Foothill Transit Agency
Battery Electric Bus Progress Report

Data Period Focus: Jan. 2019 through Jun. 2019

Leslie Eudy and Matthew Jeffers

October 2019

NREL/PR-5400-73516

Table of Contents

Introduction

This report summarizes results of a battery electric bus (BEB) evaluation at Foothill Transit, located in the San Gabriel Valley area of Los Angeles. Foothill Transit is collaborating with the California Air Resources Board and the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service. The focus of this evaluation is to compare the performance and the operating costs of the BEBs to that of conventional technology buses and to track progress over time. Previous reports documented results from April 2014 through December 2018.[1,2,3,4,5] This report extends the data analysis through June 2019. The data period focus of this report is January 2019–June 2019. NREL plans to publish progress reports on the Foothill Transit fleet every 6 months through 2020.

[1] Foothill Transit Battery Electric Bus Demonstration Results, NREL/TP-5400-65274, https://www.nrel.gov/docs/fy16osti/65274.pdf
[2] Foothill Transit Battery Electric Bus Demonstration Results: Second Report, NREL/TP-5400-67698, https://www.nrel.gov/docs/fy17osti/67698.pdf
[3] Foothill Transit Agency Battery Electric Bus Progress Report: Data Period Focus: Jan. 2017 through Dec. 2017, NREL/PR-5400-71292, https://www.nrel.gov/docs/fy18osti/71292.pdf
[4] Foothill Transit Agency Battery Electric Bus Progress Report: Data Period Focus: Jan. 2018 through Jun. 2018, NREL/PR-5400-72207, https://www.nrel.gov/docs/fy19osti/72207.pdf
[5] Foothill Transit Agency Battery Electric Bus Progress Report: Data Period Focus: Jul. 2018 through Dec. 2018, NREL/PR-5400-72209, https://www.nrel.gov/docs/fy19osti/72209.pdf

Results Summary

Bus fleets: This evaluation includes 12 Proterra 35-ft fast charge buses (BEB 35FC), two Proterra 40-ft Catalyst fast charge buses (BEB 40FC), and eight NABI 42-ft compressed natural gas (CNG) buses.

Bus use: The BEBs are operated on a 16-mile route (Line 291) that circles through the Pomona Transit Center (PTC) for charging. The average speed for this route is 10.6 mph. The CNG buses are randomly dispatched on all routes out of the operations facility, including higher speed commuter routes. The average speed for the CNG buses is 17.6 mph. This difference in duty cycle influences the comparison of mileage, fuel economy, and costs per mile between fleets.

Availability: Availability in the first half of 2019 was 63% for the BEB 35FC buses, 89% for the BEB 40FC buses, and 93% for the CNG buses. Most unavailable time for the BEBs was due to general bus-related problems. Issues with the low-voltage batteries affected BEB availability. Other downtime resulted from issues with components such as transmission, air compressor, DC-DC converter, and traction motor.

Results Summary (continued)

Fuel economy: From the beginning of the evaluation, NREL has collected miles and energy use from the Proterra data system on each bus. In 2018, Proterra transitioned its data system to a new system to increase capability. During the transition, some data were lost. In early 2018, Foothill Transit installed individual data loggers on each of its BEBs. NREL is using these data for calculating the fuel economy for the 35-ft buses. The data logger data for the BEB 40-ft buses were not available until May 2019. These data gaps are marked on the charts.

BEB efficiency in the first half of 2019 was 2.04 kWh/mi (18.47 mpdge) for the BEB 35FC fleet and 3.65 mpgge (4.18 mpdge) for the CNG bus fleet. Because of the gap in data for the BEB 40FC buses, fuel economy was calculated for May and June 2019 only—2.01 kWh/mi (18.73 mpdge). The BEB fuel economy is approximately 4 times higher than that of the CNG buses as they are currently operated by Foothill Transit. NREL collected data on CNG buses operating on Line 291 that showed an average fuel economy of 2.09 mpdge (see previous report for details[6]). The BEB fuel efficiency is 8 times higher than that of the CNG buses in the same service.

[6] Foothill Transit Battery Electric Bus Demonstration Results: Second Report, NREL/TP-5400-67698, https://www.nrel.gov/docs/fy17osti/67698.pdf

Results Summary (continued)

Fuel cost: Based on energy purchased in the first half of 2019, the BEB fleet had a fuel cost of $0.39/mi (at $0.17/kWh) and the CNG fleet had a fuel cost of $0.33/mi (at $1.19/gge). The cost per unit of energy/fuel is the average for the data period of January 2019–June 2019. Because this 6-month data period includes more winter months when the electric rates are lower, the average cost per kWh is lower than the 6-month average from the previous report.

To compare cost between buses in the same service, NREL estimated the cost per mile for the CNG buses if operated only on Line 291. An earlier analysis using data loggers to characterize the CNG bus operation on Line 291 resulted in a lower fuel economy of 2.09 mpdge.[7] This lower fuel economy would increase the fuel cost of the CNG buses to an overall average of $0.66/mi, which is slightly higher than the fuel cost of the BEB fleet.

[7] Foothill Transit Battery Electric Bus Demonstration Results: Second Report, NREL/TP-5400-67698, https://www.nrel.gov/docs/fy17osti/67698.pdf

Results Summary (continued)

Maintenance cost: Cost to maintain the buses in the first half of 2019 was $0.68/mi for the BEB 35FC buses, $0.62/mi for the BEB 40FC buses, and $0.41/mi for the CNG buses. The BEB 35FC bus cost has decreased slightly over the last data period but is higher than in earlier data periods. Several factors contributed to the high cost for the BEBs:

- The BEB 35FC buses are past the warranty period for most components, resulting in higher parts costs, such as two DC-DC converters (~$13,700) and a traction motor (~$14,000).
- On-site contractor staff handle all maintenance. For some work orders, increased labor hours were needed to troubleshoot and repair the issue. Scheduled costs have remained steady over time with an average of $0.08/mi for both the 35FC and 40FC BEBs. During the first half of 2019, scheduled costs were $0.06/mi for the BEB 35FC buses and $0.04/mi for the BEB 40FC buses. Unscheduled labor has increased over time for both. During the first half of 2019 the unscheduled cost was $0.63/mi for the BEB 35FC buses and $0.58/mi for the BEB 40FC buses. During the data period, the scheduled maintenance costs for the CNG buses were higher than for the BEBs at $0.10/mi. The unscheduled costs for the CNG buses at $0.31/mi were approximately half that of the BEBs.

Results Summary (continued)

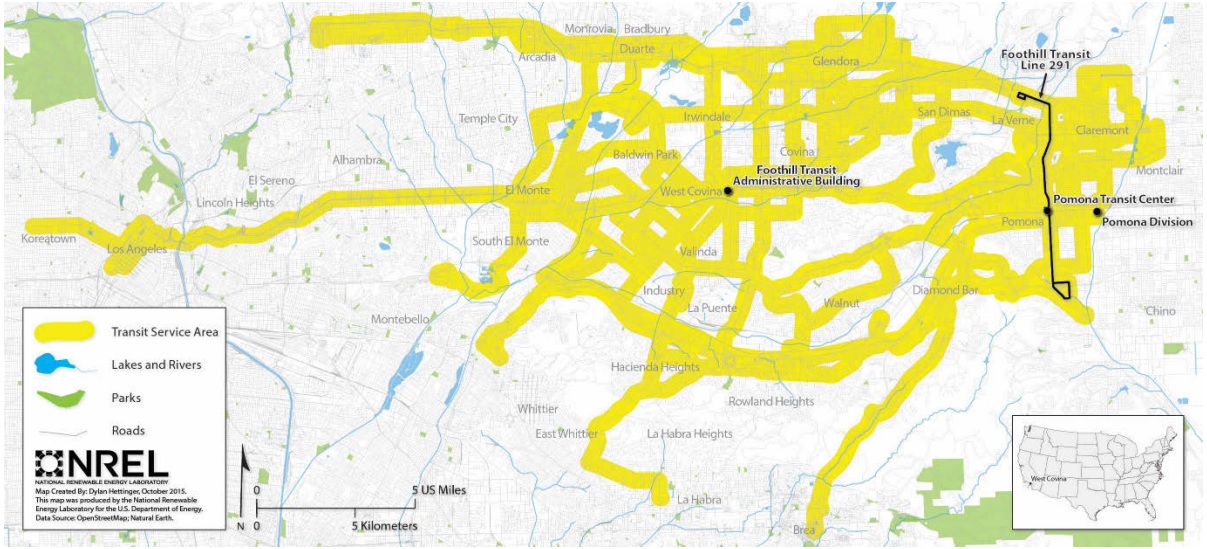
- Foothill Transit continues to have issues with the low-voltage batteries. NREL updated the low-voltage battery data analysis for all three bus fleets. The BEBs averaged 8.9 changeouts per bus at approximately 12,000 miles between changeout. The CNG buses averaged 1.6 changeouts per bus at more than 165,000 miles between changeout. One issue is that the accessories (farebox, cameras, etc.) continually draw power from these batteries. The CNG buses are equipped with an auto shutoff for the accessories; the BEBs are not. Proterra reports that it is working on an auto-shutoff feature for its new designs. The manufacturer will provide a retrofit for BEBs currently in service. Because this issue is not related to the BEB technology, NREL has provided the costs with and without the low-voltage battery replacement costs.
- Total maintenance cost without low-voltage battery costs was $0.60/mi for the BEB 35FC buses, $0.53/mi for the BEB 40FC buses, and $0.39/mi for the CNG buses.

Results Summary (continued)

Future analysis: NREL will continue to collect data on the two existing BEB fleets in comparison to the CNG baseline fleet and will add data from a fleet of 40-ft Proterra Catalyst E2 extended range buses. The new buses will be operated out of another depot and will be charged primarily through overnight depot charging. NREL will select another baseline fleet from this depot for comparison.

Fleet Profile

Foothill Transit serves a 327-square-mile area covering the San Gabriel and Pomona Valley region of Los Angeles County. Foothill Transit's administrative office is located in West Covina, California. Foothill Transit is governed by a Joint Powers Authority of 22 member-cities and the County of Los Angeles.



Foothill Transit operates 36 local and express routes including commuter runs to downtown Los Angeles. The current bus fleet consists of 343 CNG buses and 16 BEBs.

Evaluation Buses: Specifications

Vehicle System	BEB 35FC	BEB 40FC	CNG
Number of buses	12	2	8
Bus manufacturer/model	Proterra/BE35	Proterra/Catalyst Fast Charge	NABI/BRT-07.03
Model year	2014	2016	2014
Bus purchase cost[a]	$904,490	$879,845	$575,000
Length/width/height	35 ft/102 in./129 in.	42.5 ft/102 in./134 in.	42 ft/102 in./137 in.
GVWR/curb weight	37,320 lb/27,680 lb	39,050 lb/27,000 lb	42,540 lb/33,880 lb
Wheelbase	237 in.	296 in.	308 in.
Passenger capacity	35 seats, 2 wheelchair positions, 18 standees	40 seats, 2 wheelchair positions, 18 standees	38 seats, 2 wheelchair positions, 10 standees
Motor or engine	Permanent magnet, UQM, PP220	Permanent magnet, UQM, PP220	CNG engine, Cummins, 8.9 ISL G
Rated power	220 kW peak (295 hp)	220 kW peak (295 hp)	280 hp @ 2,200 rpm
Energy storage (BEB) Fuel capacity (CNG)	Lithium-titanate batteries, Altairnano, TerraVolt 368 volts, 88 kWh total energy	Lithium-titanate batteries, Toshiba, TerraVolt 331 volts, 106 kWh total energy	7 Type IV cylinders, 22,204 scf at 3,600 psi
Accessories	Electric	Electric	Mechanical
Emissions equipment	N/A	N/A	3-way catalyst
Transmission/retarder	Regenerative braking	Regenerative braking	N/A

[a] Includes amenities such as painting of bus and livery, surveillance system, PA system, radio, safety vision monitor.

Evaluation Buses

BEB 35FC

Photo by Leslie Eudy, NREL

BEB 40FC

Photo courtesy of Foothill Transit

CNG

Photo by Leslie Eudy, NREL

Infrastructure Description

Foothill worked with the City of Pomona to establish an on-route fast charging station at the PTC. The station features two Eaton chargers in a climate-controlled building with charge heads (right photo) positioned on either side (left photo). The two chargers operate as separate units with a dedicated control system for each. A common communication network serves both units with sensors to detect which charge head a bus is approaching to enable proper bus-to-charger communication for docking. The system is designed to fully charge a bus in under 10 minutes. For Foothill's Line 291, typical charge times are around 7 minutes including docking time. Foothill built a layover time into the schedule to allow enough time for charging. Software controls prevent charging from surpassing the kWh limit that results in high demand charges.

