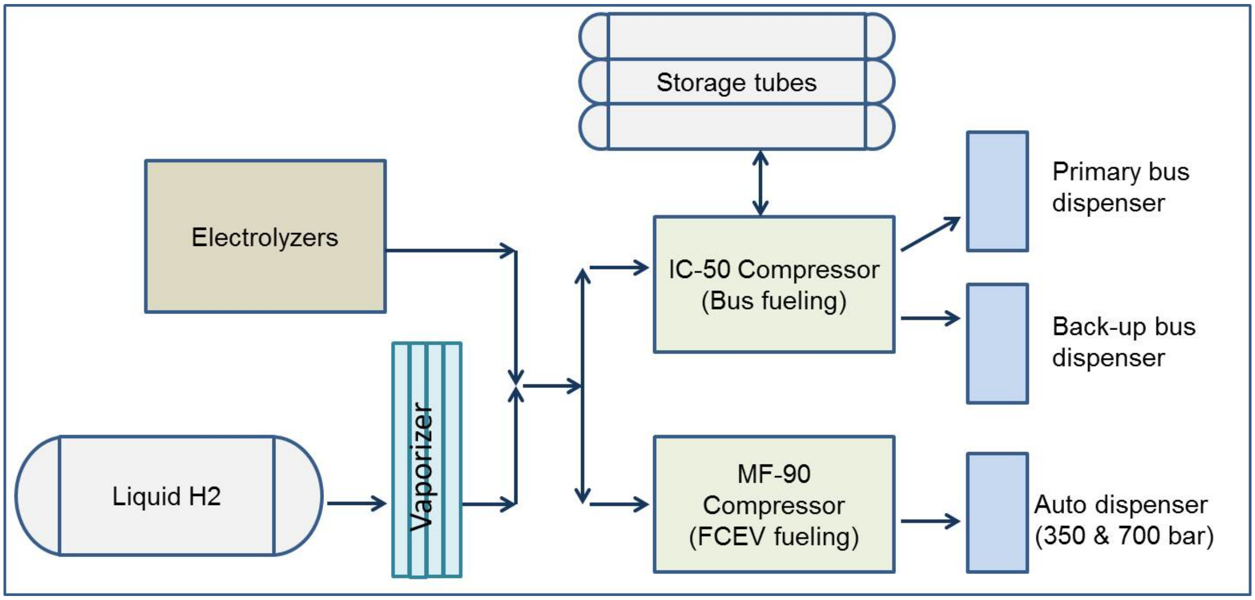

Figure 6. Block diagram of the Emeryville station

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 of hydrogen in about 6 minutes. Figure 7 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.

Figure 7. Bus fueling at the Emeryville hydrogen station: fueling area (left) and close-up of the bus dispenser (right)

Changes at Emeryville—AC Transit is in the process of upgrading the drainage at the Emeryville Division, which requires removal of all the concrete in the yard. The agency is taking this opportunity to move the hydrogen dispensers for the buses to be in-line with the diesel fueling island. This will enable the FCEBs to be integrated into the standard process for fueling and cleaning at the end of the day. The agency also plans to upgrade the storage tubes during the downtime. During this process, all of the ZEBA buses will be operated out of the Oakland Division.

Oakland Seminary Division Hydrogen Fueling

AC Transit's second hydrogen station is located at the Seminary Division in Oakland. This station was also designed and built by Linde and is similar in design to the one at Emeryville. The primary differences are as follows:

- The bus dispensers are installed in-line with the diesel fueling island.
- There is no public access for light-duty FCEV fueling because the station is at the back of the property.
- Hydrogen is available at 350 bar pressure only.
- The on-site electrolyzer is powered by a solid oxide fuel cell fueled with directed biogas.[8]
- The electrolyzer operates as needed to fill the buffer tank (the Emeryville electrolyzer operates continuously).

The Oakland station construction was completed in late 2014 and AC Transit commissioned the station in December 2014. The electrolyzer was added in January 2016 along with another storage tank to capture the hydrogen that is produced. After commissioning, the new equipment was placed into service on March 1, 2016. The electrolyzer is capable of producing 65 kg hydrogen per day. The hydrogen is captured in the buffer tank, which is the first hydrogen used when a bus is fueled. The electrolyzer operates as needed to fill the buffer tank. Figure 8 shows a simple block diagram of the primary components of the station including the electrolyzer and added buffer tank. Figure 9 shows the station equipment installed at the Oakland Division as of April 2016.

[8] 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.

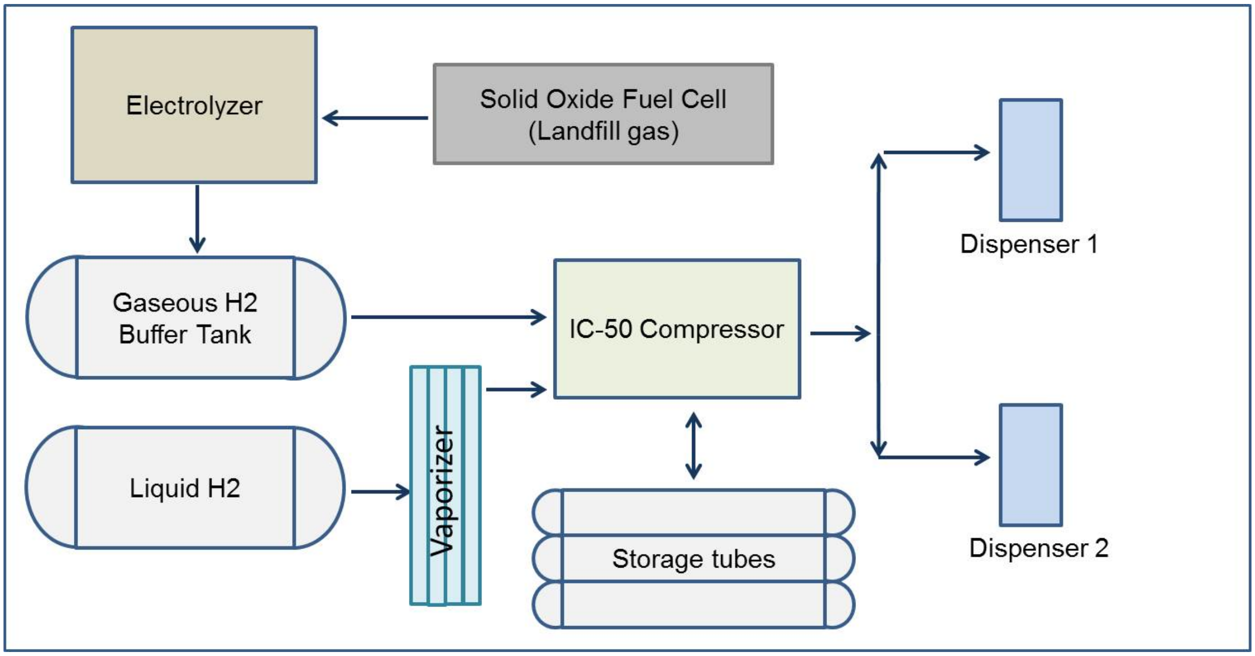

Figure 8. Block diagram of the Oakland station

Figure 9. Linde hydrogen station at the Oakland Division

The Oakland station includes one compressor for fueling the buses—a Linde IC-50 ionic compressor. The two dispensers are installed in-line with the diesel fuel island. This is an important step in integrating this new technology into standard transit practice. The ZEBA buses are fueled and prepped for the next day's service along with all of the diesel buses at the depot. The station can handle back-to-back fuelings, but it does not allow simultaneous fueling from the two dispensers.

Maintenance Facilities

AC Transit maintains the FCEBs in a maintenance bay at the Oakland Seminary Division. This bay was modified to accommodate hydrogen-fueled buses for the earlier demonstration. While the fleet was operated out of the Emeryville Division, AC Transit maintenance staff had to shuttle the buses between the divisions, which resulted in additional labor charges. The agency has begun an upgrade at the Emeryville Division to convert two bays for safe maintenance of hydrogen-fueled buses. Once this modification is complete, all maintenance for the buses stationed at Emeryville will be handled there without the need to shuttle the buses between depots. AC Transit expects the construction to begin this summer and take about 4 months. The modifications include:

- Removal of existing equipment
- Enhanced ventilation
- Ceiling/roof exhaust
- Upgraded alarm and added hydrogen sensors
- Upgraded electrical in classified areas
- Upgraded lighting
- Installation of new roll-up doors
- Updated signage
- Bridge crane for safe removal of rooftop components
- Scaffolding system to allow safe work at the roof level.

The estimated cost for these upgrades is $750,000 to $775,000. AC Transit reports that the approval process has been much smoother than when the Oakland Division was modified, likely due to the increased familiarization with hydrogen for local code officials. When the agency first began operating FCEBs in 2004, hydrogen-fueled buses were an unknown technology for the area.

Summary of Fueling Data

The Emeryville station was used to fuel all of the ZEBA buses from the time it was commissioned in August 2011 until December 2014, when the Oakland fueling station was completed. At that time, AC Transit transferred a portion of the buses from Emeryville to Oakland. Figure 10 shows the average daily hydrogen dispensed by month beginning in January 2014 and extending through the 2015 evaluation period (January 2015–December 2015). The averages only include days when hydrogen was dispensed; zero-use days were excluded. The graph includes fuel dispensed from both stations. During this period, the buses were fueled 5,568 times for a total of 110,760 kg of hydrogen. The average amount per fueling was 19.9 kg. Figure 11 tracks the total hydrogen dispensed into the buses each month from January 2014 through December 2015. The numbers are separated out by station from December 2014 when the Oakland station came on line. The increase in hydrogen dispensed from the Oakland station over the first few months clearly shows the shift in buses from Emeryville to Oakland. Figure 12 shows the cumulative hydrogen dispensed into the buses since the beginning of the demonstration. At the end of the most recent evaluation period, the fleet-wide total was more than 200,000 kg of hydrogen.

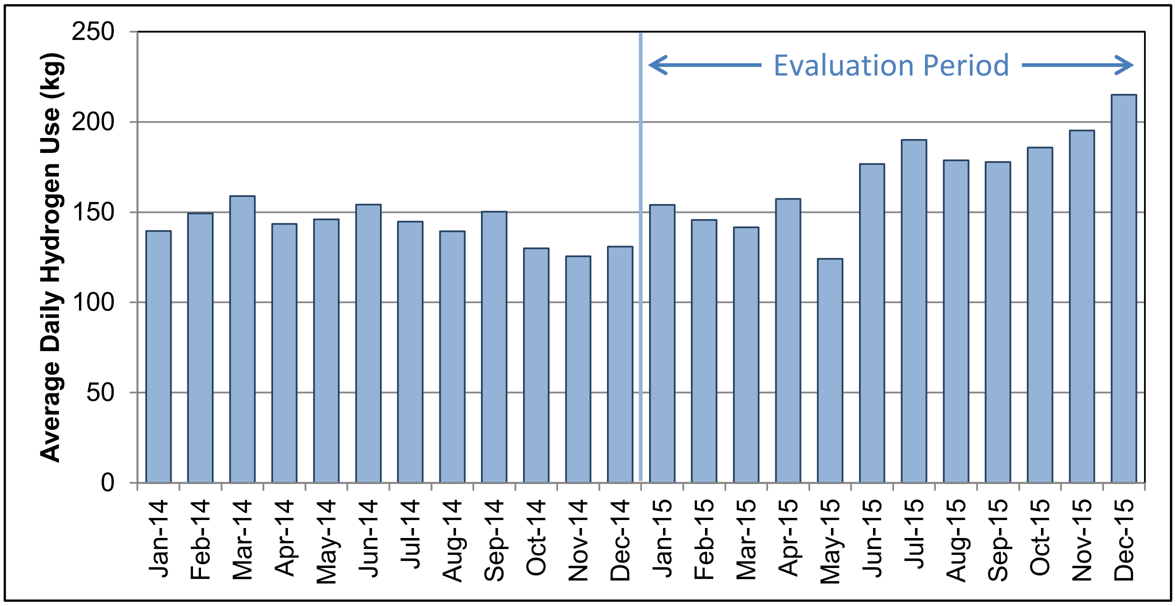

Figure 10. Average hydrogen dispensed per day at AC Transit's hydrogen stations (excluding 0 kg days)

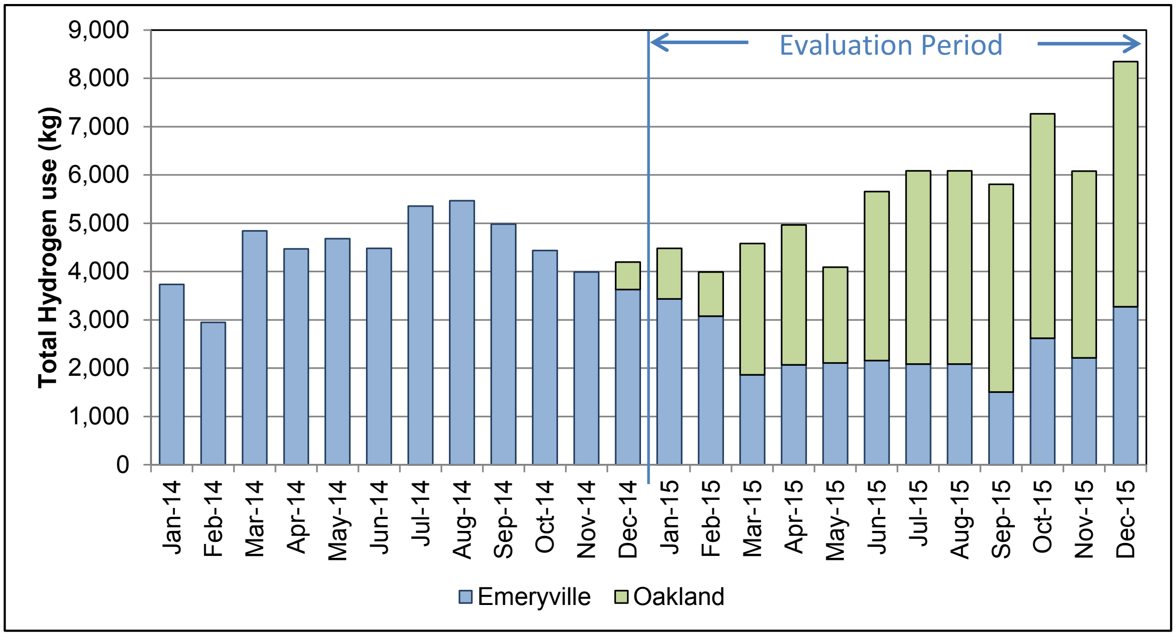

Figure 11. Total hydrogen dispensed per month at AC Transit's hydrogen stations

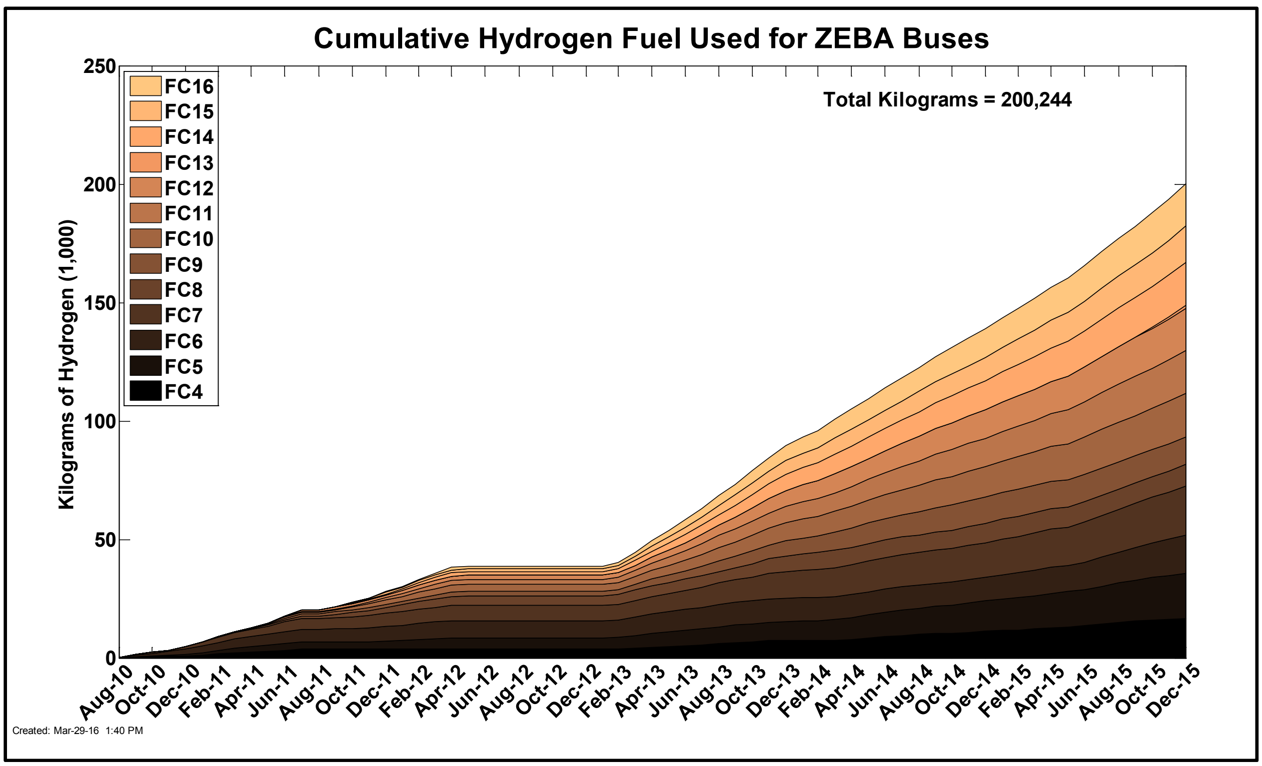

Figure 12. Cumulative hydrogen dispensed into the buses through December 2015[9]

[9] The Emeryville station was out of service from May 2012 through late January 2013; therefore no fuel was dispensed into the buses during that time. The downtime was explained in the previous report.