Photos by Leslie Eudy, NREL

Data Summary: Total from Start of Service

Data Item	BEB 35FC	BEB 40FC	CNG
Number of buses	12	2	8
Data period	4/14–6/19	1/17–6/19	10/14–6/19
Number of months	63	30	57
Total mileage in data period	1,583,078	113,943	2,153,952
Average monthly mileage per bus	2,443	1,899	4,724
Availability (85% is target)	85	82	96
Fuel consumption for BEBs (kWh/mile) or fuel economy for CNG buses (mpgge[a])	2.16	2.16	3.82
Fuel economy (mpdge[b])	17.41	17.42	4.37
Average speed, including stops (mph)	10.60	10.60	17.60
Miles between roadcalls (MBRC[c])—bus	5,555	7,121	25,341
MBRC[c]—propulsion system only	13,887	18,990	39,163
MBRC[c]—ESS[d] only	263,846	113,940	—
Total maintenance cost ($/mile)[e]	0.42	0.47	0.28
Total maintenance cost without low-voltage battery costs ($/mile)[f]	*0.37*	*0.38*	*0.27*
Maintenance cost—propulsion system only ($/mile)	0.14	0.16	0.11
Propulsion system maintenance cost without low-voltage battery costs ($/mile)[f]	*0.09*	*0.06*	*0.10*

[a] Miles per gasoline gallon equivalent
[b] Miles per diesel gallon equivalent
[c] MBRC data cumulative from the clean point of April 2014 through end of current data period
[d] Energy storage system
[e] Work order maintenance cost
[f] See issue with the low-voltage batteries explained on slide 53

Data Summary: Jan.–Jun. 2019

Data Item	BEB 35FC	BEB 40FC	CNG
Number of buses	12	2	8
Data period	1/19–6/19	1/19–6/19	1/19–6/19
Number of months	6	6	6
Total mileage in data period	132,319	20,521	221,895
Average monthly mileage per bus	1,838	1,710	4,623
Availability (85% is target)	63	89	93
Fuel consumption for BEBs (kWh/mile) or fuel economy for CNG buses (mpgge[a])	2.04	2.01	3.65
Fuel economy (mpdge[b])	18.47	18.73	4.18
Average speed, including stops (mph)	10.60	10.60	17.60
Miles between roadcalls (MBRC[c])—bus	5,555	7,121	25,341
MBRC[c]—propulsion system only	13,887	18,990	39,163
MBRC[c]—ESS[d] only	263,846	113,940	—
Total maintenance cost ($/mile)[e]	0.68	0.62	0.41
Total maintenance cost without low-voltage battery costs ($/mile)[f]	*0.60*	*0.53*	*0.39*
Maintenance cost—propulsion system only ($/mile)	0.40	0.12	0.19
Propulsion system maintenance cost without low-voltage battery costs ($/mile)[f]	*0.32*	*0.03*	*0.17*

[a] Miles per gasoline gallon equivalent
[b] Miles per diesel gallon equivalent
[c] MBRC data cumulative from the clean point of April 2014 through end of current data period
[d] Energy storage system
[e] Work order maintenance cost
[f] See issue with the low-voltage batteries explained on slide 53

Route Assignments

Foothill Transit uses the BEB 35FC buses to fully electrify Line 291, which requires seven buses during peak hours. Line 291 is a 16.1-mile route between La Verne and Pomona that loops through the PTC in both directions. The average speed for the route is 10.6 mph. The agency adjusted the schedule to accommodate time for charging the buses. The additional buses are used as spares to allow for maintenance downtime and as fill-in buses for other appropriate routes that go through the PTC, such as Line 855. The two 40-ft buses (BEB 40FC) are also used on these routes. In October 2017, Line 855 was eliminated. From that period on, the buses were operated only on Line 291.

The CNG buses are randomly dispatched on all routes out of Pomona Operations including commuter routes. Average speed for Pomona Operations is 17.6 mph.

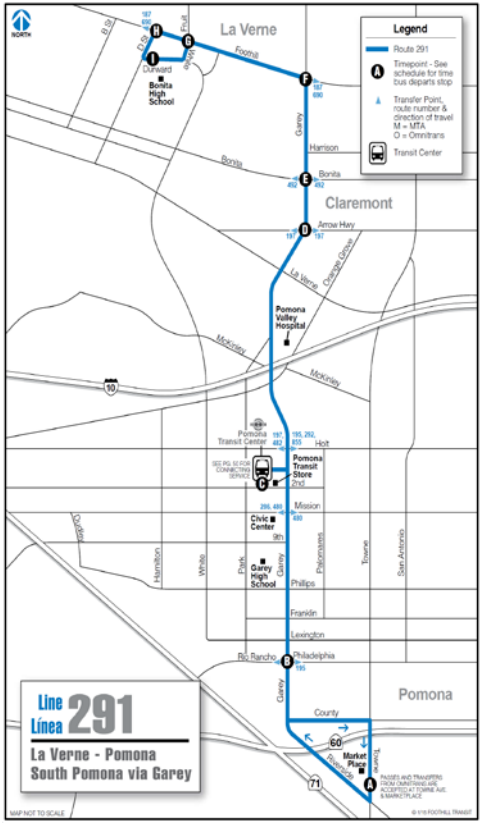
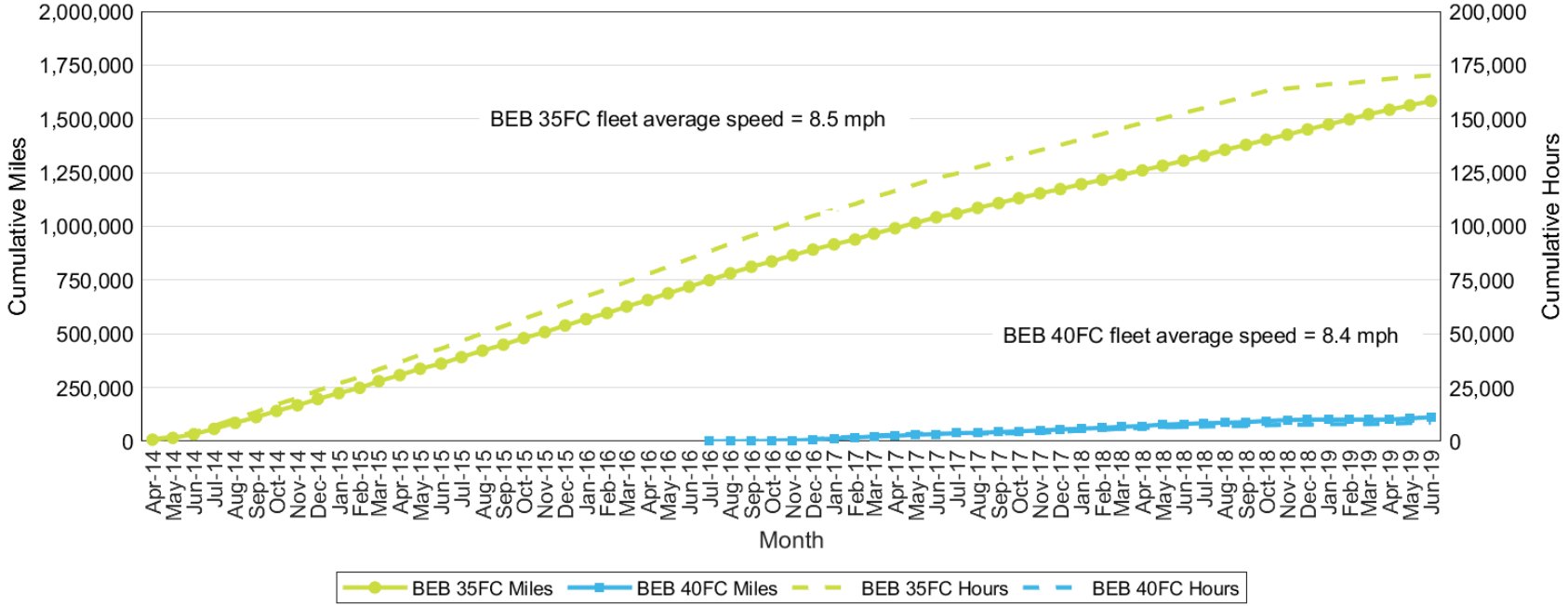


Image courtesy of Foothill Transit

BEB Fleet Total Miles



- Combined totals for 12 BEB 35FC buses and two BEB 40FC buses

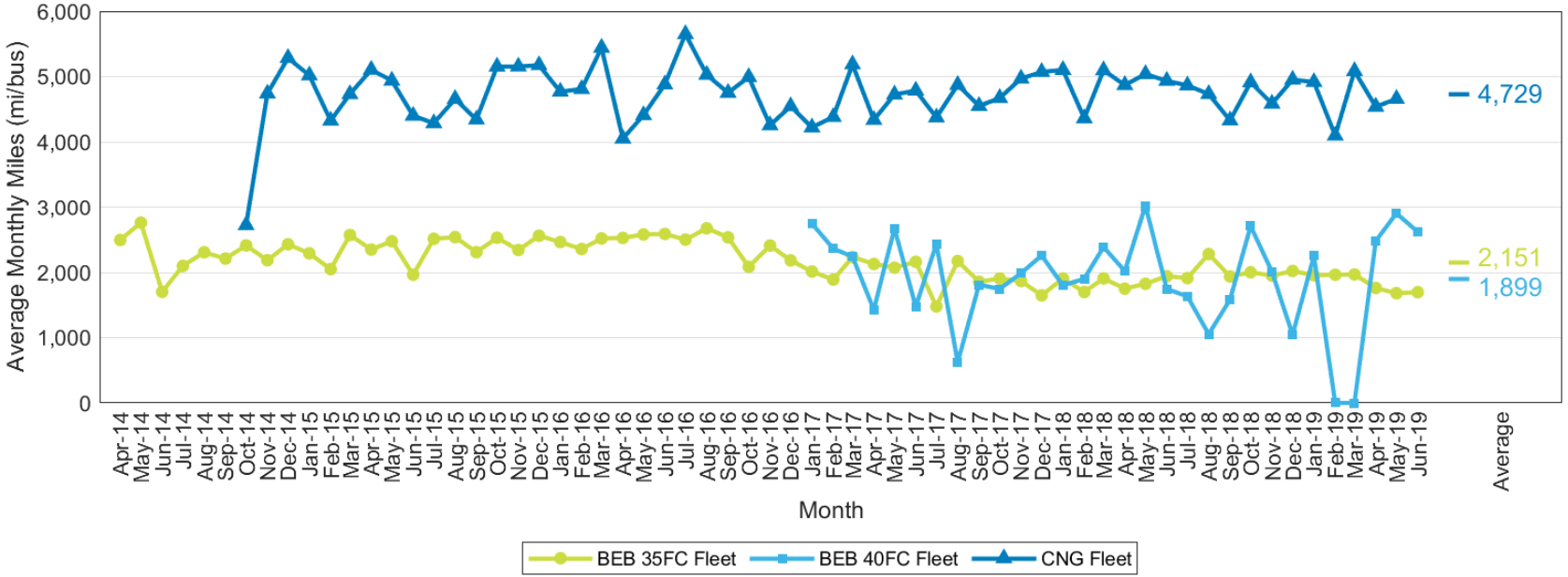
Fleet Average Monthly Miles by Bus: Jan.–Jun. 2019

Bus ID	Miles	Months	Average Monthly Mileage
2004	10,066	6	1,678
2005	9,362	6	1,560
2006	9,557	6	1,593
2007	8,168	6	1,361
2008	2,893	6	482
2009	10,116	6	1,686
2010	15,422	6	2,570
2011	13,091	6	2,182
2012	13,570	6	2,262
2013	13,695	6	2,282
2014	15,046	6	2,508
2015	11,333	6	1,889
BEB 35FC Fleet	**132,319**	**72**	**1,838**
2016	10,016	6	1,669
2017	10,506	6	1,751
BEB 40FC Fleet	**20,521**	**12**	**1,710**

Bus ID	Miles	Months	Average Monthly Mileage
2200	31,269	6	5,212
2201	26,361	6	4,394
2202	28,116	6	4,686
2203	29,019	6	4,837
2204	27,539	6	4,590
2205	22,383	6	3,731
2206	27,170	6	4,528
2207	30,038	6	5,006
CNG Fleet	**221,895**	**48**	**4,623**

The average monthly operating mileage per bus for the BEBs is less than half that of the CNG buses. This is a result of the planned operation of the buses, in which the CNG buses accumulate miles faster than the BEBs do, and it does not indicate a specific limitation of the technology.

Fleet Average Monthly Miles



- The BEB 40FC buses were not operated in February, March, and part of April 2019.

Availability Analysis

Availability, which is a measure of reliability, is presented as the percentage of days the buses are available out of days that the buses are planned for passenger service. Buses available for service may have been used in passenger service, training, or special events, or they may have been available but not used. Buses unavailable for service may have had issues with the propulsion system (energy storage system, electric drive system), general bus maintenance, or issues with the charging system. Accidents are removed from the data—the bus is considered "not planned" during the repair time.

The data presented are based on availability for morning pull-out and don't necessarily reflect all-day availability. Transit agencies typically have a target of 85% availability for their fleets to allow for time to handle scheduled and unscheduled maintenance. The Foothill Transit buses are planned to operate every day, including weekends. For Foothill Transit, the source for availability data is garage activity sheets for Pomona Operations, which list each bus that is not available for morning pull-out and provide a general reason for unavailability. These activity sheets are for the facility as a whole and include the BEBs as well as the CNG buses. The garage activity sheets are typically available for weekdays.