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 AC Transit and the manufacturers. Over the last year, AC Transit has made several changes to the demonstration program to further test the capabilities of the technology.

Operational Changes

Throughout the evaluation period, AC Transit has operated four FCEBs out of the Emeryville Division and the remaining nine FCEBs out of the Oakland Division. AC Transit continues to work toward full integration of the FCEBs into the standard operation of the fleet. The buses are now being assigned to any route that 40-foot buses operate on with the exception of commuter routes. All drivers at both depots have been trained to operate the buses to facilitate this random dispatch for the buses. When AC Transit begins the upgrades to the Emeryville Division and hydrogen station, all buses will be operated out of Oakland until the construction is complete.

Transition of Maintenance to Transit Staff

The transition of knowledge from the manufacturers to the transit staff is essential to commercializing the technology. During the early stages of the demonstration, an on-site engineer from the fuel cell manufacturer handled preventive maintenance and repair of the more advanced components. This practice changed in 2014 when the manufacturer's on-site technician handed over all maintenance work to AC Transit. The manufacturer no longer provides a permanent on-site technician. AC Transit staff continues to carry out all preventive maintenance and repair work on the fuel cell buses. Most manufacturer support is provided through remote diagnostics. AC Transit has assigned a dedicated supervisor and mechanic at each depot to lead the work on the FCEBs. These employees handle the training and bring in other staff as needed. Much of the hands-on training is performed on an as-needed basis when FCEBs need to have repairs done.

Mechanics are becoming more comfortable with new technology and procedures and the agency is training many more of its staff on the FCEBs. Troubleshooting during this stage of development can be challenging, and it is often labor intensive as staff goes through the learning curve. Work orders occasionally have multiple mechanics logging hours when several may have been in training. In this case, the time and cost of the repair will be artificially high. This added labor cost typically increases after transit staff takes over maintenance work but drops over time as the staff becomes more familiar with the technology.

Extended Manufacturer Support

AC Transit continues to fund extended support from the manufacturers through a $1.8 million grant in the final round of the National Fuel Cell Bus Program. The grant is managed through the Center for Transportation and the Environment. AC Transit negotiated agreements with US Hybrid and EnerDel and set up purchase orders with Siemens, VanHool, and Luxfer for parts as needed. The maintenance totals in the report show the cost of this extended support.

US Hybrid support agreement—AC Transit's 3-year agreement with US Hybrid includes monthly site visits to evaluate the FCPPs, diagnosis support, training, and maintaining an inventory of spare parts at the transit agency.

EnerDel support agreement—AC Transit's 3-year agreement with EnerDel covers quarterly field repairs for 13 hybrid system battery packs, on-site visits as needed, and non-warranty repairs or mechanical damage. The warranty agreement includes reconditioning of each battery pack, which was completed in January 2015.

The agreement also includes remanufacturing of the battery packs from the third quarter of 2015 through the fourth quarter of 2016. The remanufacturing process includes replacing all of the cells in the pack, reassembly, and testing. To minimize downtime for the buses, EnerDel has provided a spare battery pack. This pack is owned by EnerDel with all service and maintenance covered at the company's expense.

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 continues to experience some issues with availability of bus components that have a long lead time for delivery. This has improved over time as the project partners have learned what should be kept on hand. Under the extended support contract with AC Transit, US Hybrid maintains an inventory of spare parts for the FCPPs. Because of this, there have not been any issues with FCPP parts availability. Currently the parts availability issues are associated with the hybrid drive system components, which can have significant lead times for delivery. In some cases, bus components for the FCEB model are different from that of the diesel model so the bus parts inventory can't be shared. The industry needs to further develop a robust supply chain for these advanced components for FCEBs (as well as other electric drive buses).
- **Bus range/low fuel**—AC Transit has had issues with real-world bus range being lower than expected. The agency has reported multiple service calls when the low fuel light comes on while an FCEB is in service. At first, this was attributed to the comfort level of the drivers when the low fuel light comes on. Continued training has helped with this situation and drivers are becoming more familiar with the operational differences over time. The agency has determined that there are other factors that have an effect on the bus range. One factor is training for the staff fueling the buses. While all staff has been trained on how to fuel the buses, a small group of people handle the majority of fueling duties. That group handles the buses more frequently and has learned how to ensure the buses are getting a full fill. On the weekends or when one of those staff members is out, someone less familiar takes over the duty of fueling the FCEBs. In some cases, the buses end up not getting a full fill. Another factor that affects the ability to fully fuel the bus is the speed of fueling. The Emeryville station is capable of very fast fills—up to 5 kg per minute. The Oakland station has a slower fill rate. A fill at each station might end with the buses' hydrogen tanks being at the same pressure, but the density of the hydrogen in the tank will be lower for the bus fueled at the higher speed because the ending temperature is higher. Once the hydrogen cools, the pressure in the tanks decreases.

Occasionally staff at the Emeryville Division will top off a bus in the morning before it goes into service. Staff members that are less familiar with the process might not understand the need to check the fuel level the next morning. Also, AC Transit staff frequently transfer between divisions, making it a challenge to transfer knowledge. AC Transit can address the majority of these issues with continued training for its staff. The agency is also investigating whether to lower the fill speed at Emeryville to make the filling process consistent.

- **Costs—**At this point in the development of FCEB technology, costs continue to be high. Capital costs of the buses have dropped from that of early designs at more than $3 million. Recent orders for FCEBs in the United States (10 buses for SunLine and Stark Area Regional Transit Authority) report costs of $1.8 million per bus. Manufacturers project costs to decrease with larger orders of buses. Operating costs for the FCEBs are also higher due to several factors. As mentioned earlier, maintenance staff is still learning the new technology and spends more time troubleshooting advanced systems. Now that the buses are out of the original warranty period, parts costs have increased dramatically. The costs for advanced-technology parts are also much higher than that of conventional technology. AC Transit has purchased extended support agreements with the manufacturers that also add to the cost. This cost curve is typical of any new technology being introduced into the market and is expected to drop over time.
- **Extended downtime—**AC Transit has experienced issues with specific buses that resulted in extended downtime. During this evaluation period, two buses were out of service for long periods for maintenance activities that are considered to be atypical.
    - FC8 has had an issue with the fuel cell system that resulted in several failed inductors and caused extended downtime. The issue developed in February 2015 and kept the bus out of service for 7 months. AC Transit replaced the FCPP with a spare and changed out some hybrid system components and did not see the issue return. The agency worked with US Hybrid to troubleshoot the problem with the FCPP. The unit was shipped to US Hybrid's Fuel Cell Division in Connecticut for testing. The testing showed no issues with the FCPP; however, the team discovered that a valve in the fuel cell system had been disabled. After the valve was enabled, the problem has not occurred.
    - FC9 was out of service for more than 10 months from February 2015 through the remainder of that year. The bus system would shut down, but no error codes were generated. The lack of codes made troubleshooting a challenge. The issue was eventually traced to a failed thermal switch that caused the FCPP to shut down. The switch was not one of the components that are actively monitored by the FCPP controller. The switch was replaced and is now part of the active monitoring for the system.
- **Exhaust system retrofit—**During a routine inspection on one of the FCEBs, AC Transit staff noticed cracks in the exhaust system tubing that channels water vapor out of the bus. The entire assembly had to be changed out. Getting the system fabricated by Van Hool required a 12-week lead time. AC Transit retrofitted the four buses that had the worst problems first. Because of the cost and time involved to retrofit the entire fleet, the

systems that were removed were repaired in-house for installation in other buses. AC Transit plans to complete retrofits on all of the FCEBs.

- **Hydrogen tank valve**—One bus developed issues with malfunctioning tank valves that would not open. The solution took longer than expected to resolve because of complications with the original manufacturer. The hydrogen fueling system was designed and built by Dynetek. In September 2012, Dynetek was acquired by Luxfer. The new company no longer manufacturers the specific valve that was in the ZEBA buses. AC Transit spent time researching the issue to determine the best solution. The agency eventually was able to work with Luxfer to replace the malfunctioning valves. Luxfer provided new valves with upgraded design that would work in the existing system.

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 transit bus are 12 years or 500,000 miles. Because transit agencies typically rebuild the diesel engines at approximately mid-life, an FCPP should be able to operate for at least half the life of the bus. DOE and FTA have 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 previous reports, 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 13 shows the cumulative hours on each FCPP through December 2015. The top FCPP has now achieved more than 21,000 hours of operation without major repair or cell replacements (22,394 hours as of April 30, 2016). This is the highest number of FCPP hours documented for an FCEB; it surpasses the 2016 target and moves the technology further toward meeting the ultimate target of 25,000 hours. In all, 71% of these FCPPs (10 out of 13) have surpassed 12,000 hours of operation. Table 3 provides the total hours accumulated on each of the FCPPs since they were installed. The table includes the hours for the spare FCPPs as well as the 13 original FCPPs.

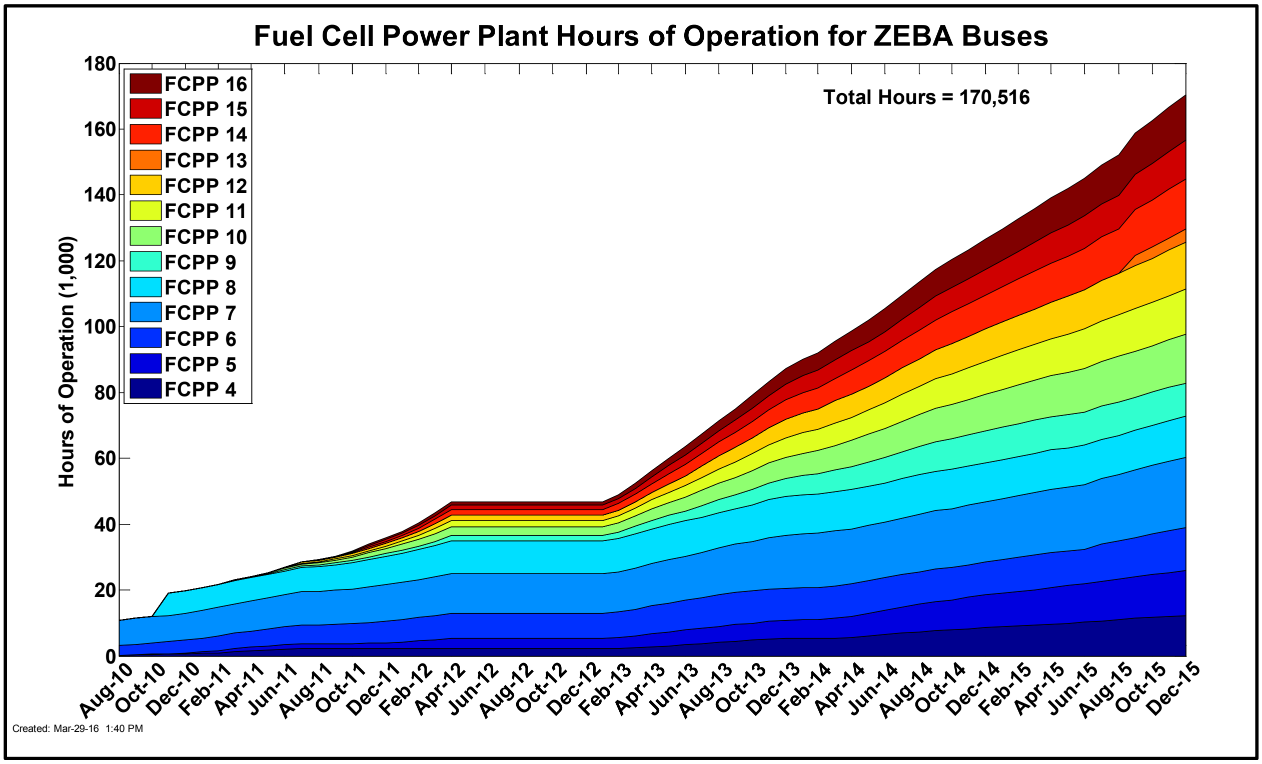

Figure 13. Cumulative FCPP hours on the ZEBA buses

Table 3. Total Hours Accumulated on the FCPPs

FCPP	Date of FCPP Installation	FCPP Hours at Installation	Total Hours through December 2014	Total Hours through December 2015
4	8/22/10	59	8,641	12,259
5	8/20/10	20	9,869	13,710
6	8/1/10	2,915	9,954	12,927
7	8/29/10	7,727	18,299	21,422
8	11/15/10	6,806	11,909	12,467
9	2/22/11	34	9,763	10,084
10	3/1/11	20	11,071	14,836
11	5/5/11	0	9,969	13,770
12	5/12/11	0	9,810	14,140
13[a]	10/1/15	0	2,865	4,099
14	8/17/11	0	10,327	15,091
15	8/15/11	0	7,839	11,843
16	9/30/11	0	9,168	13,868
Spare 1	1/1/14	0	597	597
Spare 2	4/3/14	23	1,419	1,980

[a] Bus was acquired from Connecticut Transit and put into service in October 2015 with hours already on the FCPP.

Evaluation Results

The results presented in this section focus on data from January 2015 through December 2015. During that data period, the FCEBs operated 366,267 miles over 41,229 hours of fuel cell operation. This indicates an overall operational speed of 8.9 mph. Because bus FC13 went into service in October 2015, it was only operational for 3 months during the evaluation period. As mentioned previously, FC8 had an issue that kept it out of service for 7 months. The bus was repaired and went back into service in October 2015. FC9 also experienced issues and was out of service for most of the evaluation period. The analysis results presented in this section include the overall fleet average as well as the adjusted average with these two outlier buses removed.

The diesel baseline buses include ten newer Gillig buses in operation at AC Transit.

Route Assignments

During the evaluation period presented here, four buses operated from AC Transit's Emeryville Division and nine buses operated from the Oakland Division. Earlier in the demonstration, AC Transit operated the fuel cell buses on a specific set of route blocks on the 18 and 51B local routes. AC Transit has now increased service of the FCEBs to include most routes out of Emeryville, with the exception of any commuter routes such as Transbay service. The buses at the Oakland Division are also randomly dispatched on any of the local routes serviced by 40-foot buses. This is the common practice for most transit agencies. Operating the FCEBs on any route from a depot contributes to full commercialization because it means the technology is closer to being able to replace a conventional diesel bus with little to no operational or service modifications.

The Emeryville Division has 21 local routes that are served by 40-foot buses and the Oakland division has 17. Table 4 provides a summary of the weekday local routes that the FCEBs could be operated on at each of the divisions. The data include deadhead as well as in-service time. The average speed at each of the two depots is similar at around 10 mph. The ZEBA buses are also operated on these routes during weekends.

Table 4. Daily Summary of Local Routes for AC Transit Buses

Division	Routes	Blocks	Time (h)	Distance (mi)	Average Speed (mph)
Emeryville	21	133	1,776.8	17,643	9.93
Oakland	17	113	1,380.5	13,786	9.98

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 FCEBs and baseline buses.

Table 5 summarizes average monthly mileage for the ZEBA buses during the evaluation period. Currently, the average monthly operating mileage for the FCEBs is 2,492 miles. This is nearly identical to the monthly average of 2,487 miles reported for the FCEBs during the previous data period (October 2013–December 2014). The current average for the FCEBs is 42% lower than the monthly average for the Gillig diesel buses (4,319 miles). Excluding FC8 and FC9 increases the fleet average to 2,893 miles, 33% below that of the Gillig baseline buses. Figure 14 shows the average monthly mileage trends for the FCEBs and diesel buses from January 2014 through December 2015. The monthly mileage for the FCEBs was consistently higher than 2,000 miles per month during the data period. Four of the individual ZEBA buses have achieved a monthly average above the target of 3,000 miles per month during this evaluation period. The fleet-wide monthly average for all ZEBA buses has approached this target but has not yet surpassed it. Figure 14 also shows the adjusted ZEBA average for each month, which excludes FC8 and FC9. The adjusted average was above or very near the target for 6 of the 12 months in the evaluation period.

Table 5. Average Monthly Mileage (Evaluation Period)

Bus	Ending Hubodometer	Total Mileage	Months	Average Monthly Mileage
FC4	111,180	32,470	12	2,706
FC5	117,227	39,321	12	3,277
FC6	92,282	27,618	12	2,302
FC7	117,235	31,718	12	2,643
FC8	58,502	7,811	12	651
FC9	85,187	2,592	12	216
FC10	114,773	35,024	12	2,919
FC11	108,956	34,080	12	2,840
FC12	124,917	37,565	12	3,130
FC13	51,412	8,351	3	2,784
FC14	132,431	39,707	12	3,309
FC15	103,442	33,855	12	2,821
FC16	119,522	36,155	12	3,013
Total Fuel Cell		***366,267***	***147***	***2,492***
Adjusted		***355,864***	***123***	***2,893***
1338	145,845	54,389	12	4,532
1339	150,696	55,593	12	4,633
1340	153,428	55,080	12	4,590
1341	138,973	40,363	12	3,364
1342	153,037	54,378	12	4,532
1343	144,187	56,664	12	4,722
1344	139,867	41,510	12	3,459
1345	145,819	55,355	12	4,613
1346	140,620	53,383	12	4,449
1347	132,673	51,530	12	4,294
Total Gillig Diesel		***518,245***	***120***	***4,319***

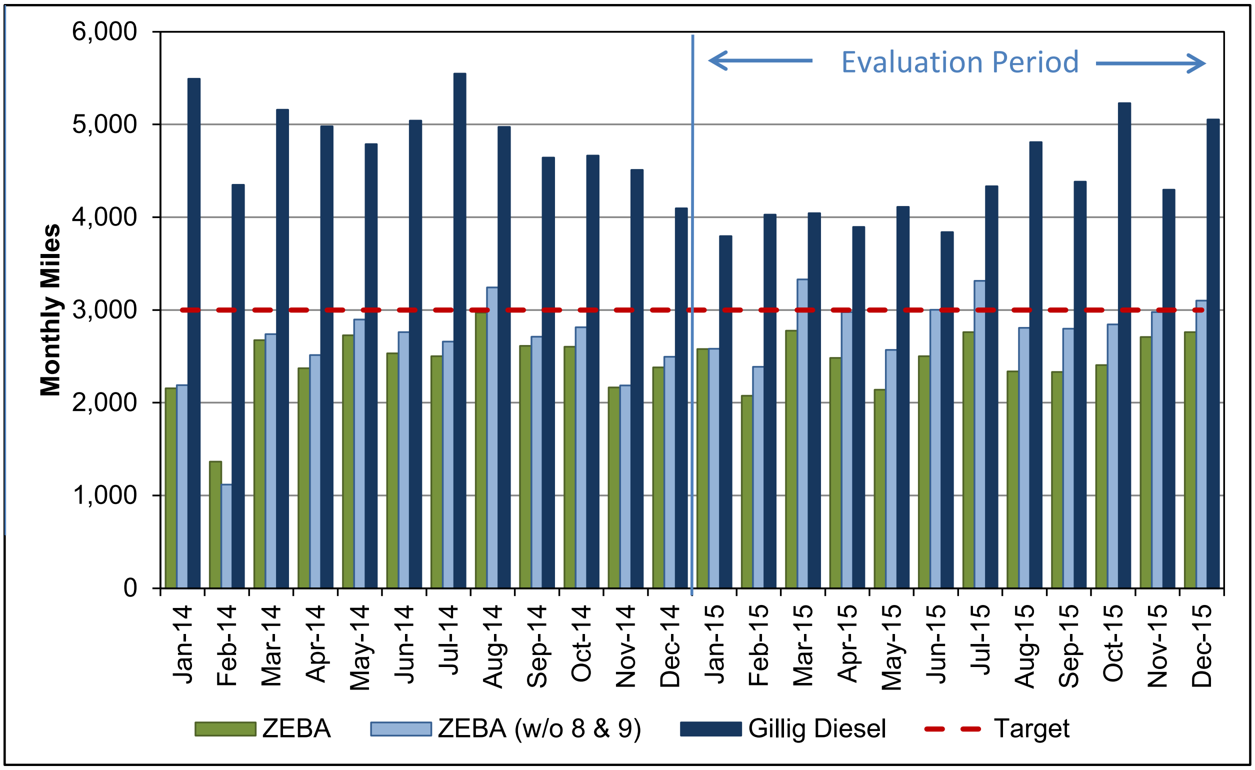

Figure 14. Monthly average miles for the ZEBA FCEBs and Gillig diesel buses

Another measure of reliability is bus availability—the percentage of days the buses are actually available for service at the time of morning pull-out compared to the days that the buses are planned for operation. The AC Transit buses are planned for service every day. Table 6 shows the availability numbers for each of the 13 ZEBA buses during the evaluation period. The availability for the individual ZEBA buses ranged from a low of 7% to a high of 95%. The overall average availability for the fleet is 74%. FC8 and FC9 were out of service for extended periods that prevented normal operation; the issues for these buses were described in the previous section. If these two buses are removed from the calculation, the average availability for the FCEBs rises to 86%, exceeding the 2016 availability target of 85%.

Table 6. Summary of ZEBA Availability by Bus (Evaluation Period)

Bus	Planned Days	Available Days	Percent Availability
FC4	365	330	90%
FC5	365	303	83%
FC6	365	294	81%
FC7	365	284	78%
FC8	365	74	20%
FC9	365	24	7%
FC10	365	346	95%
FC11	365	319	87%
FC12	365	298	82%
FC13	92	84	91%
FC14	365	324	89%
FC15	365	305	84%
FC16	365	328	90%
Total ZEBA	***4,472***	***3,313***	***74%***
ZEBA adjusted (w/o FC8 & FC9)	***3,742***	***3,215***	***86%***

Figure 15 shows monthly availability for the FCEBs (green line) and the Gillig diesel buses (dark blue line) for the same data period as Figure 14. The monthly average availability varied between 60% and 90% for the ZEBA buses and between 80% and 100% for the diesel buses. Figure 15 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, sorted into five categories (preventive maintenance is shown as PM). It is clear that the FC system issues experienced by FC8 and FC9 dominated the reasons for unavailability during this evaluation period. The second highest category was general bus-related issues not associated with the advanced propulsion technology. The high point in unavailability occurred in May 2015 when four buses were out of service for the entire month: FC8 and FC9 were out with FCPP issues, FC6 was out with the hydrogen tank valve issues, and FC7 was in the body shop for accident repairs.

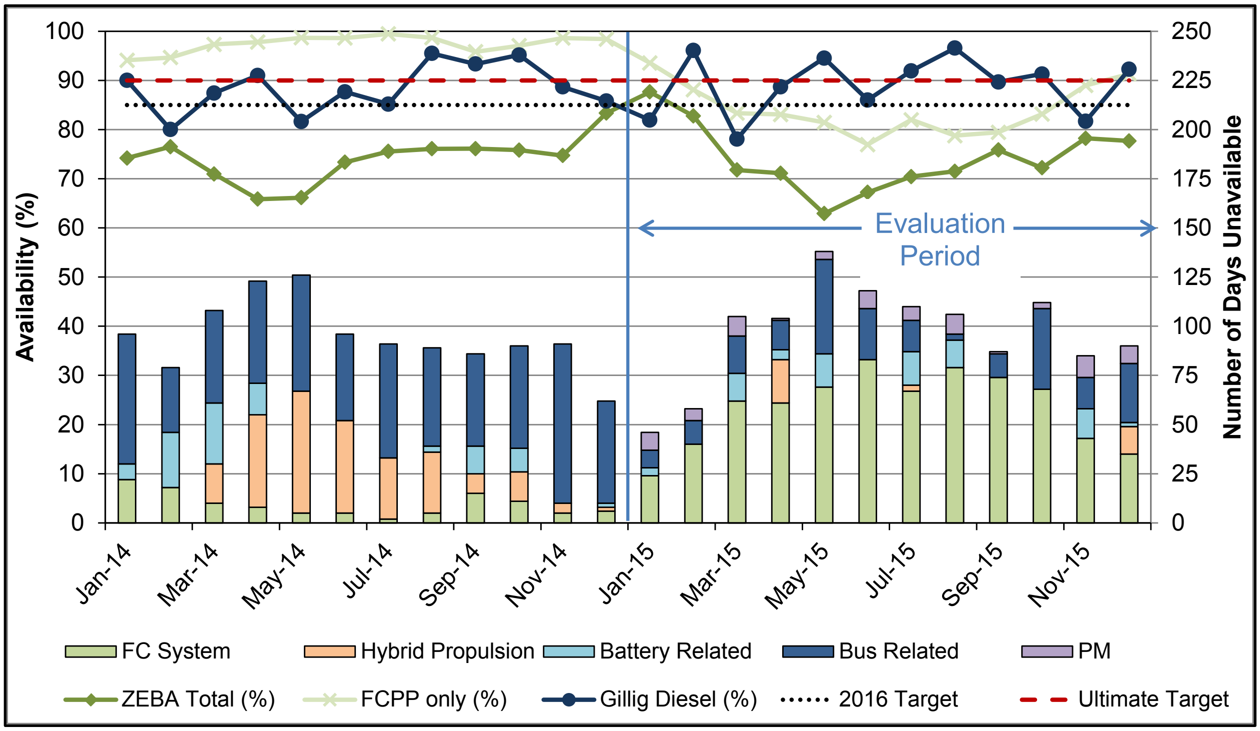

Figure 15. Availability for the ZEBA FCEBs and diesel buses

The reasons for unavailability for the fuel cell and diesel buses are summarized in Table 7. During this evaluation period, the average availability for the entire FCEB fleet was 74%, and the adjusted availability (excluding FC8 and FC9) was 86%. The Gillig diesel buses had an overall availability of 89%. When reviewing the adjusted availability, bus-related maintenance (separate from the fuel cell, hybrid, and traction battery systems) is the reason for the highest percentage of unavailability for the ZEBA buses, accounting for approximately 47% of the downtime. For the Gillig buses, just over 42% of their unavailability was due to similar bus-related issues. Power plant issues (fuel cell system or engine) caused 17.3% of the adjusted unavailability for the FCEBs, compared to 33.4% for the diesel buses. The data contained in Table 7 are also shown graphically in Figure 16, Figure 17, and Figure 18.

Table 7. Summary of Availability and Unavailability of Buses for Service (Evaluation Period)

Category	ZEBA # Days	ZEBA %	ZEBA # Days (adjusted)	ZEBA % (adjusted)	Gillig Diesel # Days	Gillig Diesel %
Planned work days	4,472		3,742		3,660	
Bus availability	3,313	74%	3,215	86%	3,259	89%
Bus unavailability	**1,159**	**100%**	**527**	**100%**	**401**	**100%**
Power plant (fuel cell/engine)	705	60.8%	91	17.3%	134	33.4%
Hybrid propulsion	39	3.4%	25	4.7%		
Traction batteries	88	7.6%	88	16.7%		
General bus issues	247	21.3%	247	46.9%	169	42.1%
Preventive maintenance (PM)	80	6.9%	76	14.4%	2	0.5%
Transmission					90	22.4%
HVAC					6	1.5%

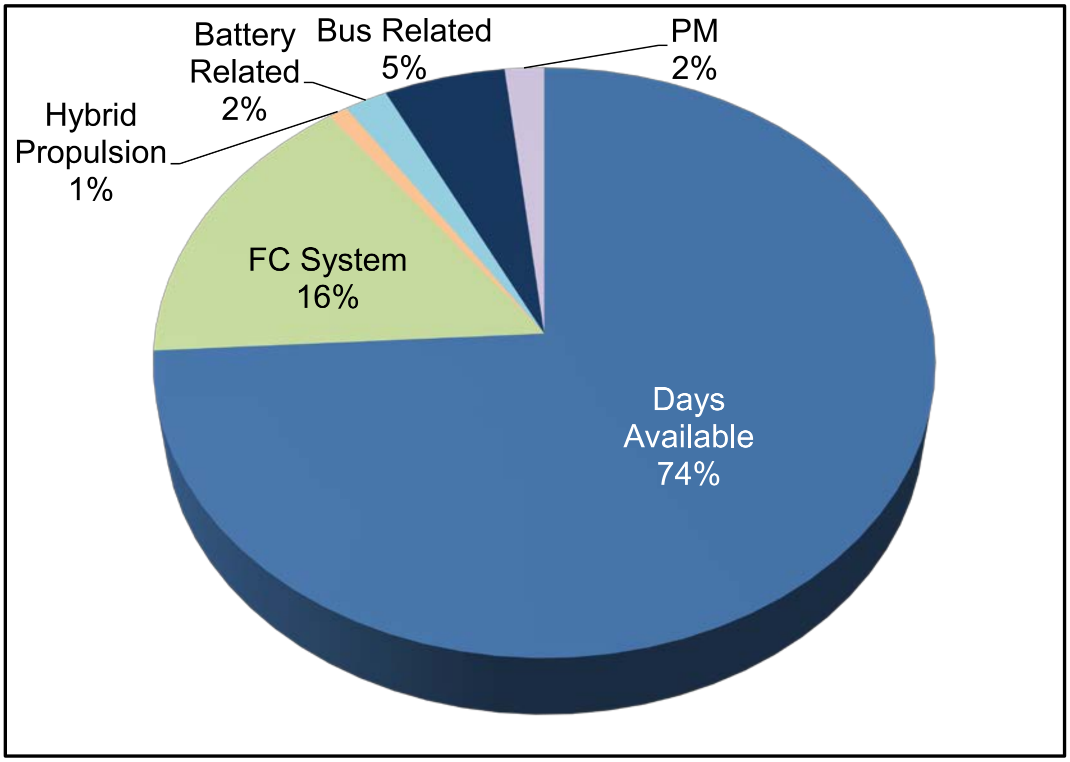

Figure 16. Availability and unavailability by category for the FCEB fleet

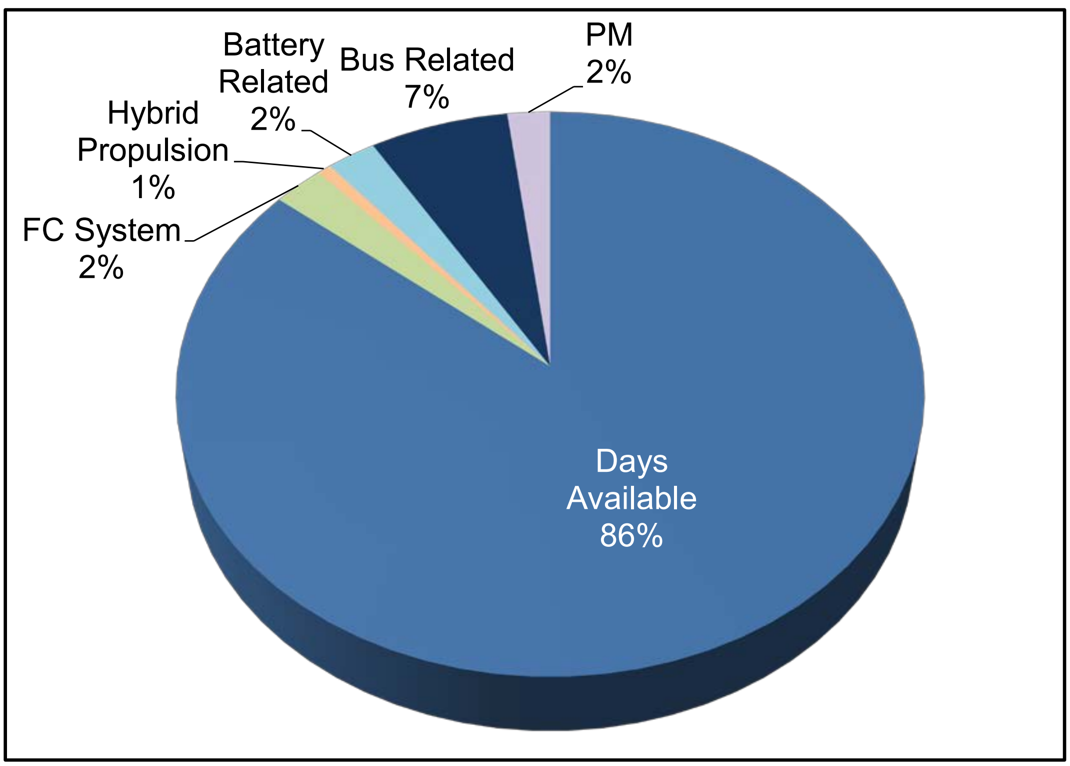

Figure 17. Adjusted availability and unavailability by category for the FCEB fleet (FC8 and FC9 excluded)