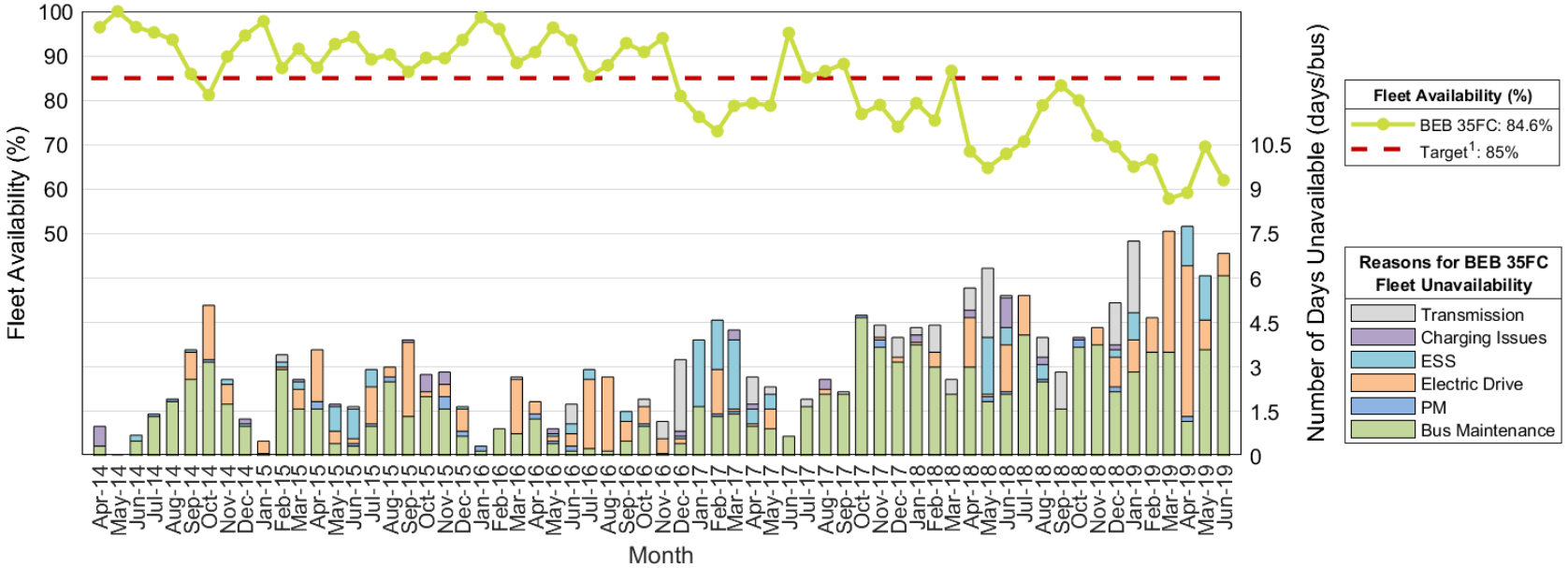
NREL presents availability as a monthly average trend and as overall availability. Unavailable time is separated into several categories to show the primary reason for downtime.

Availability Summary: Jan.–Jun. 2019

Category	BEB 35FC (# Days)	BEB 35FC (%)	BEB 40FC (# Days)	BEB 40FC (%)	CNG (# Days)	CNG (%)
Planned work days	1,317		220		880	
Days available	835	63.4	195	88.6	815	92.6
Unavailable	482	36.6	25	11.4	65	7.4
ESS	45	3.4	0	0.0	—	—
CNG engine	—	—	—	—	11	1.3
Electric drive	158	12.0	5	2.3	—	—
Charging issues	0	0.0	0	0.0	—	—
Preventive maintenance	2	0.2	1	0.5	6	0.7
General bus maintenance	248	18.8	19	8.6	35	4.0
Transmission	29	2.2	0	0.0	13	1.5

- The per-bus availability for the BEBs ranged from a low of 46% to a high of 94%.
- Most unavailable time for the BEBs and CNG buses was attributed to general bus maintenance.
- General bus maintenance includes everything that doesn't fall into one of the other categories.

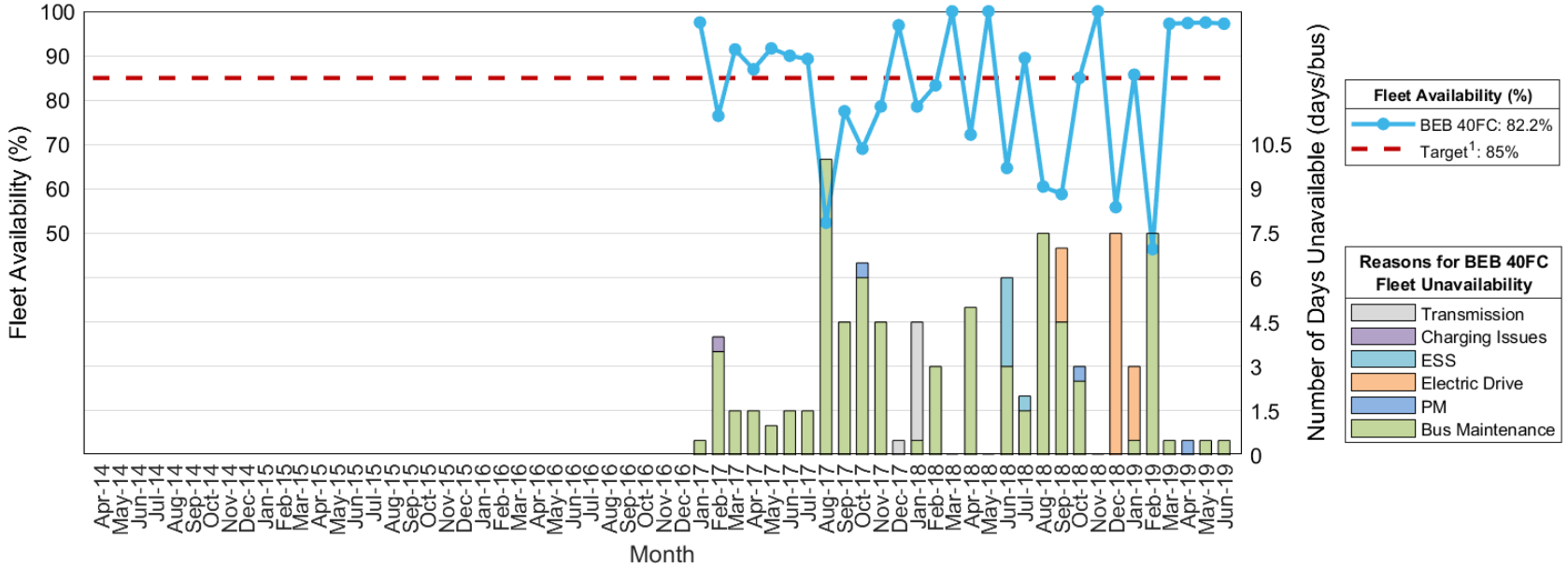
Monthly Availability: BEB 35FC Fleet



1. Target of 85% fleet availability is a general expectation for transit agencies

- The green line tracks the average monthly availability for the BEB 35FC fleet.
- The stacked bars provide the number of unavailable days by bus each month separated by six categories.
- Electric drive downtime was attributed to traction motor and DC-DC converter issues.

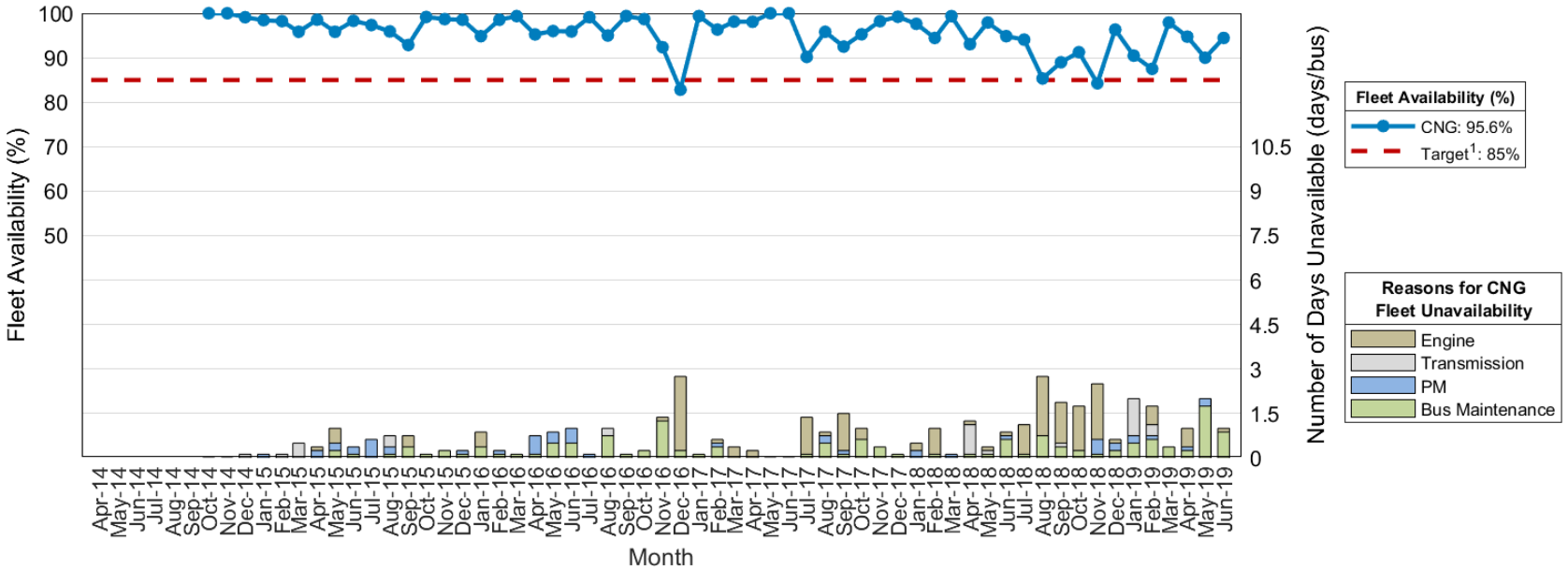
Monthly Availability: BEB 40FC Fleet



1. Target of 85% fleet availability is a general expectation for transit agencies

- The blue line tracks the average monthly availability for the BEB 40FC fleet.
- The stacked bars provide the number of unavailable days by bus each month separated by six categories.
- The buses were available but not used for several months during the first half of 2019.

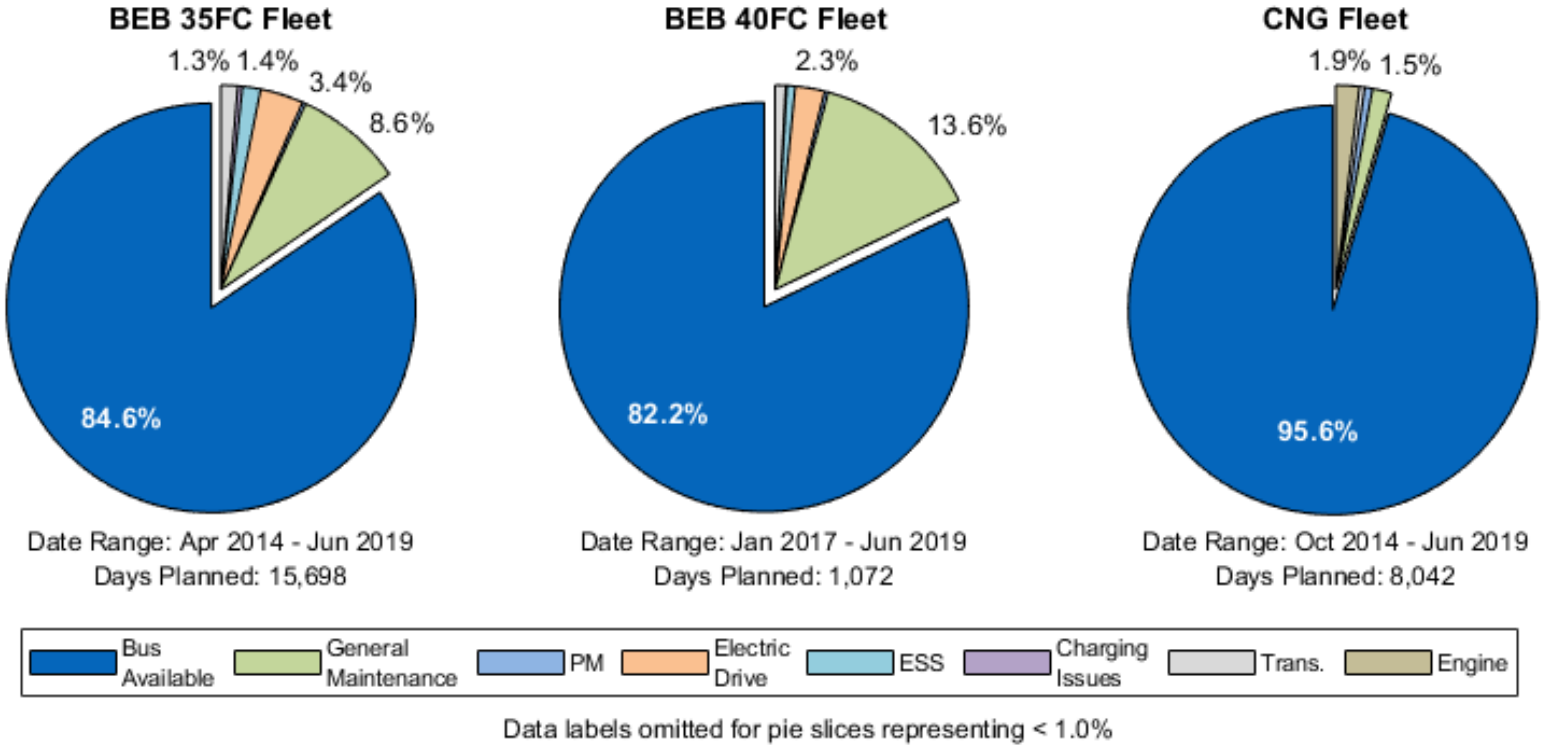
Monthly Availability: CNG Fleet



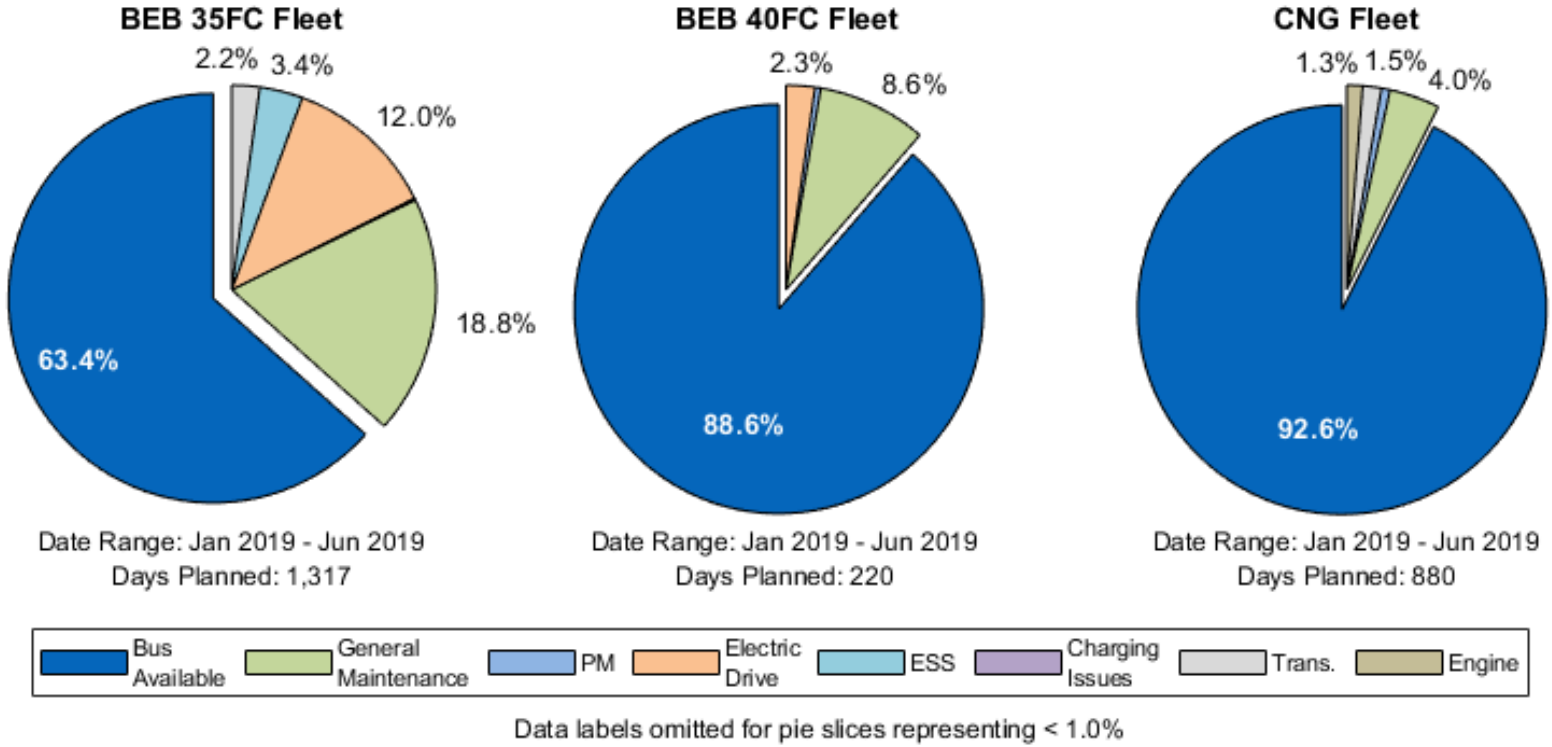
1. Target of 85% fleet availability is a general expectation for transit agencies

- The blue line tracks the average monthly availability for the CNG fleet.
- The stacked bars provide the number of unavailable days by bus each month separated by four categories.

Overall Fleet Availability: Full Data Period



Overall Fleet Availability: Jan.–Jun. 2019



Energy Use/Fuel Economy Analysis

Proterra records and stores data—including total electrical energy used (kWh), number of charges, and miles driven—on each of the buses. These data were provided to NREL for calculating efficiency of the buses in kWh per mile. Foothill Transit's CNG buses are typically fueled once each day. Foothill Transit provided individual fueling records for the CNG buses. CNG is typically tracked in units of gasoline gallon equivalent (gge).

To compare the BEBs to the baseline buses, NREL converted the electrical energy from kWh to diesel gallon equivalent (dge) and converted the CNG fuel energy from gge to dge using the following conversion factors.

Energy content of fuel (DOE Alternative Fuels Data Center: https://afdc.energy.gov/fuels/properties)

- Electricity: 3,414 Btu/kWh
- CNG: 112,114 Btu/gge (LHV)
- Diesel: 128,488 Btu/dge (LHV)

Conversion factors

- Electrical energy to dge: 37.64 kWh/dge
- CNG fuel energy to dge: 1.146 gge/dge

Btu: British thermal units; LHV: lower heating value

Fuel Economy by Bus: Jan.–Jun. 2019

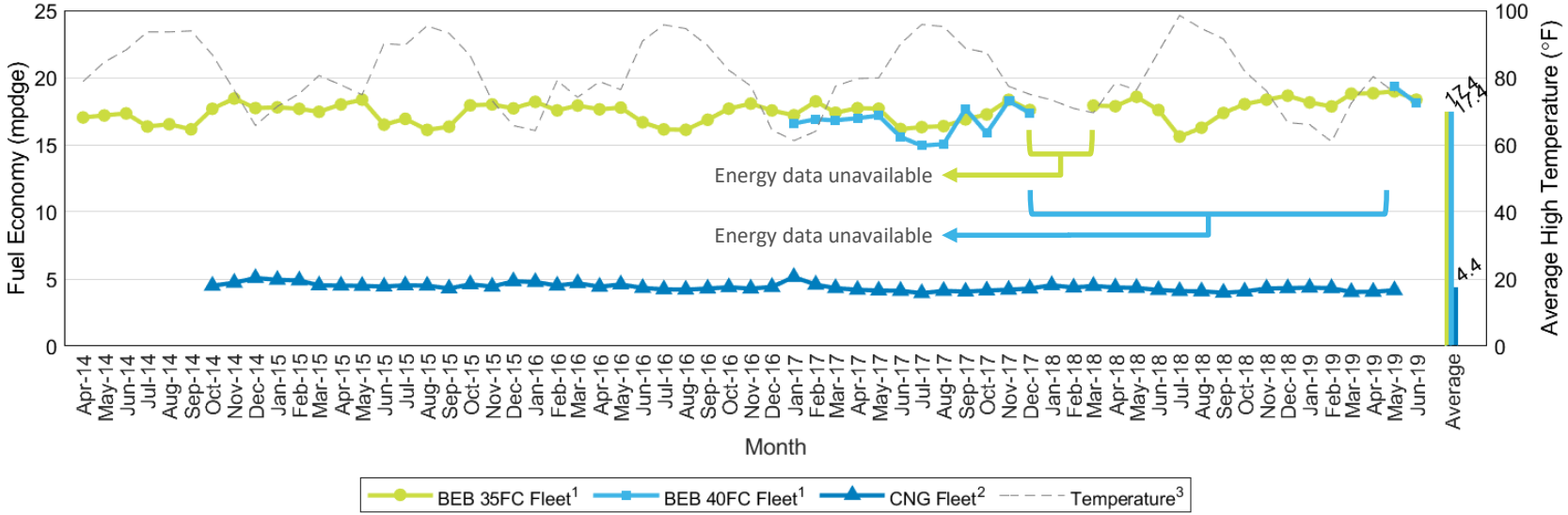
Bus ID	Miles	Energy[a] (kWh)	kWh/mi	Diesel Gallon Equiv.	Fuel economy (mpdge)
2004	10,066	20,369.8	2.02	541.2	18.60
2005	9,362	19,717.1	2.11	523.8	17.87
2006	9,557	20,058.2	2.10	532.9	17.93
2007	8,168	17,426.8	2.13	463.0	17.64
2008	2,893	6,522.5	2.25	173.3	16.69
2009	10,116	21,211.8	2.10	563.5	17.95
2010	15,422	31,666.4	2.05	841.3	18.33
2011	13,091	26,304.9	2.01	698.9	18.73
2012	13,570	25,968.4	1.91	689.9	19.67
2013	13,695	27,347.6	2.00	726.6	18.85
2014	15,046	30,625.7	2.04	813.6	18.49
2015	11,333	22,432.0	1.98	596.0	19.02
BEB 35FC Fleet	**132,319**	**269,651.2**	**2.04**	**7,164.0**	**18.47**
2016	5,127	10,292.8	2.01	273.5	18.75
2017	5,927	11,921.0	2.01	316.7	18.71
BEB 40FC Fleet	**11,053**	**22,213.9**	**2.01**	**590.2**	**18.73**

[a] Total energy consumed by the bus, does not include losses during charging

Bus ID	Miles	CNG (gge)	mpgge	Diesel Gallon Equiv.	Fuel economy (mpdge)
2200	27,354	7,308.3	3.74	6,377.0	4.29
2201	22,434	6,644.9	3.38	5,798.1	3.87
2202	26,346	7,176.5	3.67	6,261.9	4.21
2203	25,721	6,848.5	3.76	5,975.8	4.30
2204	25,650	7,156.6	3.58	6,244.6	4.11
2205	20,084	5,476.9	3.67	4,778.9	4.20
2206	25,711	6,888.6	3.73	6,010.7	4.28
2207	28,074	7,695.6	3.65	6,714.9	4.18
CNG Fleet	**201,374**	**55,195.8**	**3.65**	**48,161.9**	**4.18**

- The BEB fuel economy is 4 times higher than that of the CNG buses, as operated on current routes.
- Previous testing showed the CNG buses had a fuel economy around 2.09 mpdge on Line 291, which is nearly 9 times lower than that of the BEBs.
- Earlier data collection issues with the BEB 40FC were corrected in late April; data are from May–June 2019 only.