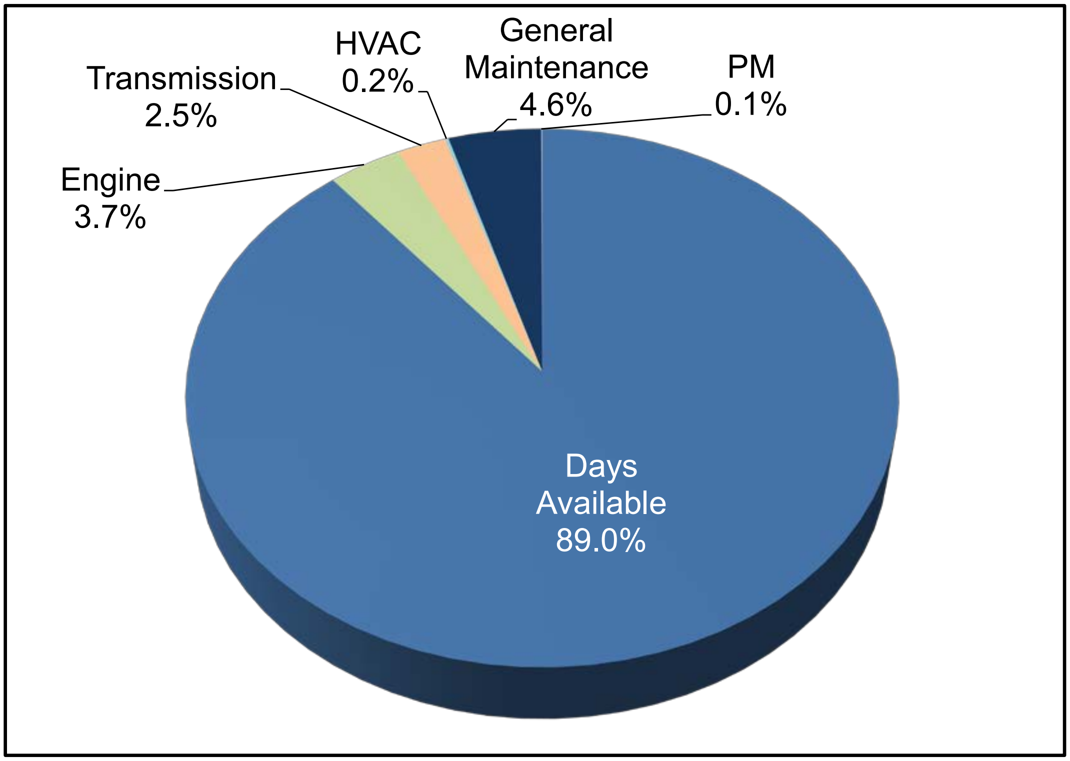

Figure 18. Availability and unavailability by category for the Gillig diesel fleet

Fuel Economy and Cost

As discussed previously, hydrogen fuel is provided by two fueling stations designed and constructed by Linde. For both stations, hydrogen is dispensed at up to 350 bar (5,000 psi). AC Transit employees perform all fueling services for the hydrogen-fueled vehicles. NREL collects fueling records from three sources: electronic records from AC Transit's Fleet Watch system, electronic fueling records from Linde, and manual logs from AC Transit. These records are merged for the analysis.

Table 8 shows hydrogen and diesel fuel consumption and fuel economy for the study buses over the last two years. For the evaluation period, the FCEBs had an overall average fuel economy of 5.47 miles per kilogram of hydrogen, which equates to 6.18 miles per diesel gallon equivalent (DGE). The energy conversion from kilograms of hydrogen to DGE appears at the end of Appendix B. (Appendices B through G contain summary statistics for the ZEBA and diesel buses.) These results indicate that the FCEBs have an average fuel economy that is 43% higher than that of the Gillig diesel buses.

Table 8. Fuel Use and Economy (Evaluation Period)

Bus	Mileage (fuel base)	Hydrogen (kg)	Miles per kg	Diesel (DGE)	Miles per DGE
FC4	29,228	5,393	5.42	4,773	6.12
FC5	33,656	6,204	5.43	5,490	6.13
FC6	26,047	6,308	4.13	5,583	4.67
FC7	29,215	5,864	4.98	5,190	5.63
FC8	7,439	1,223	6.08	1,082	6.87
FC9	1,821	279	6.54	247	7.39
FC10	32,410	5,856	5.53	5,182	6.25
FC11	30,681	6,000	5.11	5,310	5.78
FC12	35,642	5,696	6.26	5,041	7.07
FC13	7,662	1,202	6.38	1,064	7.20
FC14	36,323	6,044	6.01	5,349	6.79
FC15	31,168	5,425	5.75	4,800	6.49
FC16	33,582	5,728	5.86	5,069	6.62
ZEBA Total	***334,874***	***61,222***	***5.47***	***54,179***	***6.18***
1338	48,528			11,587	4.19
1339	52,216			12,095	4.32
1340	50,043			11,446	4.37
1341	37,658			8,893	4.23
1342	47,713			11,267	4.23
1343	49,644			11,640	4.26
1344	37,551			9,189	4.09
1345	47,499			10,930	4.35
1346	45,106			10,716	4.21
1347	42,844			10,222	4.19
Gillig Diesel Total	***458,802***			***107,985***	***4.25***

Figure 19 shows monthly average fuel economy for the FCEBs and diesel buses in miles per DGE. To account for potential differences by operating location, the FCEB fuel economy is separated out by division beginning in December 2014 when the first buses were moved to Oakland. The fuel economy is shown in blue for the buses operating out of the Emeryville Division and the fuel economy for the Oakland Division FCEBs is shown in green. 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 buses, which might require additional energy use. NREL uses data from weather stations monitored by the National Oceanic and Atmospheric Administration (NOAA).[10] For the ZEBA demonstration, NREL uses temperature data from the Oakland Airport weather station. AC Transit reports that the ambient temperature in Oakland is generally higher than that in the Emeryville area.

[10] NOAA Quality Controlled local climatological data website: http://www.ncdc.noaa.gov/qclcd/QCLCD?prior=N.

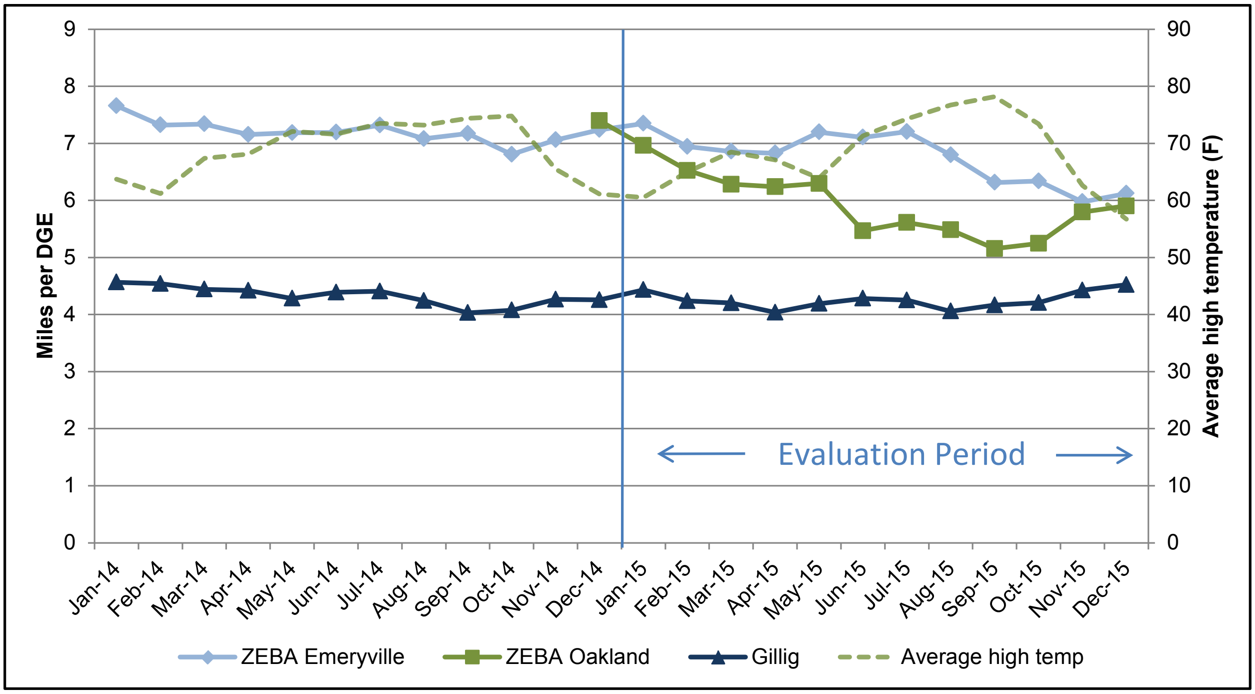

Figure 19. Average fuel economy for the fuel cell and diesel buses (evaluation period)

The fuel economy for the buses operated from the Emeryville Division was higher than that of the Oakland Division buses. The fuel economy for the FCEBs at Oakland shows a dip that coincides with the rise in temperature. That would be expected for the higher temperature days when the air conditioning would be operating more. The Emeryville FCEB fuel economy dropped, but not as significantly.

Over time, the average fuel economy for the fleet has shown a consistent decrease. This decrease could be due to a variety of factors that include:

- Duty cycle—Although the average speeds for the two divisions are essentially the same, other characteristics of the routes, such as terrain, number of stops, and passenger loading, have an effect on efficiency.
- Operators—Differences in driving styles of the operators could influence efficiency.
- Temperature—Higher ambient temperatures result in increased auxiliary loads for air conditioning.
- FCPP degradation—As fuel cells age, the ability to provide the same power decreases.
- Hydrogen station metering differences between stations—Accurately measuring the amount of hydrogen dispensed has been a challenge for the industry.

Table 9 provides the summary of fuel costs for the ZEBA and diesel baseline buses for the evaluation period. The cost of hydrogen production as dispensed during this period was $8.62 per kilogram, not including the capital cost of the station. The hydrogen fuel cost per mile calculates to $1.58. Diesel fuel cost during the reporting period was $1.86 per gallon, which calculates to $0.44 per mile for the Gillig diesel buses.

Table 9. Summary of Fuel Cost for ZEBA and Diesel Buses (Evaluation Period)

	ZEBA	Gillig
Cost per unit (kg or gal)	$8.62	$1.86
Total miles (fuel base)	334,874	458,802
Total fuel (kg or gal)	61,223	107,985
Fuel cost ($)	$527,486	$200,424
Fuel cost per mile ($)	$1.58	$0.44

Roadcall Analysis

A roadcall or revenue vehicle system failure (as named in the National Transit Database[11]) 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.[12] 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, fareboxes, or destination signs.

The transit industry measures reliability as mean distance between failures, also documented as miles between roadcall (MBRC). Table 10 provides the MBRC for the FCEBs and diesel buses categorized by bus roadcalls and propulsion-related-only roadcalls. Propulsion-related-only roadcalls include all roadcalls due to propulsion-related systems including the fuel cell system (or engine for a conventional bus), electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, and transmission systems. The fuel-cell-system-related roadcalls and MBRC are included for the FCEBs. The fuel cell system MBRC includes any roadcalls due to issues with the fuel cell stack or associated balance of plant. Figure 20 presents the cumulative MBRC by category for the FCEBs and diesel baseline buses. The bus MBRC for the ZEBA buses continues to increase over time and has surpassed the DOE/FTA ultimate target of 4,000 miles. The fuel cell MBRC shows a steady increase and has also passed the ultimate target of 20,000 miles.

Table 10. Roadcalls and MBRC

	ZEBA	Gillig Diesel
Dates	9/11–12/15	6/13–12/15
Mileage	1,209,509	1,390,732
Average miles	111,227	144,883
Bus roadcalls	268	200
Bus MBRC	4,513	6,954
Propulsion roadcalls	161	90
Propulsion MBRC	7,512	15,453
Fuel cell system roadcalls	52	N/A
Fuel cell system MBRC	23,260	N/A

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

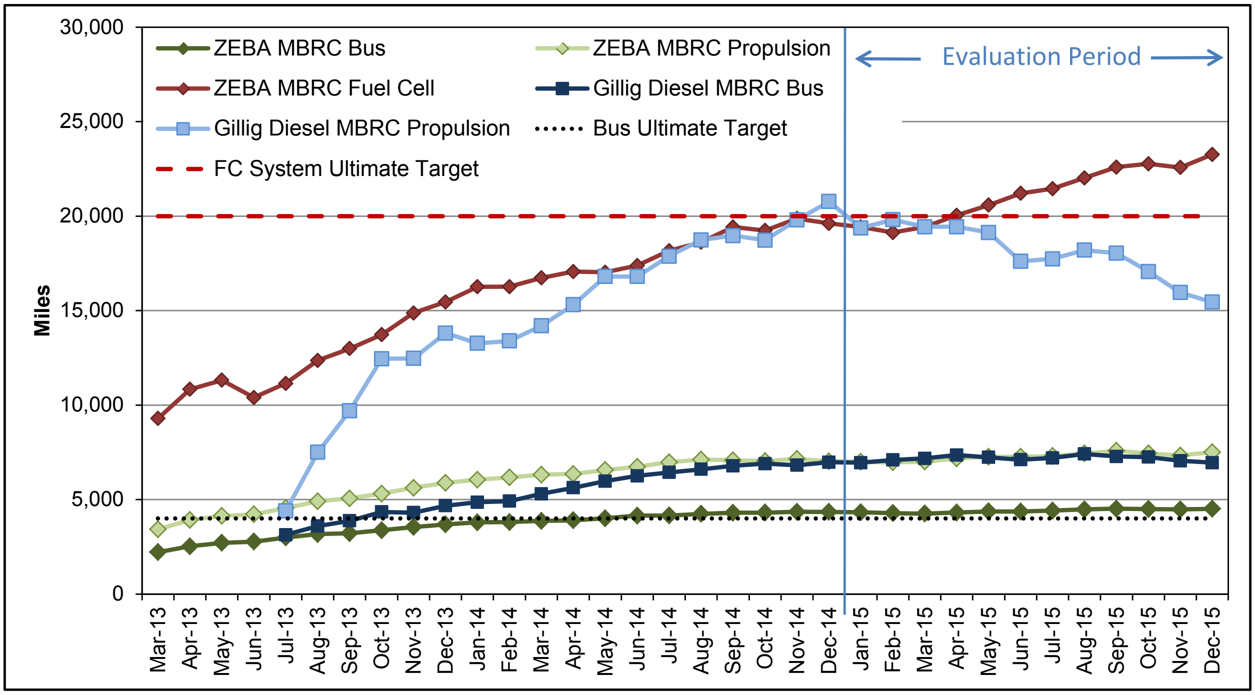

Figure 20. Cumulative MBRC for the FCEBs and diesel buses

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. Costs for accident-related repair, which are extremely variable from bus to bus, were eliminated from the analysis. 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. The ZEBA buses are now beyond the term for the original warranty. As mentioned previously, AC Transit has entered into extended support agreements with US Hybrid and EnerDel. The cost of these agreements was funded through a grant from FTA as part of the National Fuel Cell Bus Program. The cost for the agreements is outlined in the summary costs at the end of this section. AC Transit has one maintenance trainer assigned to support maintenance activities with the FCEBs and provide maintenance training for mechanics and other AC Transit staff. By the start of 2015, all regular maintenance tasks had been transitioned to AC Transit staff. The manufacturers provide support as needed with any issues that are encountered with the buses.

Total Work Order 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 11 shows total maintenance costs for the fuel cell and diesel buses. Scheduled and unscheduled maintenance cost per mile is provided for each baseline bus and FCEB. The overall fleet totals and adjusted totals (without FC8 and FC9) are provided for the ZEBA buses.

Table 11. Total Work Order Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Total Cost per Mile ($)	Scheduled Cost per Mile ($)	Unscheduled Cost per Mile ($)
FC4	32,470	16,044	548.2	1.34	0.23	1.11
FC5	39,321	13,591	425.7	0.89	0.18	0.71
FC6	27,618	47,100	540.0	2.68	0.19	2.49
FC7	31,718	32,928	460.0	1.76	0.22	1.54
FC8	7,811	6,522	335.7	2.98	0.30	2.68
FC9	2,592	1,685	330.4	7.02	0.25	6.77
FC10	35,024	6,658	318.9	0.65	0.17	0.48
FC11	34,080	3,826	329.6	0.60	0.16	0.43
FC12	37,565	29,526	408.5	1.33	0.22	1.11
FC13	8,351	986	80.1	0.60	0.17	0.43
FC14	39,707	2,094	349.2	0.49	0.21	0.29
FC15	33,855	2,272	496.6	0.80	0.20	0.60
FC16	36,155	9,682	319.4	0.71	0.22	0.49
Total Fuel Cell	***366,267***	***172,912***	***4,942***	***1.15***	***0.20***	***0.94***
FCEB Adjusted	***355,864***	***164,705***	***4,276***	***1.06***	***0.20***	***0.86***
1338	54389	6,861	370	0.47	0.16	0.31
1339	55593	9,709	346	0.49	0.14	0.35
1340	55080	8,370	324	0.45	0.14	0.31
1341	40363	7,123	298	0.55	0.16	0.38
1342	54378	9,674	348	0.50	0.14	0.36
1343	56664	6,020	303	0.37	0.13	0.24
1344	41510	8,242	316	0.58	0.16	0.42
1345	55355	11,341	337	0.51	0.13	0.38
1346	53383	7,148	302	0.42	0.15	0.26
1347	51530	5,857	308	0.41	0.15	0.26
Total Gillig Diesel	***518,245***	***80,345***	***3,253***	***0.47***	***0.14***	***0.32***

The monthly scheduled and unscheduled cost per mile for the ZEBA buses is shown in Figure 21 and Figure 22. Figure 21 shows the cost per mile adjusted without FC8 and FC9, while Figure 22 includes the average mileage for the buses. The costs for FC8 and FC9 were mostly labor hours to research and troubleshoot the issues with the FCPP. The graph clearly shows the months in which the maintenance staff was making a concentrated effort to diagnose the problem. Figure 23 shows the Gillig buses' monthly costs. Issues with the ZEBA buses resulted in higher costs for several months during the evaluation period. The high cost for many of the FCEB parts was the primary factor for the increases. High-cost parts included an inverter, bus air compressor, hydrogen tank valves, coolant pump, and air dryers. Some of these high-cost parts are part of the bus systems and not the electric propulsion system. AC Transit reports that the FCEBs have several bus system components that are not common with the diesel buses of the same model. Those FCEB components are more costly than that of the diesel buses. The costs for the Gillig buses were fairly consistent over the evaluation period.