Fleet Average Monthly Fuel Economy

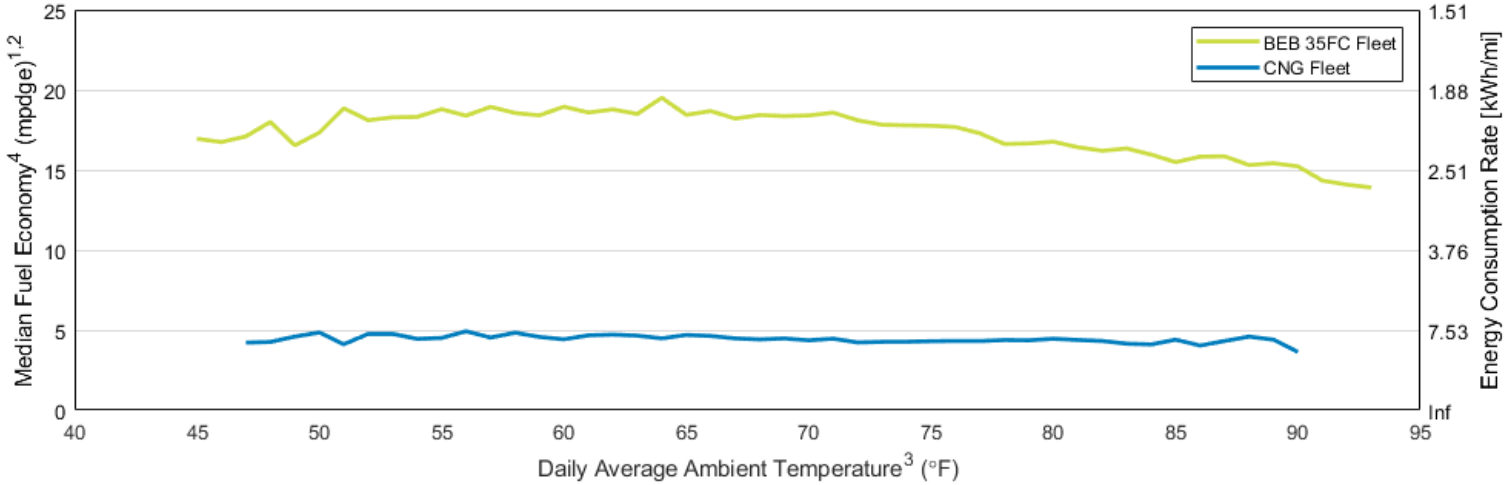


1. Electrical energy converted from kWh to diesel gallon equivalent (dge); conversion factor = 37.64 kWh/dge
2. CNG fuel energy converted from gasoline gallon eqivalent (gge) to diesel gallon equivalent (dge); conversion factor = 1.146 gge/dge
3. Average daily high temperatures at Ontario International Airport, CA; data acquired from: *https://www.ncdc.noaa.gov/*

	Overall		Jan.–Jun. 2019	
Fleet	**kWh/mi, mpgge**	**mpdge**	**kWh/mi, mpgge**	**mpdge**
BEB 35FC	2.16	17.41	2.04	18.47
BEB 40FC	2.16	17.42	2.01	18.73
CNG	3.82	4.37	3.65	4.18

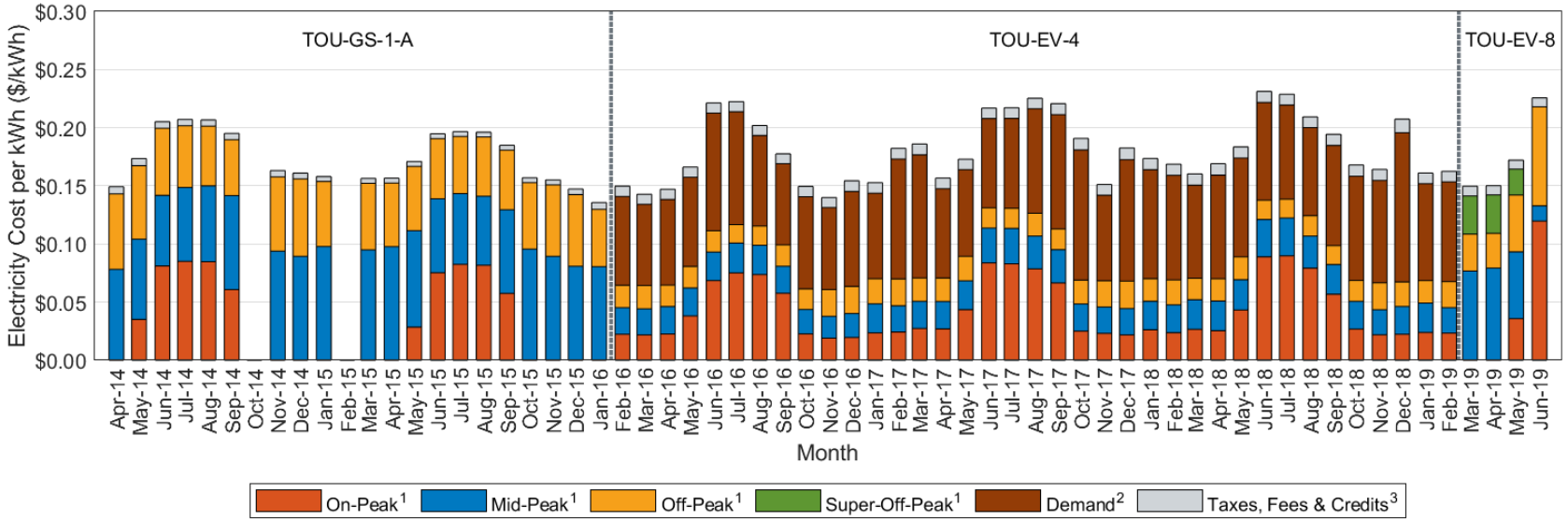
Fuel Economy by Ambient Temperature

To begin evaluating the sensitivity of bus fuel economy to ambient temperature, daily average temperature data for the entire evaluation period (2014–2019) were compared to daily fuel economy values for all BEB 35FC buses and all CNG buses. Median absolute deviation method was used to identify outliers and remove those data points from the analysis. The median fuel economy of each fleet was calculated for every unique daily average temperature and plotted below. The chart shows the overall impact of ambient temperature on bus fuel economy (primarily cabin heating and cooling effects) but does not account for other major factors such as passenger loading, driver behavior, or traffic conditions. The equivalent energy consumption rate (kWh/mi) is included on the right for reference.



1. Electrical energy converted from kWh to diesel gallon equivalent (dge); conversion factor = 37.64 kWh/dge
2. CNG fuel energy converted from gasoline gallon eqivalent (gge) to diesel gallon equivalent (dge); conversion factor = 1.146 gge/dge
3. Daily average temperatures at Ontario International Airport, CA; data acquired from: *https://www.ncdc.noaa.gov/*
4. Median fuel economy for fleet calculated for each unique daily average temperature

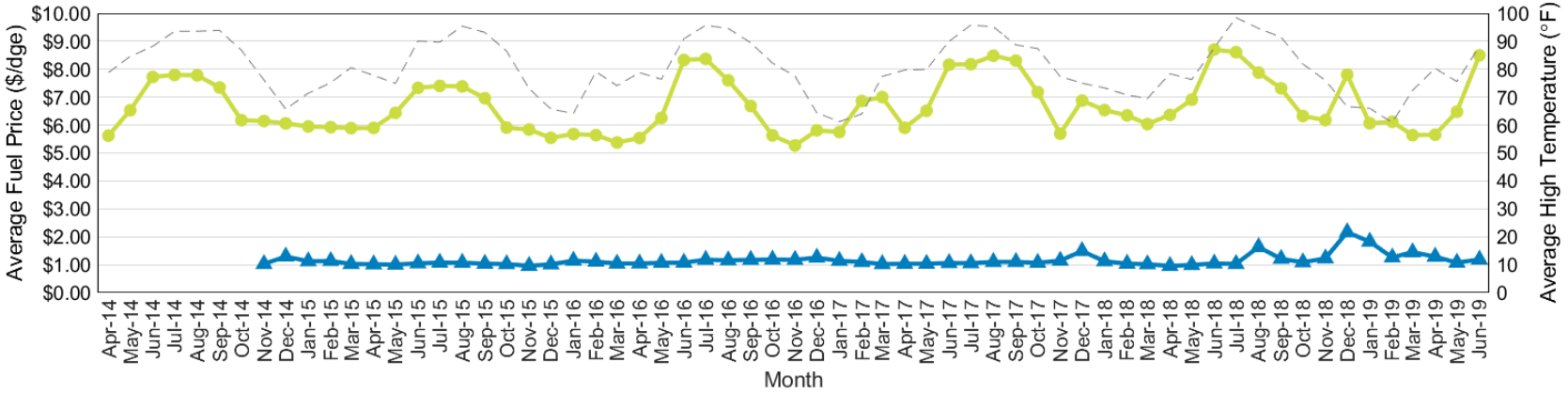
Monthly Electric Utility Costs



1. On-Peak, Mid-Peak, Off-Peak and Super-Off-Peak charge categories include respective costs for delivery and generation
2. Rate structure changed to TOU-EV-4 February 2016, introducing demand charges, and changed to TOU-EV-8 March 2019, eliminating demand charges
3. 'Taxes, Fees & Credits' category includes all remaining utility bill items (positive & negative charges)

- Data are based on utility billing periods, not calendar months
- Seasonal rates apply: average summer rate (Jun–Sep): $0.21/kWh; average winter rate (Oct–May): $0.16/kWh
- Average rates under each rate structure: TOU-GS-1-A = $0.17/kWh; TOU-EV-4 = $0.18/kWh; TOU-EV-8: $0.18/kWh
- Average rate for first half of 2019 calendar year: $0.17/kWh; overall average: $0.18/kWh

Monthly Average Fuel Price



	Electricity Price (dge)[1]	CNG Price (dge)[2]
Overall average fuel price	$6.73/dge	$1.14/dge
Data period average fuel price	$6.46/dge	$1.37/dge

1. Electrical energy converted from kWh to diesel gallon equivalent (dge); conversion factor = 37.64 kWh/dge
2. CNG fuel energy converted from gasoline gallon eqivalent (gge) to diesel gallon equivalent (dge); conversion factor = 1.146 gge/dge
3. Average daily high temperatures at Ontario International Airport, CA; data acquired from: *https://www.ncdc.noaa.gov/*

- Electricity prices vary seasonally; CNG prices are consistent throughout the data period, but CNG prices increased in August 2018 and December 2018 due to temporary disruptions in regional CNG supply.
- CNG cost includes price of fuel, transmission, and operations and maintenance cost for station.
- On average, electricity cost is approximately 6 times the cost of CNG.

Fuel Cost Per Mile

The operating duty cycle of a bus has a significant effect on fuel economy and therefore cost. Earlier in the evaluation, NREL collected drive cycle data on a selection of CNG buses that were operated on a variety of Foothill Transit routes including Line 291. On Line 291, the average fuel economy for the CNG buses was 2.09 mpdge.

During the first half of 2019, Foothill Transit paid an average of $1.19/gge ($1.37/dge) for CNG. The average cost of electricity during the first half of 2019 was $0.17/kWh ($6.46/dge). The table provides the cost per mile for the BEBs and CNG buses as used by the fleet and estimates the cost per mile of the CNG buses if they were only operated on Line 291. The lower fuel economy would increase the CNG fuel cost to an average of $0.52/mi, which is slightly higher than the BEBs' fuel cost of $0.45/mi.

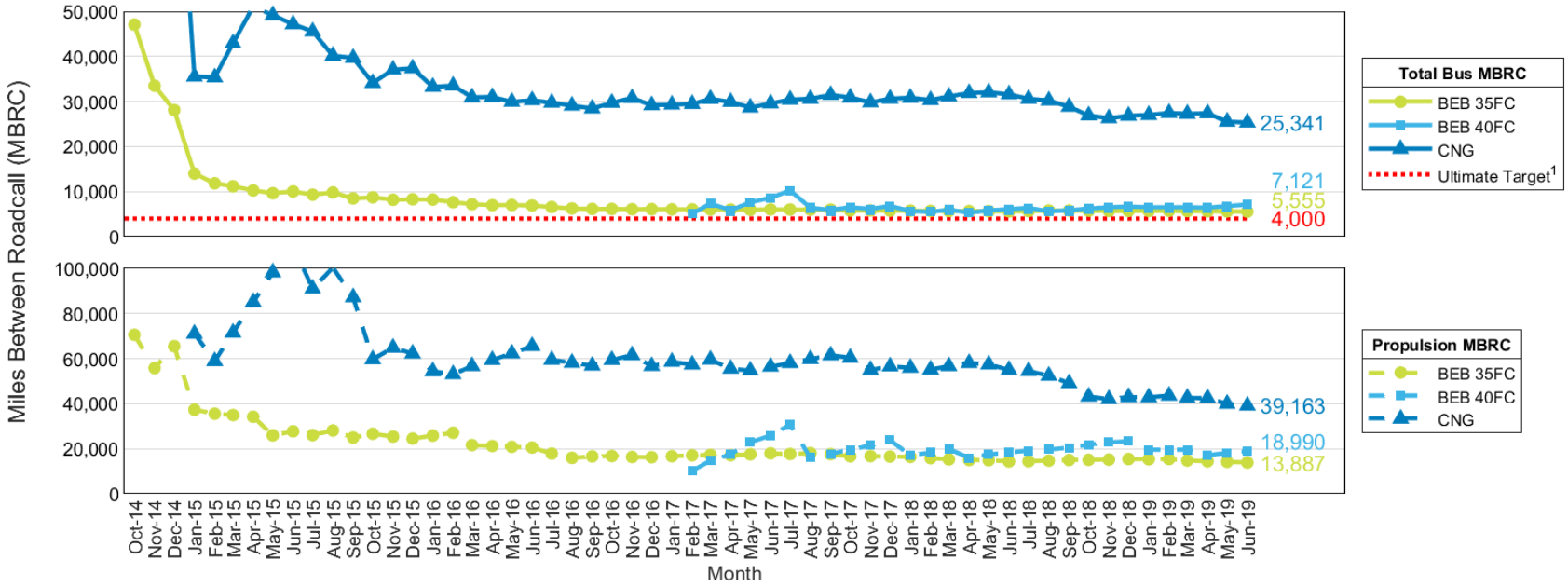
	Average Service Speed (mph)	Fuel Economy (mpdge)	Overall Fuel $/mi	Data Period Fuel $/mi
BEB 35FC	10.6	17.41	0.45	0.39
BEB 40FC	10.6	17.42	0.45	0.39
CNG	17.6	4.37	0.26	0.33
CNG on Line 291	10.6	2.09	0.52	0.66

Roadcall Analysis

A roadcall, or revenue vehicle system failure, 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. If the problem with the bus can be repaired during a layover and the schedule is kept, it 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 MBRC. NREL tracks MBRC by total bus roadcalls, propulsion-related roadcalls, and ESS-related roadcalls (for electric buses). Total bus roadcalls include all chargeable roadcalls. Propulsion-related roadcalls is a subset of total roadcalls and includes all roadcalls due to propulsion-related systems including the battery system (or engine for a conventional bus), electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, and transmission systems. The ESS-related roadcalls—a subset of the propulsion-related roadcalls—and MBRC are included for the BEBs.

Cumulative MBRC



1. Ultimate Target adopted from: DOE FCTO Program Record #12012, Sept. 2012, *http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf*

- The upper chart shows cumulative MBRC for all chargeable roadcalls.
- The lower chart shows MBRC for propulsion-related roadcalls.
- The ESS-related MBRC for the BEB 35FC fleet is 263,846.
- The ESS-related MBRC for the BEB 40FC fleet is 113,940.

Maintenance Analysis

NREL collects all work orders for the evaluation buses to calculate a maintenance cost per mile. Costs for accident-related repair, which are extremely variable from bus to bus, were eliminated from the analysis. Warranty costs are not included in the cost-per-mile calculations because those costs are covered in the capital cost of the buses. For consistency, NREL uses a constant $50 per hour labor rate. This does not reflect an average rate for Foothill Transit. Cost per mile is calculated as follows:

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

NREL calculates total cost per mile, scheduled maintenance cost per mile, and unscheduled maintenance cost per mile. NREL also categorizes maintenance cost by system to provide insight into what systems have the most costs for each technology. The work orders are coded using vehicle maintenance reporting standards (VMRS) developed by the American Trucking Association to aid the industry in tracking equipment and maintenance using a common standard.

The propulsion system costs are of particular interest. Propulsion-related vehicle systems include the exhaust, fuel, engine, battery modules, 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 different advanced propulsion systems for the buses.

Maintenance Analysis Results: Jan.–Jun. 2019

Bus ID	Mileage	Parts ($)	Labor Hours	Scheduled Cost ($/mi)	Unscheduled Cost ($/mi)	Total Cost ($/mi)
2004	10,066	$16,305.31	54.8	$0.07	$1.82	$1.89
2005	9,362	$2,136.83	55.9	$0.04	$0.48	$0.53
2006	9,557	$1,744.72	58.5	$0.09	$0.40	$0.49
2007	8,168	$1,488.11	104.6	$0.09	$0.73	$0.82
2008	2,893	$2,314.75	65.0	$0.00	$1.92	$1.92
2009	10,116	$16,656.14	71.0	$0.04	$1.96	$2.00
2010	15,422	$1,793.30	64.0	$0.04	$0.28	$0.32
2011	13,091	$2,268.83	48.5	$0.04	$0.32	$0.36
2012	13,570	$1,715.39	65.8	$0.04	$0.33	$0.37
2013	13,695	$1,299.32	94.6	$0.08	$0.36	$0.44
2014	15,046	$2,281.07	38.6	$0.06	$0.22	$0.28
2015	11,333	$1,142.24	62.1	$0.05	$0.33	$0.37
BEB 35FC Fleet	**132,319**	**$51,146.01**	**783.4**	**$0.06**	**$0.63**	**$0.68**
2016	10,016	$2,216.33	37.5	$0.03	$0.38	$0.41
2017	10,506	$2,699.99	119.8	$0.06	$0.77	$0.83
BEB 40FC Fleet	**20,521**	**$4,916.32**	**157.3**	**$0.04**	**$0.58**	**$0.62**

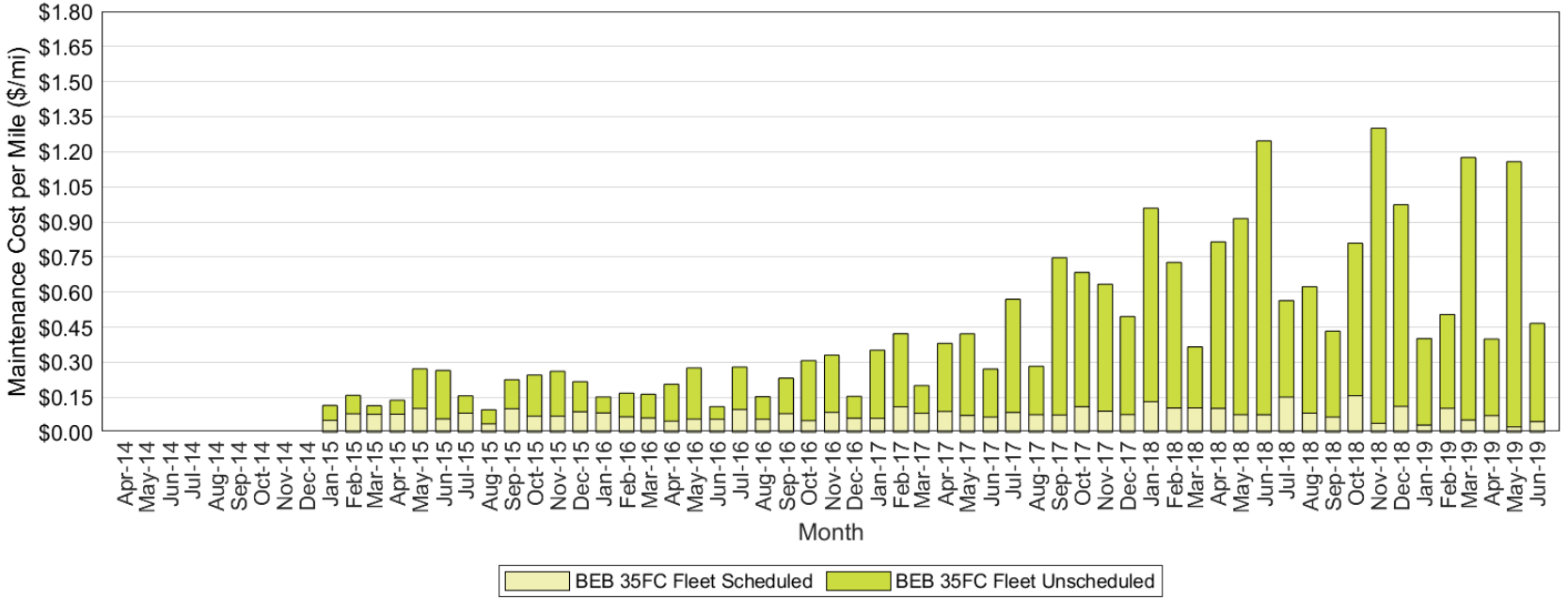
OEM: original equipment manufacturer

Bus ID	Mileage	Parts ($)	Labor Hours	Scheduled Cost ($/mi)	Unscheduled Cost ($/mi)	Total Cost ($/mi)
2200	31,269	$4,807.22	62.7	$0.08	$0.17	$0.25
2201	26,361	$6,734.88	114.2	$0.11	$0.37	$0.47
2202	28,116	$5,316.18	91.0	$0.09	$0.26	$0.35
2203	29,019	$4,979.24	113.9	$0.11	$0.25	$0.37
2204	27,539	$4,670.61	171.8	$0.11	$0.37	$0.48
2205	22,383	$9,157.97	114.0	$0.10	$0.57	$0.66
2206	27,170	$6,213.22	84.4	$0.12	$0.26	$0.38
2207	30,038	$5,782.40	105.5	$0.08	$0.29	$0.37
CNG Fleet	**221,895**	**$47,661.72**	**857.4**	**$0.10**	**$0.31**	**$0.41**

BEB issues included:

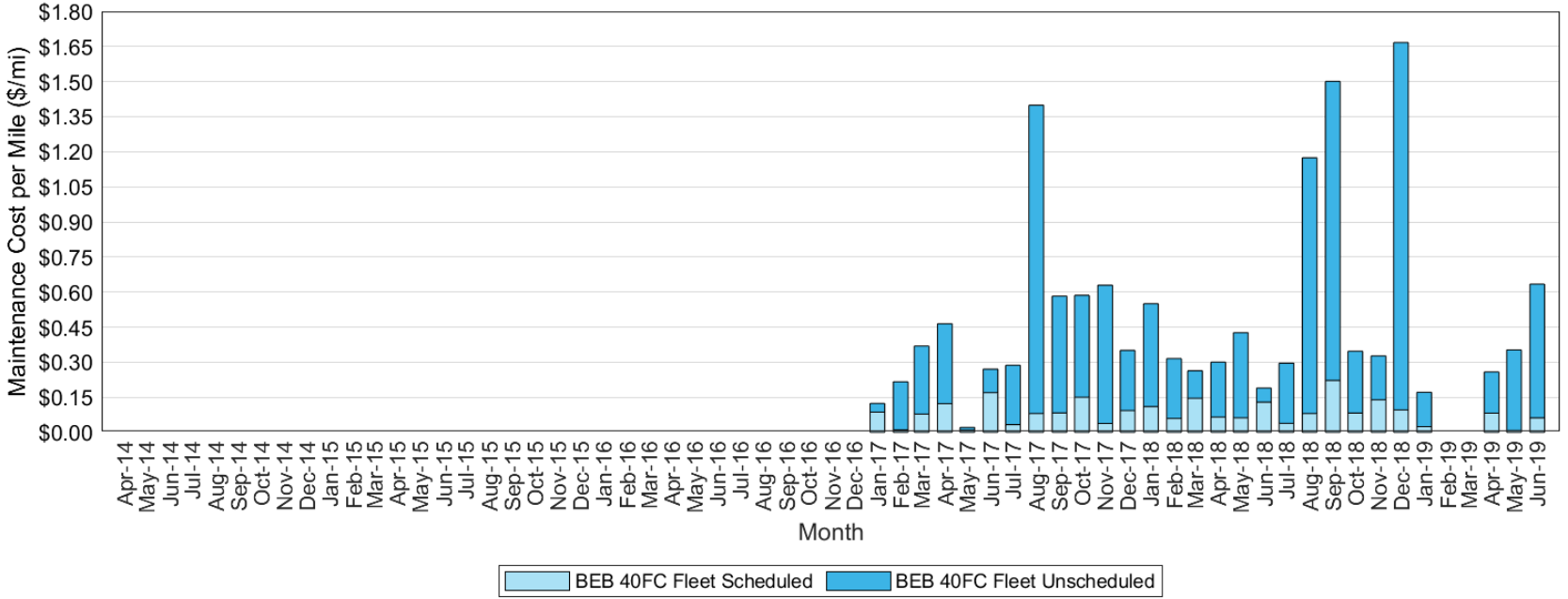
- Low-voltage battery replacement
- Two DC-DC converters replaced
- Transmission leak and one transmission was replaced
- Traction motors
- Transmission.

Monthly Scheduled and Unscheduled Maintenance Cost: BEB 35FC Fleet



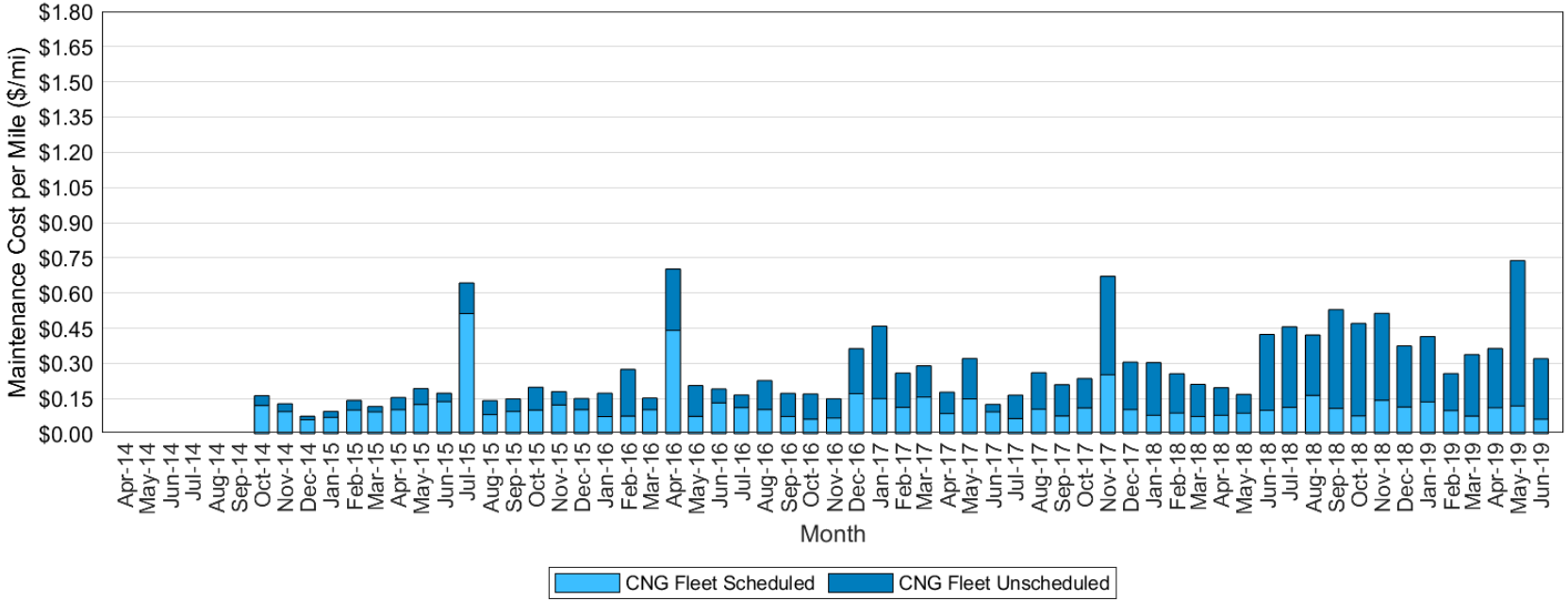
- The warranty period has ended, and transit staff are handling all the maintenance work.
- Issues with the low-voltage batteries continue to result in increasing costs.
- High-dollar parts and lower mileage accumulation result in higher per-mile costs (DC-DC converter, traction motor).