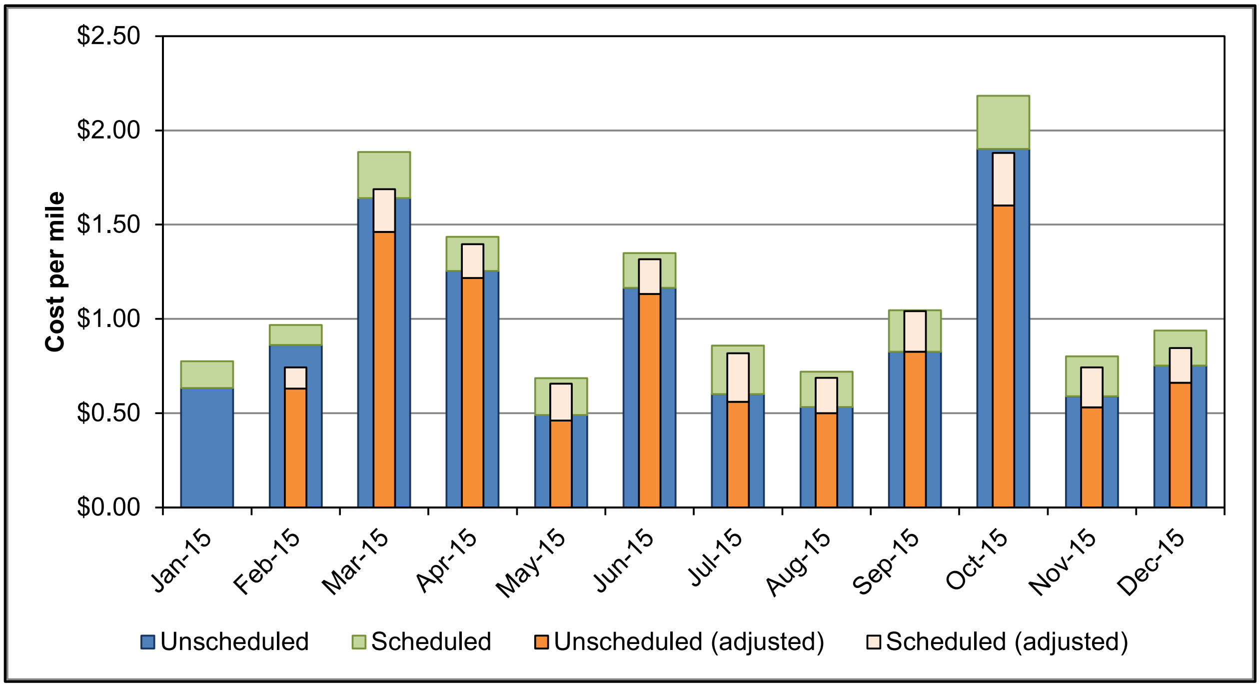

Figure 21. Monthly scheduled and unscheduled costs per mile for the ZEBA buses (evaluation period)

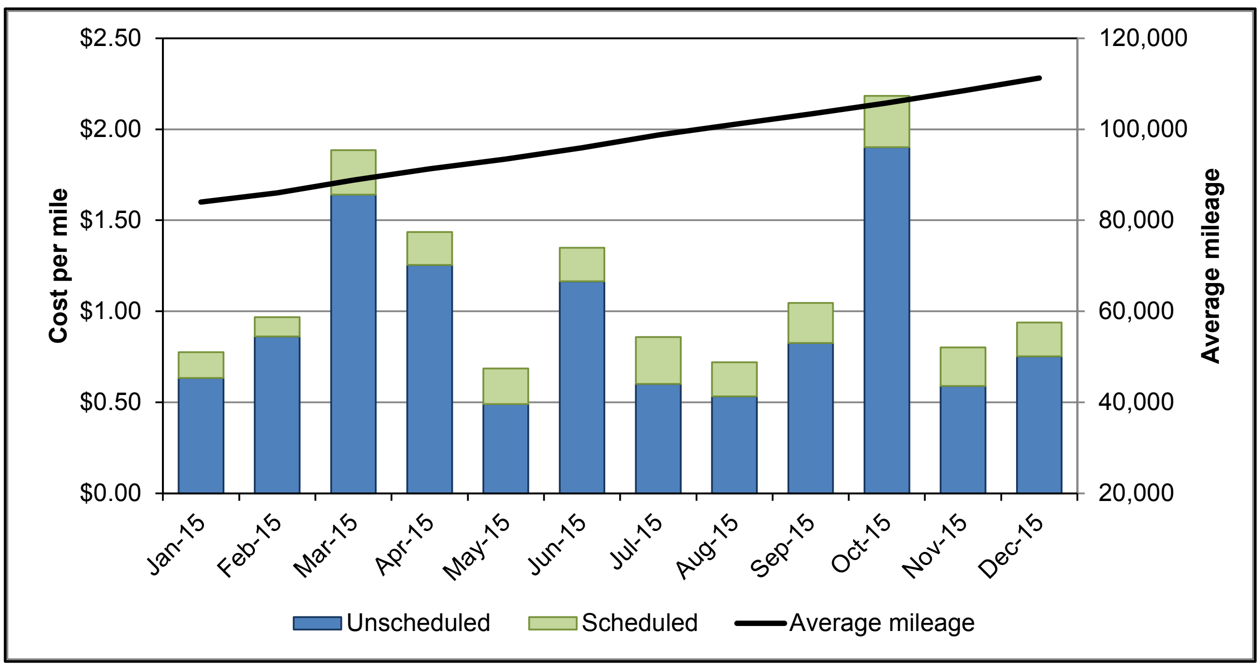

Figure 22. Monthly scheduled and unscheduled costs per mile (unadjusted) for the ZEBA buses (evaluation period)

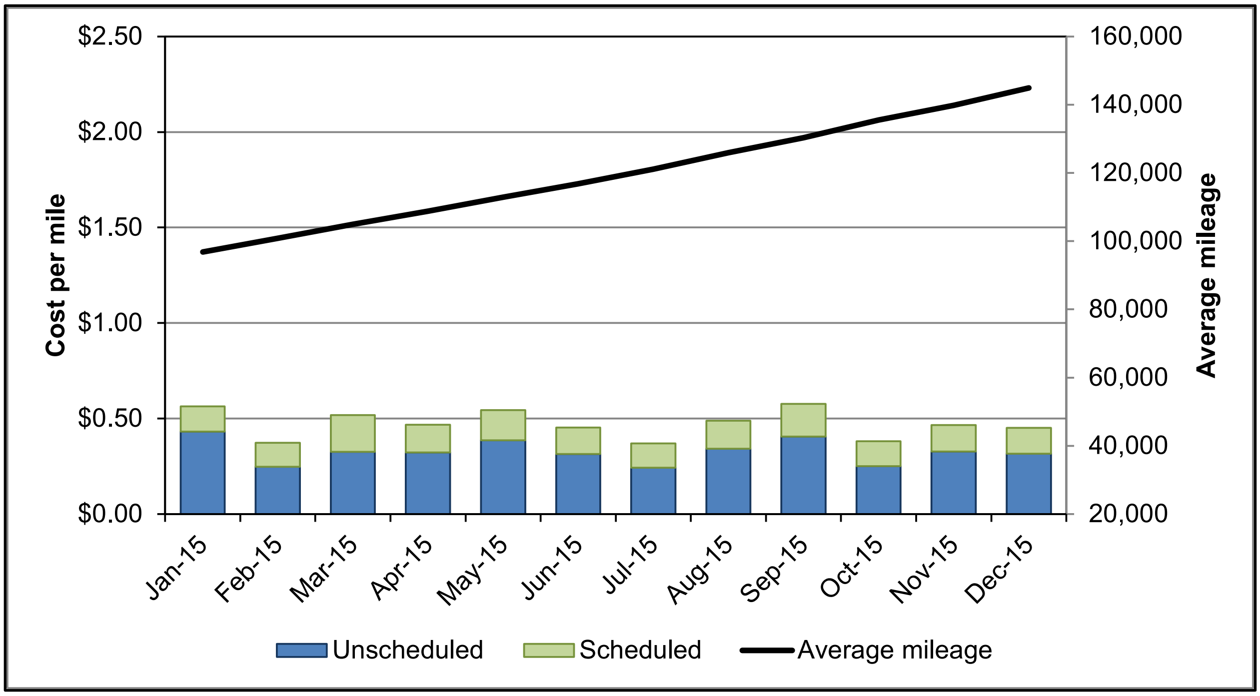

Figure 23. Monthly scheduled and unscheduled costs per mile for the Gillig diesel buses (evaluation period)

Work Order Maintenance Costs Categorized by System

Table 12 shows maintenance costs by vehicle system and bus study group (without warranty costs). The table provides the total ZEBA bus costs and the adjusted costs without FC8 and FC9. 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 12. Work Order Maintenance Cost per Mile by System (Evaluation Period)

System	ZEBA Cost per Mile ($)	ZEBA Percent of Total (%)	Adjusted ZEBA Cost per Mile ($)	Adjusted ZEBA Percent of Total (%)	Gillig Diesel Cost per Mile ($)	Gillig Diesel Percent of Total (%)
Propulsion-related	0.65	57	0.57	54	0.14	30
Cab, body, and accessories	0.19	17	0.18	17	0.13	28
PMI	0.13	12	0.13	13	0.08	17
Brakes	0.04	4	0.04	4	0.07	15
Frame, steering, and suspension	0.03	3	0.03	3	0.00	1
HVAC	0.06	5	0.06	5	0.01	3
Lighting	0.01	1	0.01	1	0.00	1
General air system repairs	0.02	2	0.02	2	0.02	5
Axles, wheels, and drive shaft	0.02	1	0.02	2	0.01	1
Tires	0.00	0	0.00	0	0.00	0
Total	***1.15***	*100*	***1.06***	100	***0.47***	*100*

The systems with the highest percentage of maintenance costs for the fuel cell buses were propulsion-related; cab, body, and accessories; and PMI. The Gillig diesel bus systems with the highest percentage of maintenance costs were the same as for the FCEBs. Figure 24 shows the monthly cost per mile by system for the ZEBA buses. Figure 25 shows the monthly cost per mile by system for the Gillig diesel buses. Appendix D provides additional graphs showing the monthly labor hours and maintenance costs by system for the ZEBA buses and Appendix G provides monthly maintenance graphs for the diesel buses.

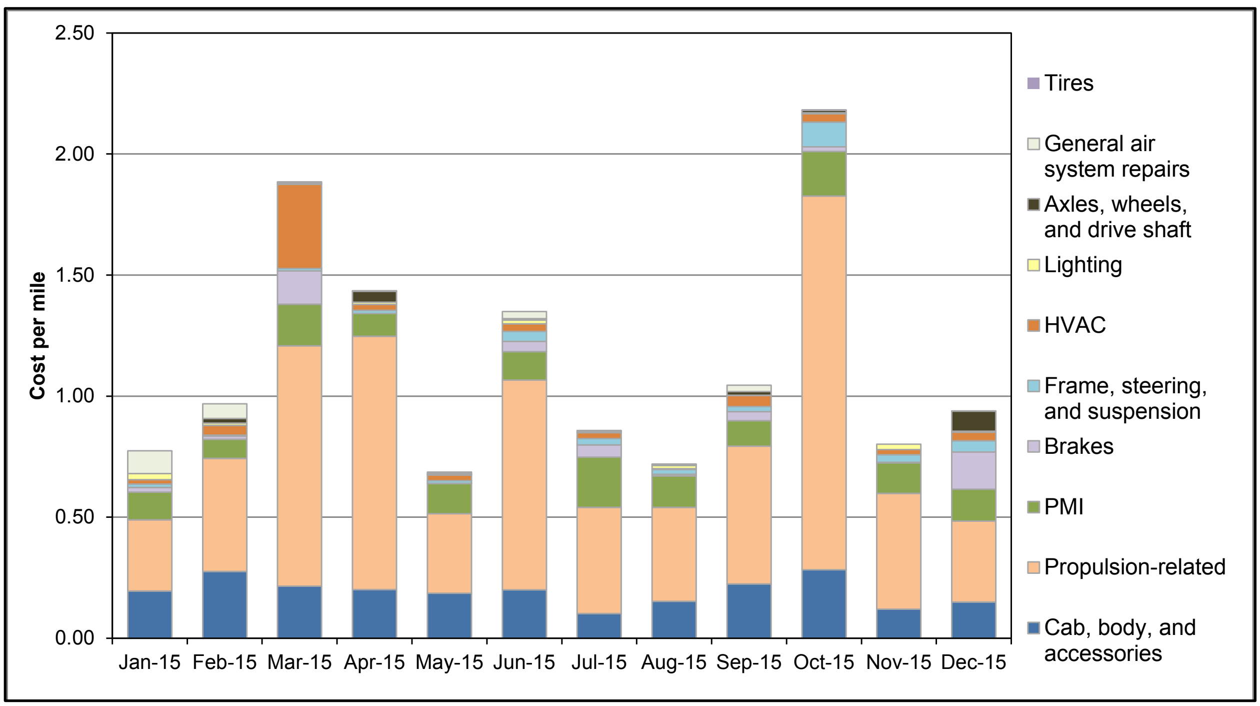

Figure 24. Monthly cost per mile by category for the ZEBA buses (evaluation period)

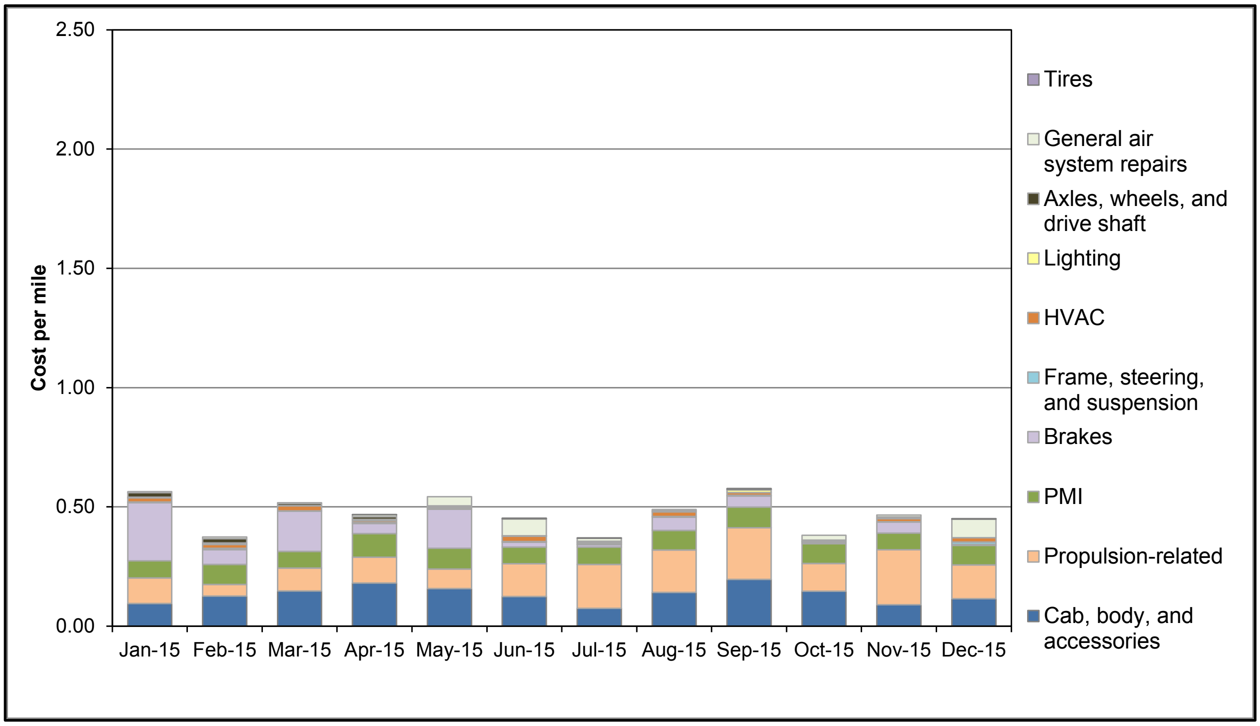

Figure 25. Monthly cost per mile by category for the Gillig diesel buses (evaluation period)

Propulsion-Related Work Order 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 13. P shows the propulsion-related system repairs by category for the study groups during the evaluation period. When compared to the new Gillig buses, the FCEBs' propulsion-related maintenance costs were 4.7 times higher. Removing the FC8 and FC9 data lowers the propulsion costs for the ZEBA buses from $0.65 per mile to $0.57 per mile.

Fuel system repairs accounted for 30% of the total propulsion costs for the FCEBs, due to the high parts cost of replacing the hydrogen tank valves on FC6. Electric propulsion system maintenance costs accounted for 25% of the total propulsion cost for the FCEBs. Power plant system repairs accounted for 15% of the total propulsion system costs. The majority of the propulsion costs for the Gillig diesel buses were for the non-lighting electric system (25%), exhaust system (24%), and power plant (18%). Appendix D and Appendix G provide figures showing the monthly labor and maintenance costs for the propulsion systems by sub-category.

Table 13. Propulsion-Related Work Order Maintenance Costs by System (Evaluation Period)

Maintenance System Costs	ZEBA	Gillig Diesel
Mileage	366,267	518,245
Total Propulsion-Related Systems (Roll-up)		
Parts cost ($)	127,316.39	34,570.55
Labor hours	2,210.4	746.5
Total cost ($)	237,836.89	71,895.05
Total cost ($) per mile	**0.65**	**0.14**
Exhaust System Repairs		
Parts cost ($)	2,357.20	7,937.56
Labor hours	83.0	189.1
Total cost ($)	6,507.20	17,391.06
Total cost ($) per mile	**0.02**	**0.03**
Fuel System Repairs		
Parts cost ($)	52,829.69	2,444.91
Labor hours	346.8	28.4
Total cost ($)	70,170.19	3,864.91
Total cost ($) per mile	**0.19**	**0.01**
Power Plant System Repairs		
Parts cost ($)	43.29	5,043.75
Labor hours	735.8	156.36
Total cost ($)	36,831.79	12,861.75
Total cost ($) per mile	**0.10**	**0.02**
Electric Propulsion System Repairs		
Parts cost ($)	26,322.26	0.00
Labor hours	683.4	0.0
Total cost ($)	60,493.76	0.00
Total cost ($) per mile	**0.17**	**0.00**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts cost ($)	1,034.31	10,965.17
Labor hours	110.5	139.7
Total cost ($)	6,558.81	17,950.17
Total cost ($) per mile	**0.02**	**0.03**
Air Intake System Repairs		
Parts cost ($)	26,914.91	5,056.63
Labor hours	15.3	65.37
Total cost ($)	27,681.41	8,325.13
Total cost ($) per mile	**0.08**	**0.02**
Cooling System Repairs		
Parts cost ($)	17,814.74	5,056.63
Labor hours	235.6	94.21
Total cost ($)	29,593.74	9,767.13
Total cost ($) per mile	**0.08**	**0.02**
Transmission System Repairs		
Parts cost ($)	0.00	488.19
Labor hours	0.0	70.55
Total cost ($)	0.00	4,015.69
Total cost ($) per mile	**0.00**	**0.01**

Total Project Costs

Throughout the demonstration, the ZEBA buses have incurred some costs that fall outside of the typical maintenance costs reported above. These costs were not included in the analysis presented in the previous maintenance cost sections. The following three activities have been handled primarily 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 have dropped over time as the maintenance staff has become familiar with the technology and taken over more of the maintenance work. During the evaluation period for the report, no hours were attributed to research activities. Any time spent in training was attributed to the specific system being worked on.
- **Shuttling FCEBs between depots**: During the evaluation period, the buses were operated out of both the Emeryville and Oakland divisions. Because Emeryville does not have a maintenance bay equipped to allow work on a hydrogen-fueled bus, AC Transit staff have 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 is currently retrofitting one of the Emeryville maintenance bays similar to what was done at the Oakland depot. Once the retrofit is complete, this shuttling activity will no longer be necessary. Occasionally, the baseline diesel buses were also shuttled from one depot to another for maintenance repair. For a fair comparison, NREL also removed the costs for shuttling the diesel buses from the analysis.
- **Fueling and cleaning**: In the early stage of the demonstration, AC Transit assigned maintenance staff 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. Over the evaluation period for the report, the FCEBs have been worked into the overall process. There were no hours attributed to this activity during the evaluation period.

These costs are considered non-recurring costs for the FCEBs; however, they add to the current cost per mile of the ZEBA buses. Table 14 shows the breakdown of these costs and how they affect the total cost per mile of the project. The table shows the non-recurring costs during three periods to show the decrease over time. The first time period was during the extended Emeryville hydrogen station downtime (as described in previous reports) when the buses were not operating and therefore not accumulating miles. The second period was the evaluation period from the previous report, and the third is the evaluation period that is the focus of this report. The non-recurring costs for the ZEBA fleet have dropped dramatically over the last year and add only $0.04 per mile to the operating cost of the buses for the evaluation period in this report. Once the Emeryville maintenance bay is completed, these costs should be completely eliminated.

Table 14. Maintenance Costs for ZEBA Buses, Including Non-Recurring Labor

	Mileage	Labor Hours	Total Cost	Cost per Mile
Emeryville station downtime period (May 2012–Feb 2013)				
Shuttle FCEBs	19,296	118.5	5,925	0.31
Research/training	19,296	1,703	85,169	4.41
Fuel and clean	19,296	908	45,412	2.35
Total	***19,296***	***2,730***	***136,506***	***7.07***
Previous report evaluation period (Mar 2013–Dec 2014)				
Shuttle FCEBs	676,822	543	27,134	0.04
Research/training	676,822	368	18,425	0.03
Fuel and clean	676,822	95	4,740	0.01
Total	***676,822***	***1,006***	***50,298***	***0.07***
Evaluation period for this report (Jan 2015–Dec 2015)				
Shuttle FCEBs	366,267	305	15,242	0.04
Research/training	366,267	0	0	0.00
Fuel and clean	366,267	0	0	0.00
Total	***366,267***	***305***	***15,242***	***0.04***

Costs for AC Transit's extended support agreements with US Hybrid and EnerDel began in April 2014. While the cost for these agreements is covered through the FTA grant, other interested agencies should understand the current costs for FCEBs outside of the initial warranty period. Table 15 summarizes the total costs for the ZEBA and diesel baseline buses including the extra labor and extended support during the evaluation period. The cost for shuttling the diesel buses between depots adds less than one cent to the total cost per mile.

Table 15. Total Maintenance Cost per Mile Including Extra Labor and Extended Support (Evaluation Period)

	ZEBA	Gillig
Maintenance labor hours	4,942.4	3,252.9
Extra labor hours	304.8	38.3
Total labor hours	5,247.2	3,291.2
Total parts cost	$172,912	$80,345
Extended warranty cost	$335,957	—
Total cost per mile	$2.11	$0.47

What's Next for ZEBA

AC Transit's plans for the ZEBA demonstration are to continue operating the buses for the full 12 year expected life. All of the buses will operate from the Oakland Division while upgrades are made to the Emeryville Division. After the construction is complete, AC Transit will operate four buses out of Emeryville and nine buses at Oakland. NREL will continue to evaluate the buses for at least one more year and will collect data and experience from the other operators should they decide to put the buses in service.

Contacts

DOE
1000 Independence Ave., SW
Washington, DC 20585

Jason Marcinkoski, Technology Development Manager, Fuel Cell Technologies Office
Phone: 202-586-7466
Email: jason.marcinkoski@ee.doe.gov

NREL
15013 Denver West Parkway
Golden, CO 80401

Leslie Eudy, Senior Project Leader
Phone: 303-275-4412
Email: leslie.eudy@nrel.gov

AC Transit
1700 Franklin Street
Oakland, CA 94612

Salvador Llamas, Director of Maintenance
Phone: 510-577-8803
Email: sllamas@actransit.org

US Hybrid Corporation
445 Maple Avenue
Torrance, CA 90503

Abas Goodarzi, President, CEO
Phone: 310-212-1200, Ext. 111
Email: abas@ushybrid.com

EnerDel Inc.
15425 Herriman Blvd.
Noblesville, IN 46060

Tomasz Posnar, Vice President, Transportation and Aftermarket
Phone: 954-401-0338
Email: tomasz.poznar@enerdel.com

Van Hool
Bernard Van Hoolstraat 58
B-2500 Lier Koningshooikt, Belgium

Paul Jenné, Automotive Relations
Phone: +32 (3) 420 22 10
Email: paul.jenne@vanhool.be

Linde, LLC
2389 Lincoln Avenue
Hayward, CA 94545

Nitin Natesan, Engineering Manager, Alternative Energy Projects
Phone: 510-786-5931
Email: nitin.natesan@lindeus.com

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.

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Appendix A: TRL Guideline Table

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.

Appendix B: ZEBA Fleet Summary Statistics

ZEBA Fleet Operations and Economics

	ZEBA 9/11–4/12 (Early Service)	ZEBA 5/12–2/13 (Station Downtime Period)	ZEBA 3/13–12/15 (Data Period)	ZEBA 1/15–12/15 (Report Evaluation Period)
Number of vehicles	12	12	12	13
Period used for fuel and oil op analysis	9/11–4/12	5/12–2/13	3/13–12/15	1/15–12/15
Total number of months in period	8	10	34	12
Fuel and oil analysis base fleet mileage	120,355	16,281	967,318	334,874
Period used for maintenance op analysis	9/11–4/12	5/12–2/13	3/13–12/15	1/15–12/15
Total number of months in period	8	10	34	12
Maintenance analysis base fleet mileage	147,129	19,296	1,043,089	366,267
Average monthly mileage per vehicle	1,598	—	2,538	2,492
Availability	56%	—	76%	74%
Fleet fuel usage (H_2 in kg / diesel in gallons)	18,016.0	2,125.2	159,855.0	61,221.9
Total roadcalls	73	—	188	74
MBRC – all systems	2,014	—	5,548	4,950
Propulsion roadcalls	49	—	109	41
Propulsion MBRC	3,000	—	9,570	8,933
Fleet miles/kg hydrogen (1.13 kg H_2)	6.68	7.66	6.05	5.47
Representative fleet MPG (energy equivalent)	7.55	8.66	6.84	6.18
Hydrogen cost per kg	9.34	8.47	8.94	8.62
Fuel cost per mile	**1.40**	**1.11**	**1.48**	**1.58**
Total scheduled repair cost per mile	0.26	0.08	0.17	0.20
Total unscheduled repair cost per mile	1.05	3.11	0.45	0.94
Total maintenance cost per mile	**1.31**	**3.20**	**0.62**	**1.15**
Total operating cost per mile	***2.71***	***4.30***	***2.09***	***2.72***
Extended Support cost (beginning in April 2014)			$335,957	$335,957
Extra labor costs per mile (research, shuttling)	0.27	7.07	0.06	0.04
Total operating cost per mile (incl. extended support and extra costs)	***2.98***	***11.38***	***2.94***	***3.68***

Maintenance Costs

	ZEBA 9/11–4/12 (Early Service)	ZEBA 5/12–2/13 (Station Downtime Period)	ZEBA 3/13–12/15 (Data Period)	ZEBA 1/15–12/15 (Report Evaluation Period)
Fleet mileage	147,007	19,296	1,043,089	366,267
Total parts cost	31,727.9	10,720.0	139,781.4	172,911.9
Total labor hours	3,219.70	1,020.2	5,532.0	4,942.4
Average labor cost (@ $50.00 per hour)	160,985.00	51,009.00	276,600.00	247,120.00
Total maintenance cost	192,712.88	61,729.00	416,381.43	420,031.93
Total maintenance cost per bus	16,059.41	5,144.08	34,698.45	35,002.66
Total maintenance cost per mile	***1.31***	***3.20***	***0.40***	***1.15***

Breakdown of Maintenance Costs by Vehicle System

	ZEBA 9/11–4/12 (Early Service)	ZEBA 5/12–2/13 (Station Downtime Period)	ZEBA 3/13–12/15 (Data Period)	ZEBA 1/15–12/15 (Report Evaluation Period)
Fleet mileage	147,007	19,296	1,043,089	366,267
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	5,957.71	9,454.37	78,177.83	127,316.39
Labor hours	1,012.7	672.0	2,211.0	2,210.4
Average labor cost	50,633.50	33,599.50	110,550.00	110,520.50
Total cost (for system)	56,591.21	43,053.87	188,727.83	237,836.89
Total cost (for system) per bus	4,715.93	3,587.82	15,727.32	19,819.74
Total cost (for system) per mile	**0.38**	**2.23**	**0.18**	**0.65**
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	0.00	2,357.20
Labor hours	0.0	0.0	0.0	83.0
Average labor cost	0.00	0.00	0.00	4,150.00
Total cost (for system)	0.00	0.00	0.00	6,507.20
Total cost (for system) per bus	0.00	0.00	0.00	542.27
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.02**
Fuel System Repairs (ATA VMRS 44)				
Parts cost	15.47	0.00	26.75	52,829.69
Labor hours	166.7	30.4	161.6	346.8
Average labor cost	8,335.00	1,520.50	8,080.50	17,340.50
Total cost (for system)	8,350.47	1,520.50	8,107.25	70,170.19
Total cost (for system) per bus	695.87	126.71	675.60	5,847.52
Total cost (for system) per mile	**0.06**	**0.08**	**0.01**	**0.19**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	260.89	165.98	259.96	43.29
Labor hours	204.0	203.2	590.8	735.8
Average labor cost	10,200.50	10,160.50	29,538.50	36,788.50
Total cost (for system)	10,461.39	10,326.48	29,798.46	36,831.79
Total cost (for system) per bus	871.78	860.54	2,483.21	3,069.32
Total cost (for system) per mile	**0.07**	**0.54**	**0.03**	**0.10**
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	1,251.77	0.00	26,048.55	26,322.26
Labor hours	458.5	329.3	830.4	683.4
Average labor cost	22,924.00	16,463.00	41,520.00	34,171.50
Total cost (for system)	24,175.77	16,463.00	67,568.55	60,493.76
Total cost (for system) per bus	2,014.65	1,371.92	5,630.71	5,041.15
Total cost (for system) per mile	**0.16**	**0.85**	**0.06**	**0.17**

Breakdown of Maintenance Costs by Vehicle System (continued)

	ZEBA 9/11–4/12 (Early Service)	ZEBA 5/12–2/13 (Station Downtime Period)	ZEBA 3/13–12/15 (Data Period)	ZEBA 1/15–12/15 (Report Evaluation Period)
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	1,747.91	2,823.98	3,675.76	1,034.31
Labor hours	81.3	46.7	125.9	110.5
Average labor cost	4,064.50	2,337.00	6,293.50	5,524.50
Total cost (for system)	5,812.41	5,160.98	9,969.26	6,558.81
Total cost (for system) per bus	484.37	430.08	830.77	546.57
Total cost (for system) per mile	**0.04**	**0.27**	**0.01**	**0.02**
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	2,152.28	6,096.88	25,288.54	26,914.91
Labor hours	8.7	13.6	271.9	15.3
Average labor cost	435.50	678.00	13,594.50	766.50
Total cost (for system)	2,587.78	6,774.88	38,883.04	27,681.41
Total cost (for system) per bus	215.65	564.57	3,240.25	2,306.78
Total cost (for system) per mile	**0.02**	**0.35**	**0.04**	**0.08**
Cooling System Repairs (ATA VMRS 42)				
Parts cost	529.39	367.53	22,878.26	17,814.74
Labor hours	93.5	48.8	230.5	235.6
Average labor cost	4,674.00	2,440.50	11,523.00	11,779.00
Total cost (for system)	5,203.39	2,808.03	34,401.26	29,593.74
Total cost (for system) per bus	433.62	234.00	2,866.77	2,466.14
Total cost (for system) per mile	**0.04**	**0.15**	**0.03**	**0.08**
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	0.0	0.0	0.0	0.0
Average labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	0.00	0.00
Total cost (for system) per bus	0.00	0.00	0.00	0.00
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)				
Parts cost	3,875.75	0.00	35,074.27	2,570.36
Labor hours	66.4	10.3	147.0	81.7
Average labor cost	3,321.50	516.00	7,349.00	4,083.00
Total cost (for system)	7,197.25	516.00	42,423.27	6,653.36
Total cost (for system) per bus	599.77	43.00	3,535.27	554.45
Total cost (for system) per mile	**0.05**	**0.03**	**0.04**	**0.02**

Breakdown of Maintenance Costs by Vehicle System (continued)