Monthly Scheduled and Unscheduled Maintenance Cost: BEB 40FC Fleet



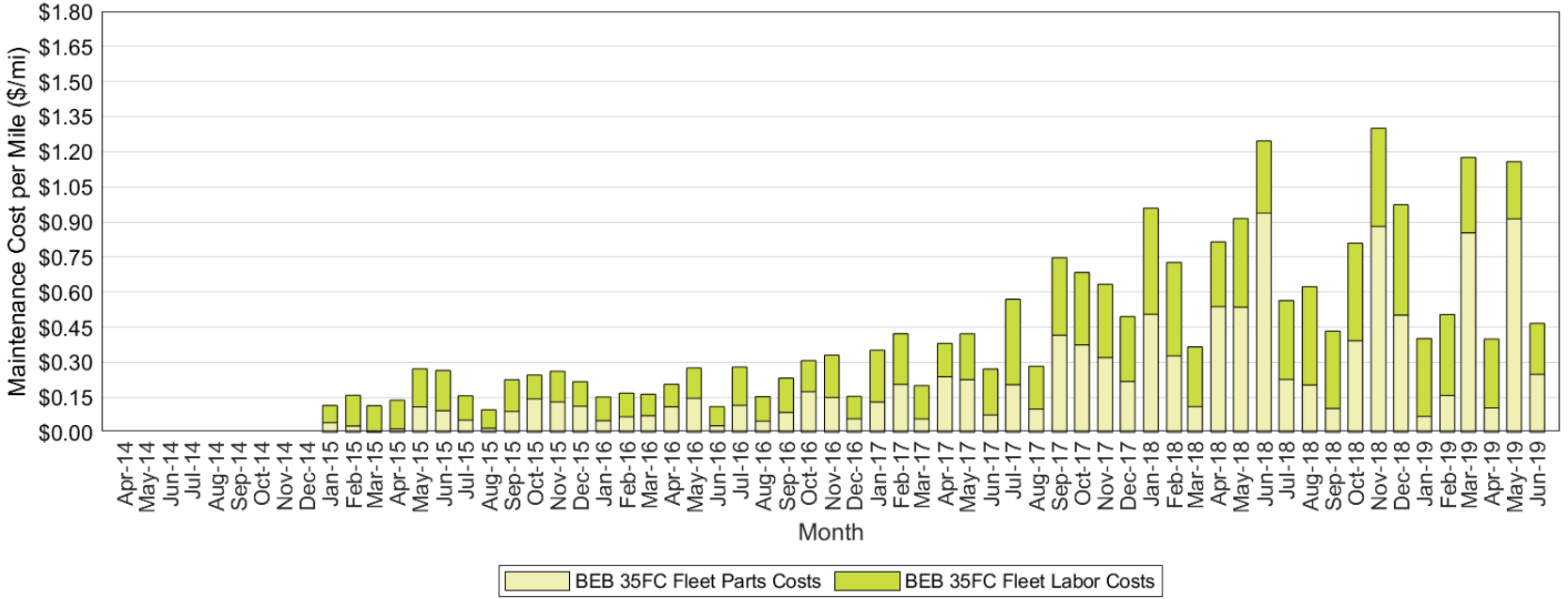
- Issues with the low-voltage batteries resulted in costs that were higher than expected.
- Because the fleet consists of only two buses, the cost per mile is more sensitive to cost increases.
- The fleet accumulated low or no mileage February 2019 through April 2019.

Monthly Scheduled and Unscheduled Maintenance Cost: CNG Fleet



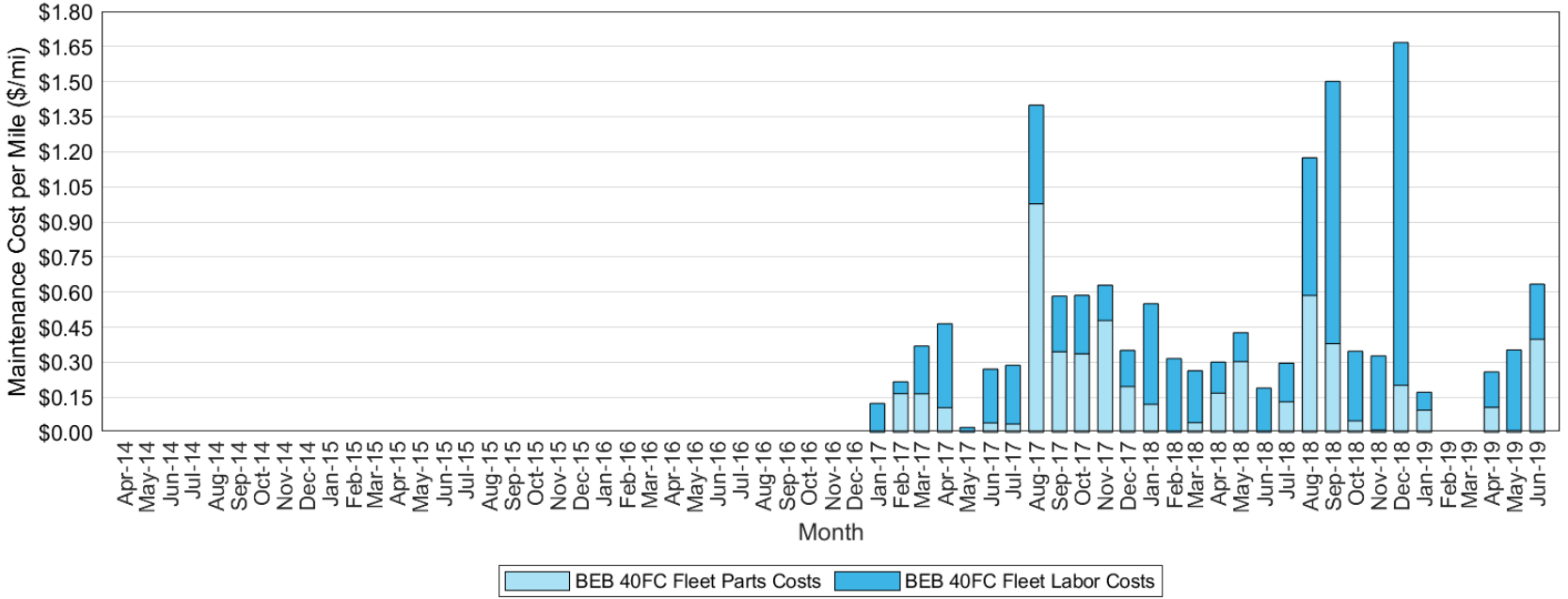
- Spikes in costs are caused by multiple buses reaching the mileage target for a major preventive maintenance (PM).
- Unscheduled costs in the last 8 months have risen primarily due to engine issues.

Monthly Parts and Labor Maintenance Cost: BEB 35FC Fleet



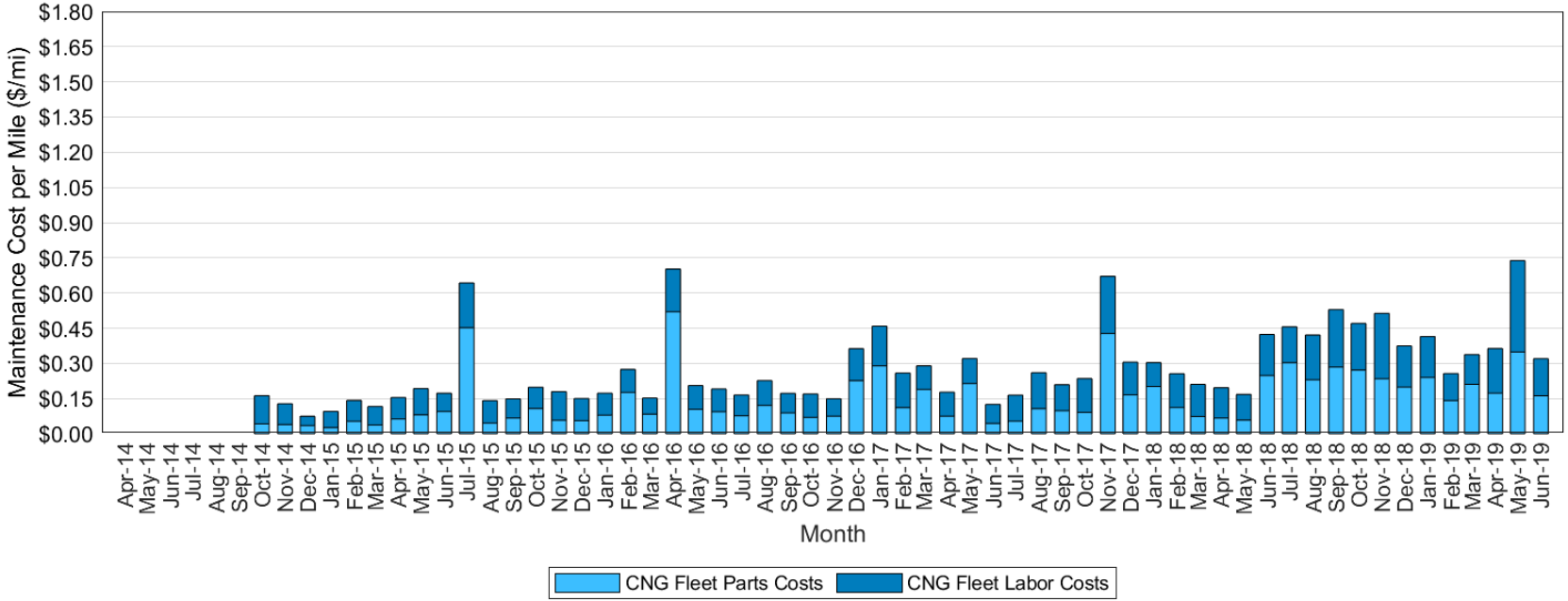
- The warranty period has ended, and transit staff are handling all the maintenance work.
- Issues with the low-voltage batteries continue to result in increasing costs.
- High-dollar parts and lower mileage accumulation result in higher per-mile costs.

Monthly Parts and Labor Maintenance Cost: BEB 40FC Fleet



- Issues with the low-voltage batteries resulted in costs that were higher than expected.
- Because the fleet consists of only two buses, the cost per mile is more sensitive to cost increases.
- The fleet accumulated low or no mileage February 2019 through April 2019.

Monthly Parts and Labor Maintenance Cost: CNG Fleet



- Spikes in costs are caused by multiple buses reaching the mileage target for a major preventive maintenance (PM).
- Unscheduled costs in the last 8 months have risen primarily due to engine issues.