	ZEBA 9/11–4/12 (Early Service)	ZEBA 5/12–2/13 (Station Downtime Period)	ZEBA 3/13–12/15 (Data Period)	ZEBA 1/15–12/15 (Report Evaluation Period)
Brake System Repairs (ATA VMRS 13)				
Parts cost	321.45	0.00	2,729.83	10,094.68
Labor hours	24.0	0.0	117.9	116.3
Average labor cost	1,200.00	0.00	5,897.00	5,816.50
Total cost (for system)	1,521.45	0.00	8,626.83	15,911.18
Total cost (for system) per bus	126.79	0.00	718.90	1,325.93
Total cost (for system) per mile	**0.01**	**0.00**	**0.01**	**0.04**
Transmission Repairs (ATA VMRS 27)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	0.0	0.0	0.0	0.0
Average labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	0.00	0.00
Total cost (for system) per bus	0.00	0.00	0.00	0.00
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Inspections Only - no parts replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	669.0	19.5	1,239.6	981.8
Average labor cost	33,449.50	975.00	61,980.50	49,089.50
Total cost (for system)	33,449.50	975.00	61,980.50	49,089.50
Total cost (for system) per bus	2,787.46	81.25	5,165.04	4,090.79
Total cost (for system) per mile	**0.23**	**0.05**	**0.06**	**0.13**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	18,550.84	1,120.55	10,735.34	7,965.98
Labor hours	1,281.2	257.9	1,475.5	1,228.7
Average labor cost	64,059.00	12,896.50	73,775.00	61,433.00
Total cost (for system)	82,609.84	14,017.05	84,510.34	69,398.98
Total cost (for system) per bus	6,884.15	1,168.09	7,042.53	5,783.25
Total cost (for system) per mile	**0.56**	**0.73**	**0.08**	**0.19**
HVAC System Repairs (ATA VMRS 01)				
Parts cost	897.40	0.00	3,129.51	14,978.19
Labor hours	14.7	5.0	105.8	114.3
Average labor cost	735.00	249.00	5,291.50	5,716.00
Total cost (for system)	1,632.40	249.00	8,421.01	20,694.19
Total cost (for system) per bus	136.03	20.75	701.75	1,724.52
Total cost (for system) per mile	**0.01**	**0.01**	**0.01**	**0.06**

Breakdown of Maintenance Costs by Vehicle System (continued)

	ZEBA 9/11–4/12 (Early Service)	ZEBA 5/12–2/13 (Station Downtime Period)	ZEBA 3/13–12/15 (Data Period)	ZEBA 1/15–12/15 (Report Evaluation Period)
Lighting System Repairs (ATA VMRS 34)				
Parts cost	290.00	27.62	1,317.14	459.11
Labor hours	24.4	3.3	82.0	61.4
Average labor cost	1,220.50	165.50	4,099.50	3,070.00
Total cost (for system)	1,510.50	193.12	5,416.64	3,529.11
Total cost (for system) per bus	125.88	16.09	451.39	294.09
Total cost (for system) per mile	**0.01**	**0.01**	**0.01**	**0.01**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	1,751.91	108.48	8,614.90	4,290.00
Labor hours	103.2	52.2	138.7	129.8
Average labor cost	5,161.00	2,607.50	6,932.50	6,491.50
Total cost (for system)	6,912.91	2,715.98	15,547.40	10,781.50
Total cost (for system) per bus	576.08	226.33	1,295.62	898.46
Total cost (for system) per mile	**0.05**	**0.14**	**0.01**	**0.03**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	5.48	0.00	2.61	5,237.23
Labor hours	22.6	0.0	13.5	16.0
Average labor cost	1,131.50	0.00	675.00	800.00
Total cost (for system)	1,136.98	0.00	677.61	6,037.23
Total cost (for system) per bus	94.75	0.00	56.47	503.10
Total cost (for system) per mile	**0.01**	**0.00**	**0.00**	**0.02**
Tire Repairs (ATA VMRS 17)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	0.0	0.0	1.0	2.0
Average labor cost	0.00	0.00	50.00	100.00
Total cost (for system)	0.00	0.00	50.00	100.00
Total cost (for system) per bus	0.00	0.00	4.17	8.33
Total cost (for system) per mile	**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 C: ZEBA Fleet Summary Statistics—SI Units

ZEBA Fleet Operations and Economics

	ZEBA 9/11–4/12 (Early Service)	ZEBA 5/12–2/13 (Station Downtime Period)	ZEBA 3/13–12/15 (Data Period)	ZEBA 1/15–12/15 (Report Evaluation Period)
Number of vehicles	12	12	12	12
Period used for fuel and oil op analysis	9/11–4/12	5/12–2/13	3/13–12/15	1/15–12/15
Total number of months in period	8	10	34	12
Fuel and oil analysis base fleet kilometers	193,687	26,201	1,556,705	538,913
Period used for maintenance op analysis	9/11–4/12	5/12–2/13	3/13–12/15	1/15–12/15
Total number of months in period	8	10	34	12
Maintenance analysis base fleet kilometers	236,775	31,053	1,678,643	589,433
Average monthly kilometers per vehicle	2,572	—	4,084	4,010
Availability	1	—	76%	74%
Fleet fuel usage (H_2 in kg / diesel in liters)	18,016	2,125	159,855	61,222
Total roadcalls	73	—	188	74
KMBRC – all systems	3,243	—	8,929	7,965
Propulsion roadcalls	49	—	109	41
Propulsion KMBRC	4,832	—	15,400	14,376
Fleet kg hydrogen/100 km (1.13 kg H_2)	9.30	8.11	10.27	11.36
Representative fleet fuel consumption (L/100 km)	31.16	27.17	34.40	38.05
Hydrogen cost per kg	9.34	8.47	8.94	8.62
Fuel cost per kilometer	**0.87**	**0.69**	**0.92**	**0.98**
Total scheduled repair cost per kilometer	0.01	0.05	0.07	0.13
Total unscheduled repair cost per kilometer	0.25	1.94	0.18	0.59
Total maintenance cost per kilometer	**0.26**	**1.99**	**0.25**	**0.71**
Total operating cost per kilometer	***1.13***	***2.67***	***1.17***	***1.69***
Extended Warranty cost (beginning in April 2014)			$335,957	$335,957
Extra labor costs per kilometer (research, shuttling)	0.17	4.40	0.04	0.03
Total operating cost per kilometer (incl. warranty and extra costs)	***1.30***	***7.07***	***1.41***	***2.29***

Maintenance Costs

	ZEBA 9/11–4/12 (Early Service)	ZEBA 5/12–2/13 (Station Downtime Period)	ZEBA 3/13–12/15 (Data Period)	ZEBA 1/15–12/15 (Report Evaluation Period)
Fleet mileage	236,775	31,053	1,678,643	589,433
Total parts cost	31,727.9	10,720.0	139,781.4	172,911.9
Total labor hours	3,219.70	1,020.18	5,532.00	4,942.40
Average labor cost (@ $50.00 per hour)	160,985.00	51,009.00	276,600.00	247,120.00
Total maintenance cost	192,712.88	61,729.00	416,381.43	420,031.93
Total maintenance cost per bus	16,059.41	5,144.08	34,698.45	35,002.66
Total maintenance cost per kilometer	***0.81***	***1.99***	***0.25***	***0.71***

Appendix D: ZEBA Monthly Maintenance Analysis Graphs

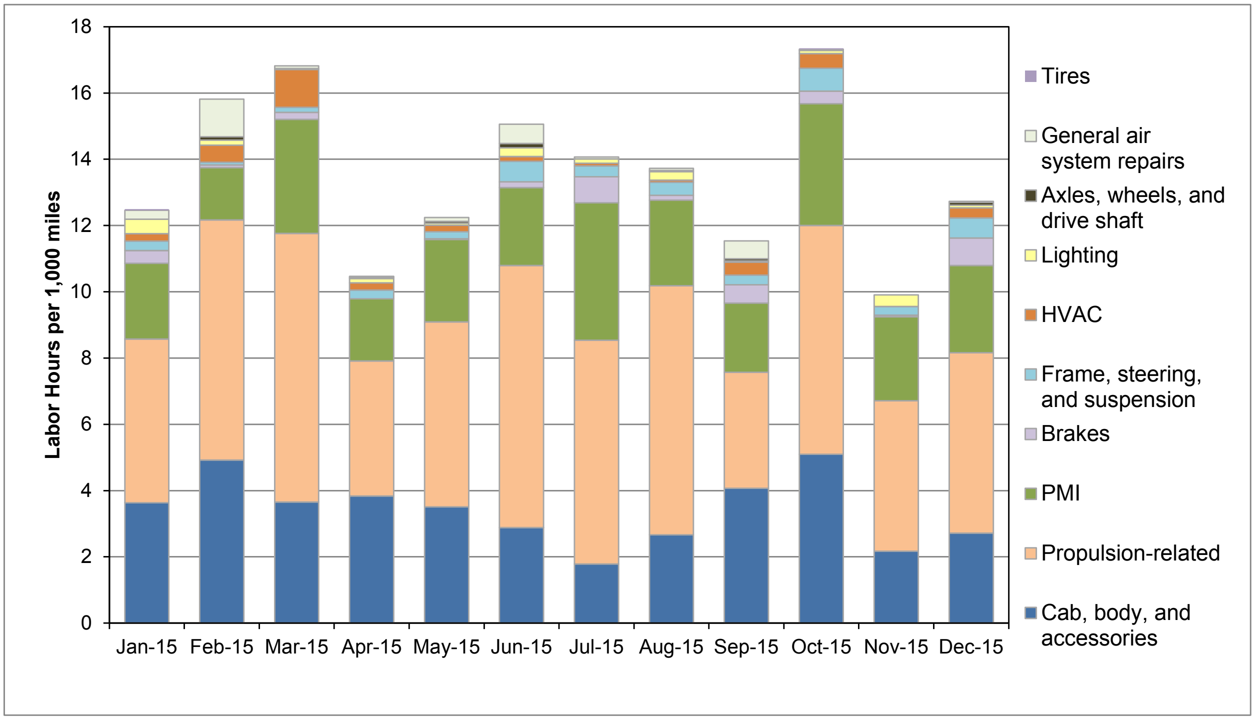

Figure D-1. Monthly labor hours by category for the ZEBA buses

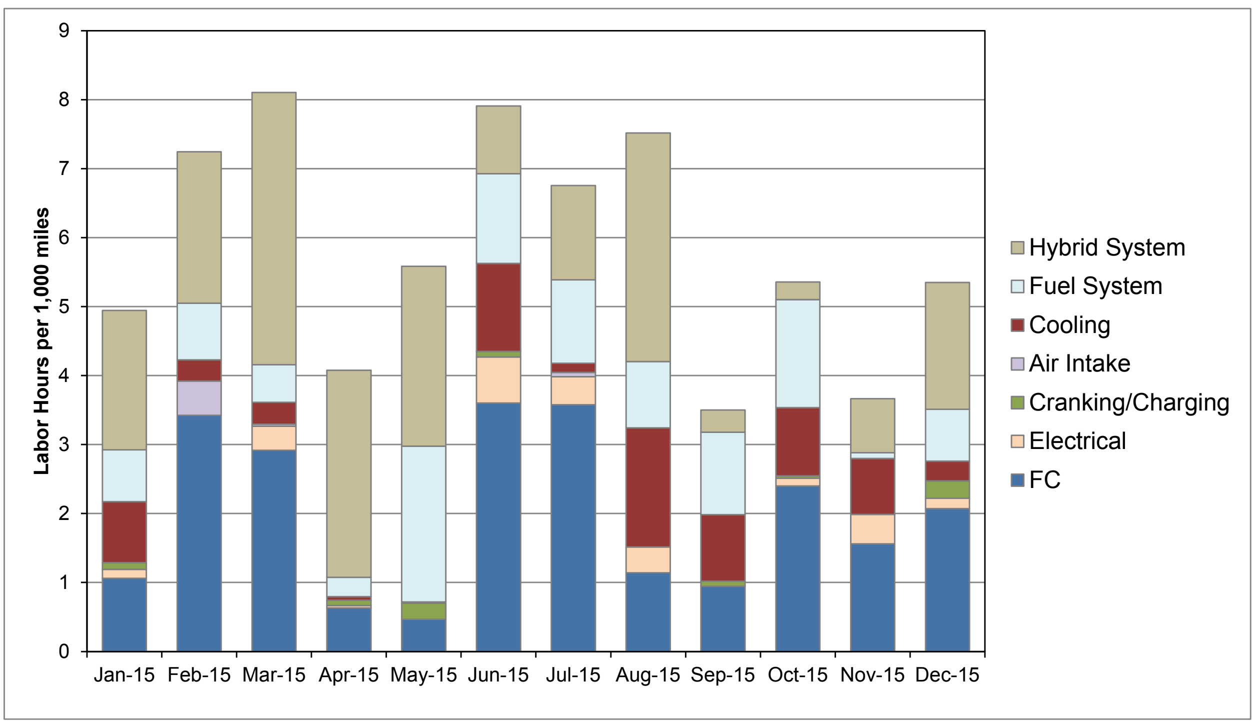

Figure D-2. Monthly propulsion system labor hours by sub-category for the ZEBA buses

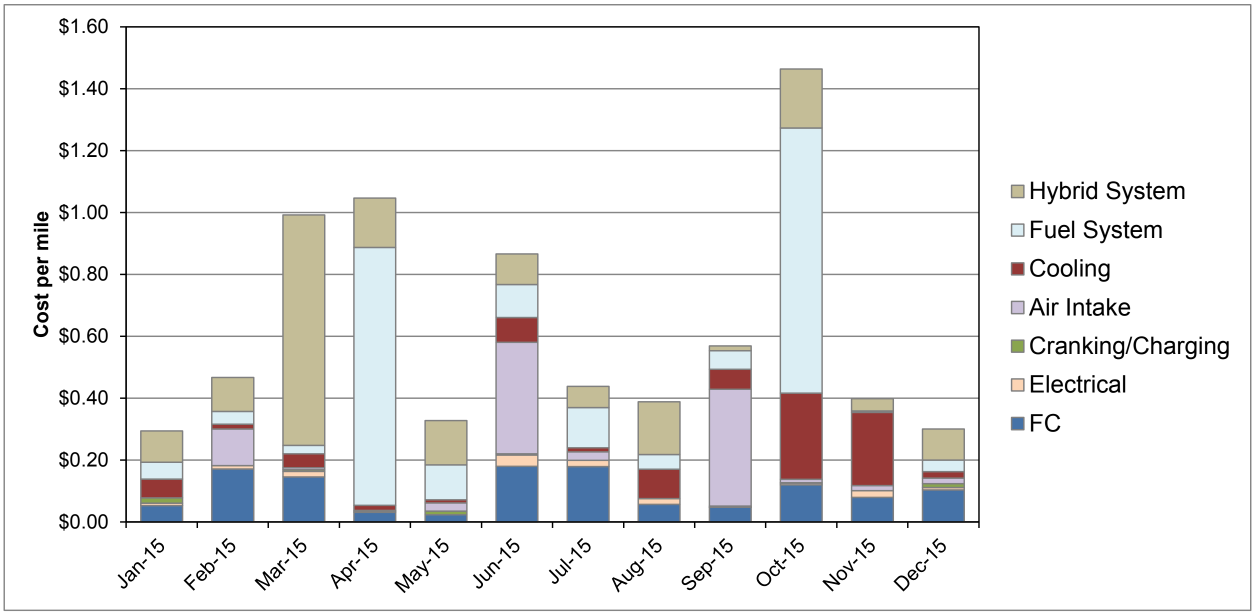

Figure D-3. Monthly propulsion system cost per mile by sub-category for the ZEBA buses

Appendix E: Diesel Fleet Summary Statistics

Gillig Diesel Fleet Operations and Economics

	Gillig Diesel 7/13–12/15 (Data Period)	Gillig Diesel 1/15–12/15 (Report Evaluation Period)
Number of vehicles	10	10
Period used for fuel and oil op analysis	7/13–12/15	1/1–12/15
Total number of months in period	30	12
Fuel and oil analysis base fleet mileage	1,266,012	458,802
Period used for maintenance op analysis	7/1–12/15	1/1–12/15
Total number of months in period	30	12
Maintenance analysis base fleet mileage	1,390,732	518,245
Average monthly mileage per vehicle	4,636	4,319
Availability	88%	89%
Fleet fuel usage (gallons)	296,043.0	107,985.1
Roadcalls	200	75
RCs MBRC	6,954	6,910
Propulsion roadcalls	90	48
Propulsion MBRC	15,453	10,797
Representative fleet MPG (energy equivalent)	4.28	4.25
Diesel cost per gallon	2.56	1.86
Fuel cost per mile	**0.60**	**0.44**
Total scheduled repair cost per mile	0.13	0.14
Total unscheduled repair cost per mile	0.20	0.32
Total maintenance cost per mile	**0.32**	**0.47**
Total operating cost per mile	***0.92***	***0.91***

Maintenance Costs

	Gillig Diesel 7/13–12/15 (Data Period)	Gillig Diesel 1/15–12/15 (Report Evaluation Period)
Fleet mileage	1,390,732	518,245
Total parts cost	122,583.8	80,344.9
Total labor hours	6532.0	3252.9
Average labor cost (@ $50.00 per hour)	326,597.50	162,643.00
Total maintenance cost	449,181.31	242,987.91
Total maintenance cost per bus	44,918.13	24,298.79
Total maintenance cost per mile	***0.32***	***0.47***

Breakdown of Maintenance Costs by Vehicle System

	Gillig Diesel 7/13–12/15 (Data Period)	Gillig Diesel 1/15–12/15 (Report Evaluation Period)
Fleet mileage	1,390,732	518,245
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)		
Parts cost	56,787.82	34,570.55
Labor hours	1,333.6	746.5
Average labor cost	66,679.50	37,324.50
Total cost (for system)	123,467.32	71,895.05
Total cost (for system) per bus	12,346.73	7,189.50
Total cost (for system) per mile	**0.09**	**0.14**
Exhaust System Repairs (ATA VMRS 43)		
Parts cost	7,980.27	7,937.56
Labor hours	213.3	189.1
Average labor cost	10,664.00	9,453.50
Total cost (for system)	18,644.27	17,391.06
Total cost (for system) per bus	1,864.43	1,739.11
Total cost (for system) per mile	**0.01**	**0.03**
Fuel System Repairs (ATA VMRS 44)		
Parts cost	6,620.46	2,444.91
Labor hours	77.9	28.4
Average labor cost	3,893.00	1,420.00
Total cost (for system)	10,513.46	3,864.91
Total cost (for system) per bus	1,051.35	386.49
Total cost (for system) per mile	**0.01**	**0.01**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts cost	9,825.57	5,043.75
Labor hours	320.2	156.4
Average labor cost	16,009.00	7,818.00
Total cost (for system)	25,834.57	12,861.75
Total cost (for system) per bus	2,583.46	1,286.18
Total cost (for system) per mile	**0.02**	**0.02**
Electric Propulsion Repairs (ATA VMRS 46)		
Parts cost	0.00	0.00
Labor hours	0.0	0.0
Average labor cost	0.00	0.00
Total cost (for system)	0.00	0.00
Total cost (for system) per bus	0.00	0.00
Total cost (for system) per mile	**0.00**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Gillig Diesel 7/13–12/15 (Data Period)	Gillig Diesel 1/15–12/15 (Report Evaluation Period)
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts cost	12,987.16	10,965.17
Labor hours	271.1	139.7
Average labor cost	13,555.00	6,985.00
Total cost (for system)	26,542.16	17,950.17
Total cost (for system) per bus	2,654.22	1,795.02
Total cost (for system) per mile	**0.02**	**0.03**
Air Intake System Repairs (ATA VMRS 41)		
Parts cost	9,885.32	5,056.63
Labor hours	124.7	65.4
Average labor cost	6,232.50	3,268.50
Total cost (for system)	16,117.82	8,325.13
Total cost (for system) per bus	1,611.78	832.51
Total cost (for system) per mile	**0.01**	**0.02**
Cooling System Repairs (ATA VMRS 42)		
Parts cost	6,808.36	2,000.89
Labor hours	153.0	94.2
Average labor cost	7,648.00	4,710.50
Total cost (for system)	14,456.36	6,711.39
Total cost (for system) per bus	1,445.64	671.14
Total cost (for system) per mile	**0.01**	**0.01**
Hydraulic System Repairs (ATA VMRS 65)		
Parts cost	1,420.18	633.45
Labor hours	12.1	2.8
Average labor cost	604.00	141.50
Total cost (for system)	2,024.18	774.95
Total cost (for system) per bus	202.42	77.50
Total cost (for system) per mile	**0.00**	**0.00**
General Air System Repairs (ATA VMRS 10)		
Parts cost	6,390.24	6,339.47
Labor hours	120.2	100.4
Average labor cost	6,010.50	5,019.50
Total cost (for system)	12,400.74	11,358.97
Total cost (for system) per bus	1,240.07	1,135.90
Total cost (for system) per mile	**0.01**	**0.02**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Gillig Diesel 7/13–12/15 (Data Period)	Gillig Diesel 1/15–12/15 (Report Evaluation Period)
Brake System Repairs (ATA VMRS 13)		
Parts cost	19,809.30	17,589.63
Labor hours	457.8	356.3
Average labor cost	22,888.50	17,812.50
Total cost (for system)	42,697.80	35,402.13
Total cost (for system) per bus	4,269.78	3,540.21
Total cost (for system) per mile	**0.03**	**0.07**
Transmission Repairs (ATA VMRS 27)		
Parts cost	1,260.50	488.19
Labor hours	161.5	70.6
Average labor cost	8,074.00	3,527.50
Total cost (for system)	9,334.50	4,015.69
Total cost (for system) per bus	933.45	401.57
Total cost (for system) per mile	**0.01**	**0.01**
Inspections Only - no parts replacements (101)		
Parts cost	0.00	0.00
Labor hours	1,810.5	827.9
Average labor cost	90,524.50	41,397.00
Total cost (for system)	90,524.50	41,397.00
Total cost (for system) per bus	9,052.45	4,139.70
Total cost (for system) per mile	**0.07**	**0.08**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts cost	33,029.76	17,657.06
Labor hours	2,376.0	1,028.6
Average labor cost	118,799.00	51,429.00
Total cost (for system)	151,828.76	69,086.06
Total cost (for system) per bus	15,182.88	6,908.61
Total cost (for system) per mile	**0.11**	**0.13**
HVAC System Repairs (ATA VMRS 01)		
Parts cost	4,371.33	3,032.04
Labor hours	202.0	73.1
Average labor cost	10,097.50	3,653.00
Total cost (for system)	14,468.83	6,685.04
Total cost (for system) per bus	1,446.88	668.50
Total cost (for system) per mile	**0.01**	**0.01**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Gillig Diesel 7/13–12/15 (Data Period)	Gillig Diesel 1/15–12/15 (Report Evaluation Period)
Lighting System Repairs (ATA VMRS 34)		
Parts cost	1,197.78	610.36
Labor hours	64.2	28.5
Average labor cost	3,211.00	1,424.50
Total cost (for system)	4,408.78	2,034.86
Total cost (for system) per bus	440.88	203.49
Total cost (for system) per mile	**0.00**	**0.00**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts cost	280.70	62.31
Labor hours	68.1	32.6
Average labor cost	3,404.50	1,631.50
Total cost (for system)	3,685.20	1,693.81
Total cost (for system) per bus	368.52	169.38
Total cost (for system) per mile	**0.00**	**0.00**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts cost	716.88	483.50
Labor hours	73.8	50.0
Average labor cost	3,691.00	2,501.50
Total cost (for system)	4,407.88	2,985.00
Total cost (for system) per bus	440.79	298.50
Total cost (for system) per mile	**0.00**	**0.01**
Tire Repairs (ATA VMRS 17)		
Parts cost	0.00	0.00
Labor hours	25.8	9.0
Average labor cost	1,291.50	450.00
Total cost (for system)	1,291.50	450.00
Total cost (for system) per bus	129.15	45.00
Total cost (for system) per mile	**0.00**	**0.00**

Appendix F: Diesel Fleet Summary Statistics—SI Units

Gillig Diesel Fleet Operations and Economics

	Gillig Diesel 7/13–12/15 (Data Period)	Gillig Diesel 1/15–12/15 (Report Evaluation Period)
Number of vehicles	10	10
Period used for fuel and oil op analysis	7/13-12/15	1/15-12/15
Total number of months in period	30	12
Fuel and oil analysis base fleet kilometers	2,037,393	738,350
Period used for maintenance op analysis	7/13-12/15	1/15-12/15
Total number of months in period	30	12
Maintenance analysis base fleet kilometers	2,238,105	834,012
Average monthly kilometers per vehicle	7,460	6,950
Availability	88%	89%
Fleet fuel usage (L)	1,120,645	408,768
Roadcalls	200	75
KMBRC – all systems	11,191	11,120
Propulsion roadcalls	90	48
Propulsion KMBRC	24,868	17,375
Representative fleet fuel consumption (L/100 km)	55.00	55.36
Diesel cost/liter	0.68	0.49
Fuel cost per kilometer	**0.37**	**0.27**
Total scheduled repair cost per kilometer	0.08	0.09
Total unscheduled repair cost per kilometer	0.12	0.20
Total maintenance cost per kilometer	**0.20**	**0.29**
Total operating cost per kilometer	***0.57***	***0.56***

Maintenance Costs

	Gillig Diesel 7/13–12/15 (Data Period)	Gillig Diesel 1/15–12/15 (Report Evaluation Period)
Fleet kilometers	2,238,105	834,012
Total parts cost	122,583.8	80,344.9
Total labor hours	6,532.0	3,252.9
Average labor cost (@ $50.00 per hour)	326,597.50	162,643.00
Total maintenance cost	449,181.31	242,987.91
Total maintenance cost per bus	44,918.13	24,298.79
Total maintenance cost per kilometer	***0.20***	***0.29***

Appendix G: Diesel Monthly Labor Hour Graphs

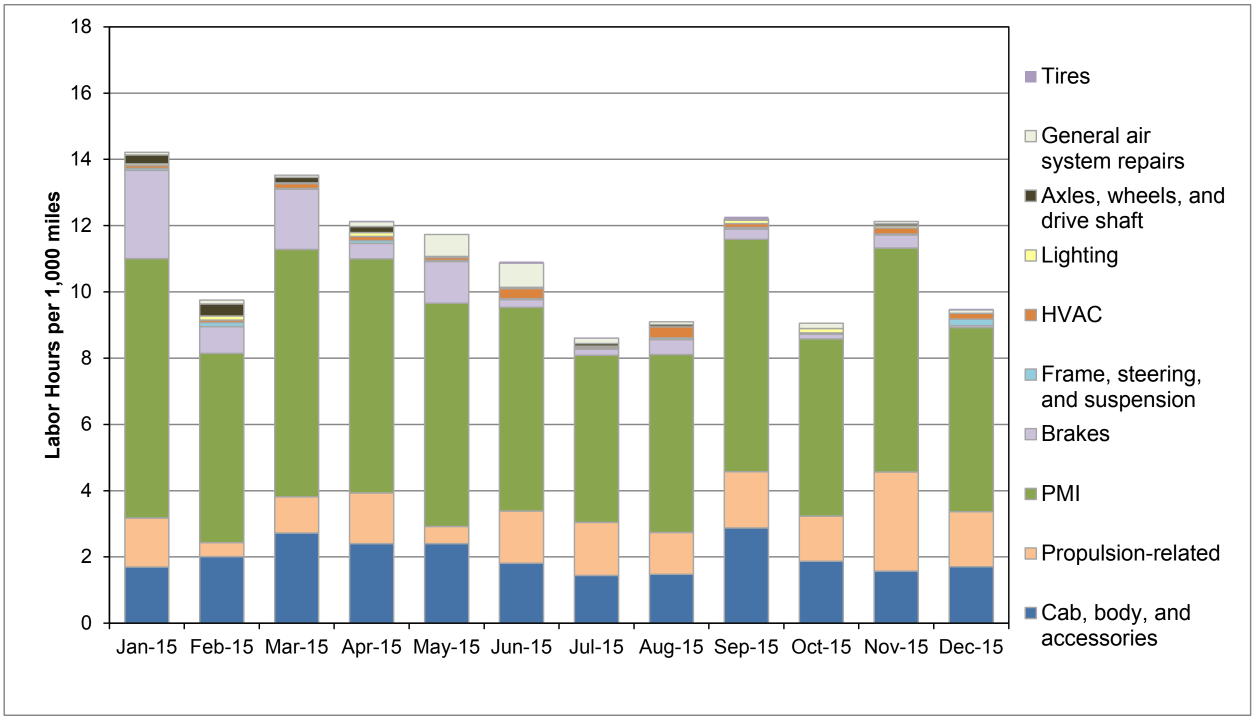

Figure G-1. Monthly labor hours by category for the Gillig diesel buses

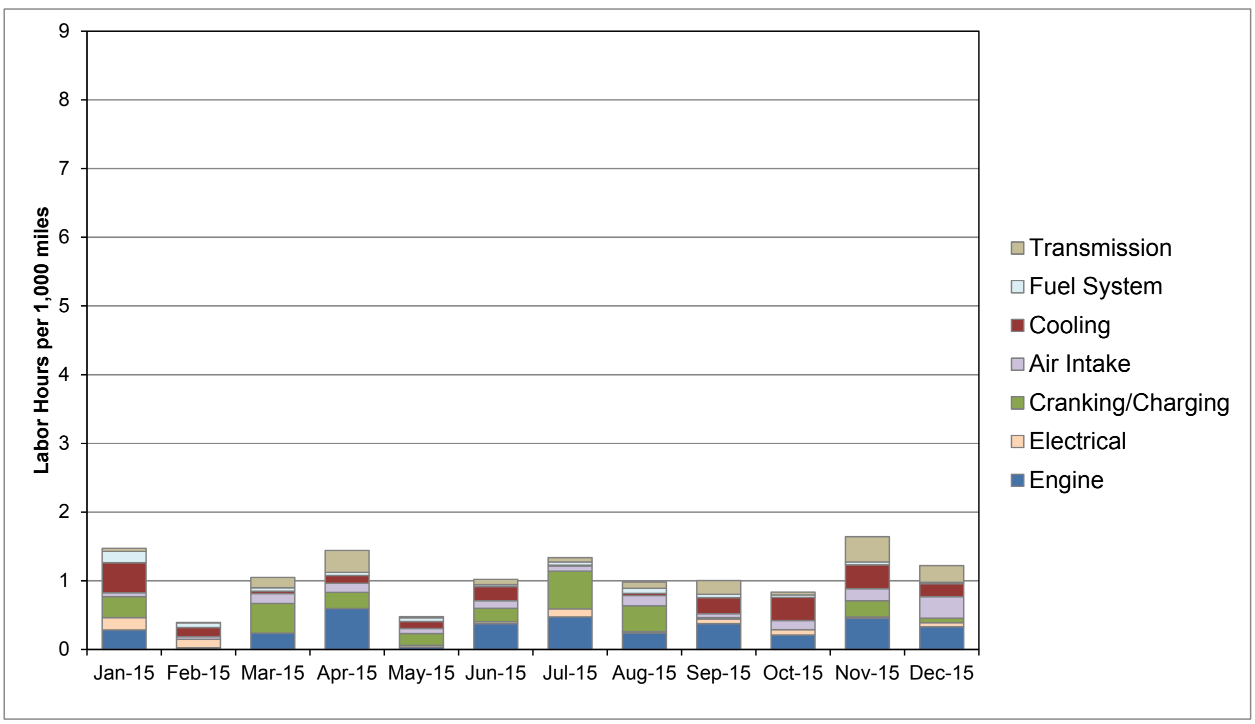

Figure G-2. Monthly propulsion system labor hours by sub-category for the Gillig diesel buses

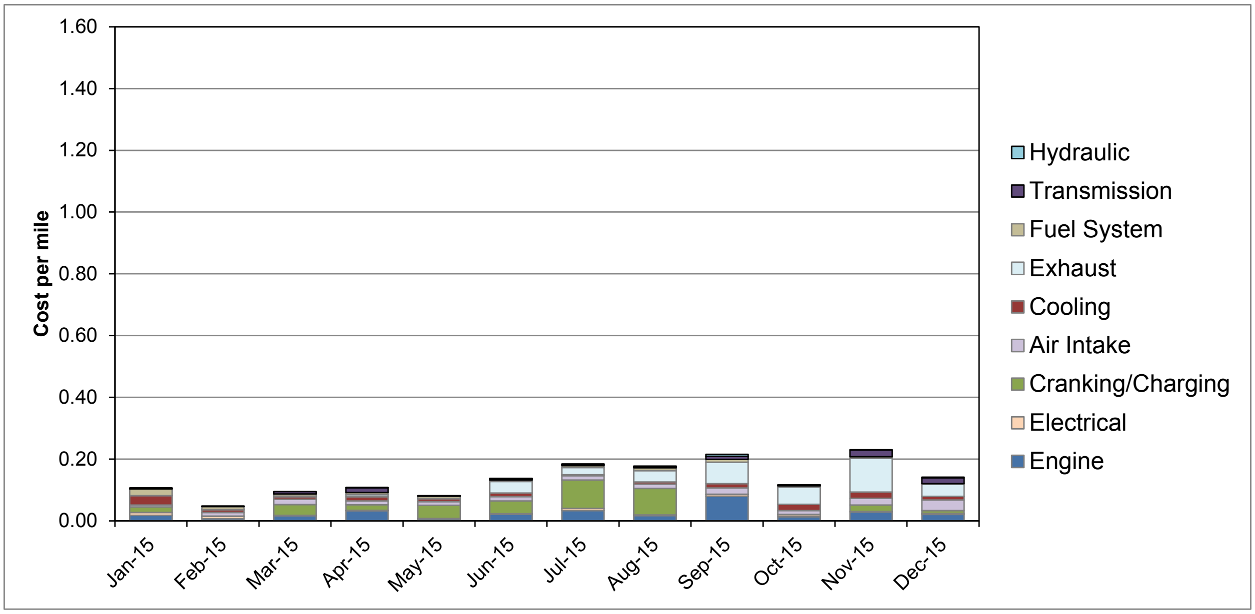

Figure G-3. Monthly propulsion system cost per mile by sub-category for the Gillig diesel buses