Maintenance Cost per Mile by System: Jan.–Jun. 2019

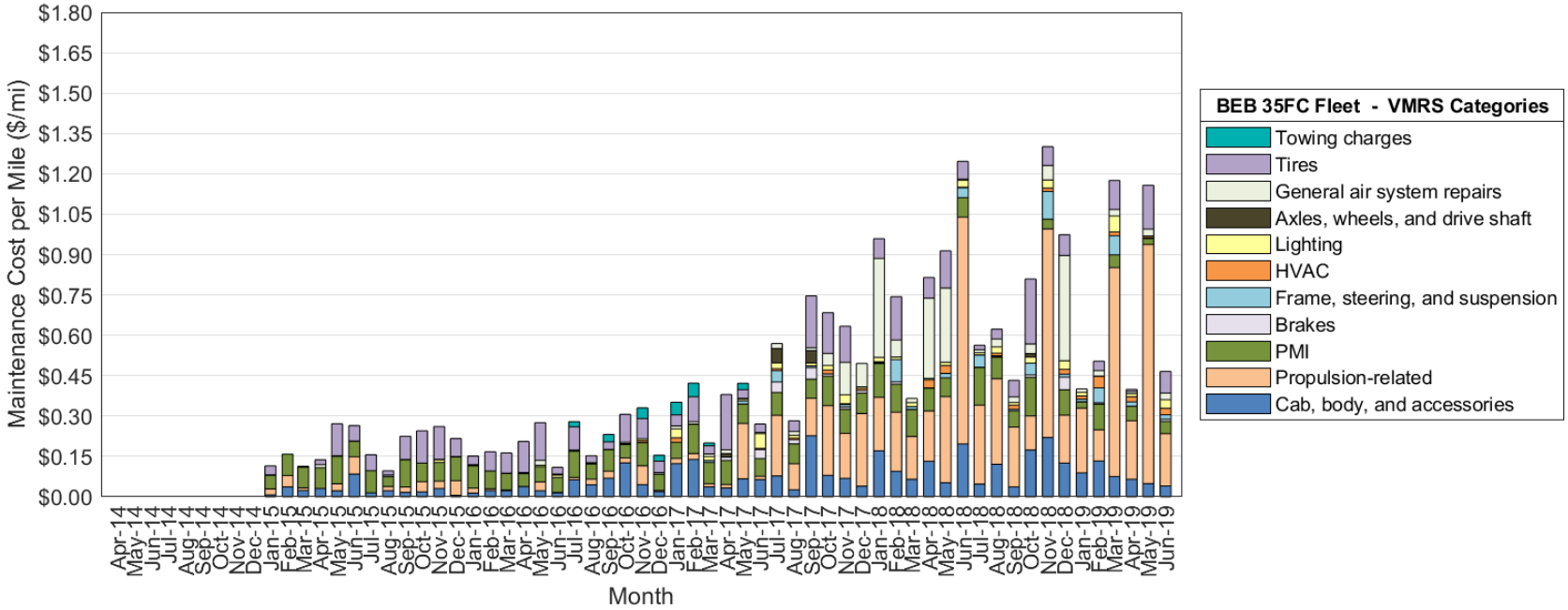
System	BEB 35FC		BEB 40FC		CNG	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Cab, body, and accessories	0.402	59	0.123	20	0.191	47
Propulsion-related	0.077	11	0.116	19	0.067	16
PMI	0.048	7	0.036	6	0.042	10
Brakes	0.002	0	0.020	3	0.054	13
Frame, steering, and suspension	0.030	4	0.000	0	0.001	0
HVAC	0.020	3	0.004	1	0.007	2
Lighting	0.020	3	0.006	1	0.003	1
General air system repairs	0.000	0	0.175	28	0.006	1
Axles, wheels, and drive shaft	0.019	3	0.019	3	0.006	2
Tires	0.064	9	0.124	20	0.030	7
Towing charges	0.000	0	0.000	0	0.000	0
Total	***0.683***	***100***	***0.623***	***100***	***0.408***	***100***
Total w/o low voltage battery costs	***0.60***		***0.53***		***0.39***	

Color coding:

- Highest cost
- Second highest cost
- Third highest cost

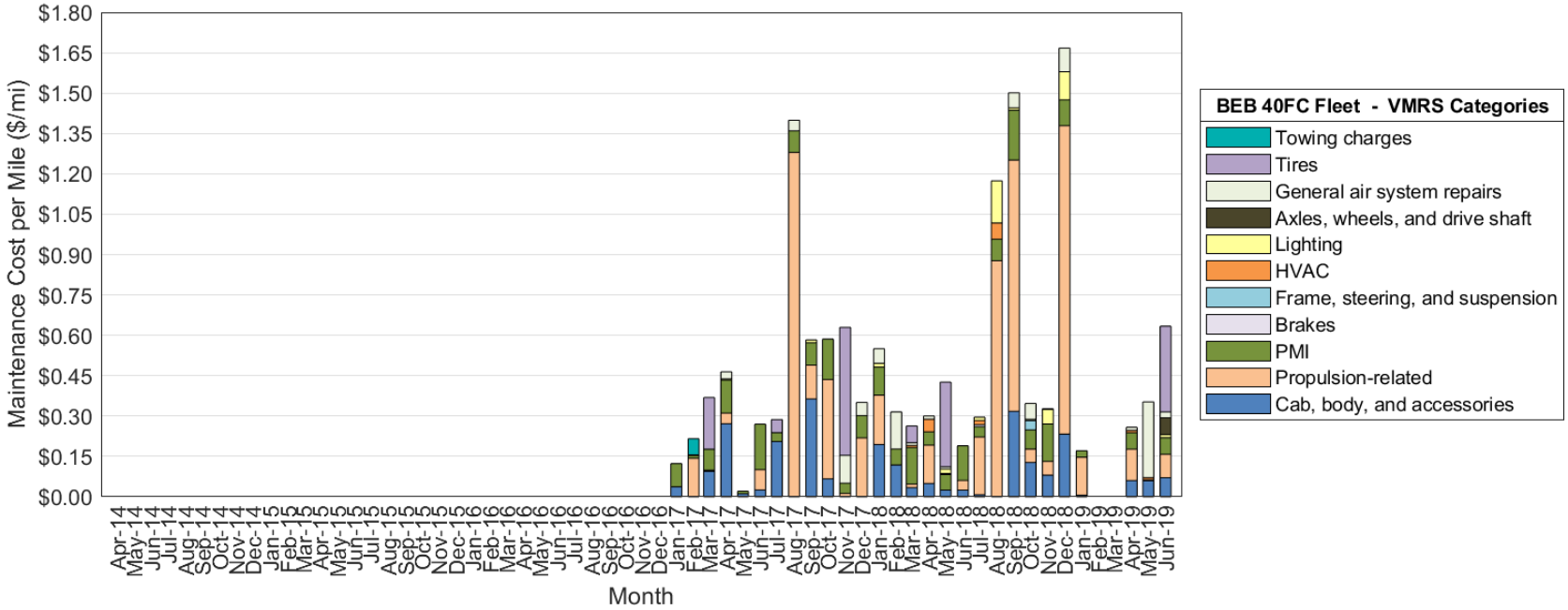
- Propulsion-related repairs for the BEBs were for low-voltage batteries, battery equalizer, cooling system, DC-DC converter, traction motor, and transmission.
- Overall cost per mile without low-voltage battery costs for the BEB 35FC buses was 1.5 times higher than the CNG bus cost; cost for the BEB 40FC buses was 1.4 times higher than the CNG bus cost.

Maintenance Cost by System: BEB 35FC Fleet



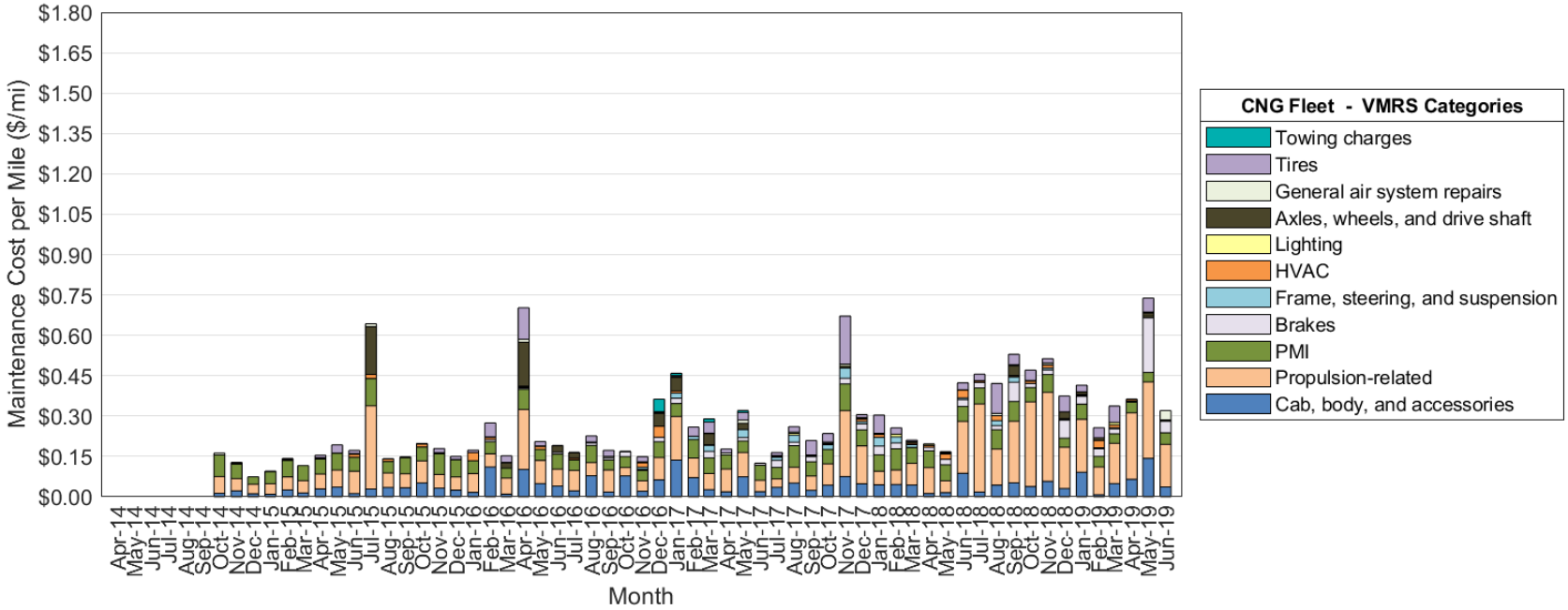
- The primary driver for the higher propulsion-related cost was issues with the low-voltage batteries (see cost per mile by propulsion subsystem for BEB 35FC fleet).
- High-cost parts and multiple labor hours were required for several repairs including DC-DC converters, traction motor, transmission, suspension, and electrical system.

Maintenance Cost by System: BEB 40FC Fleet



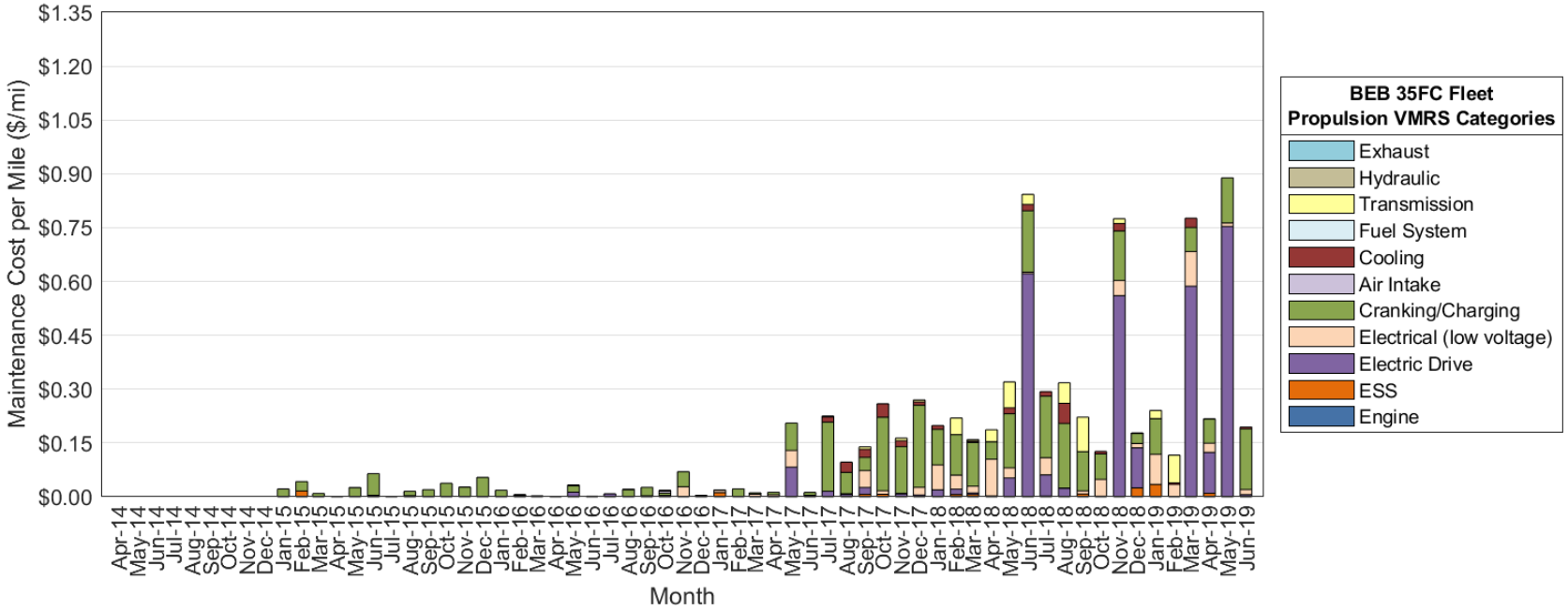
- Because the BEB 40FC fleet consists of only two buses, the cost per mile is more sensitive to cost increases. The buses were not operated in February, March, and most of April 2019.
- The buses still experience issues with the low-voltage batteries (see cost per mile by propulsion subsystem for BEB 40FC fleet).

Maintenance Cost by System: CNG Fleet



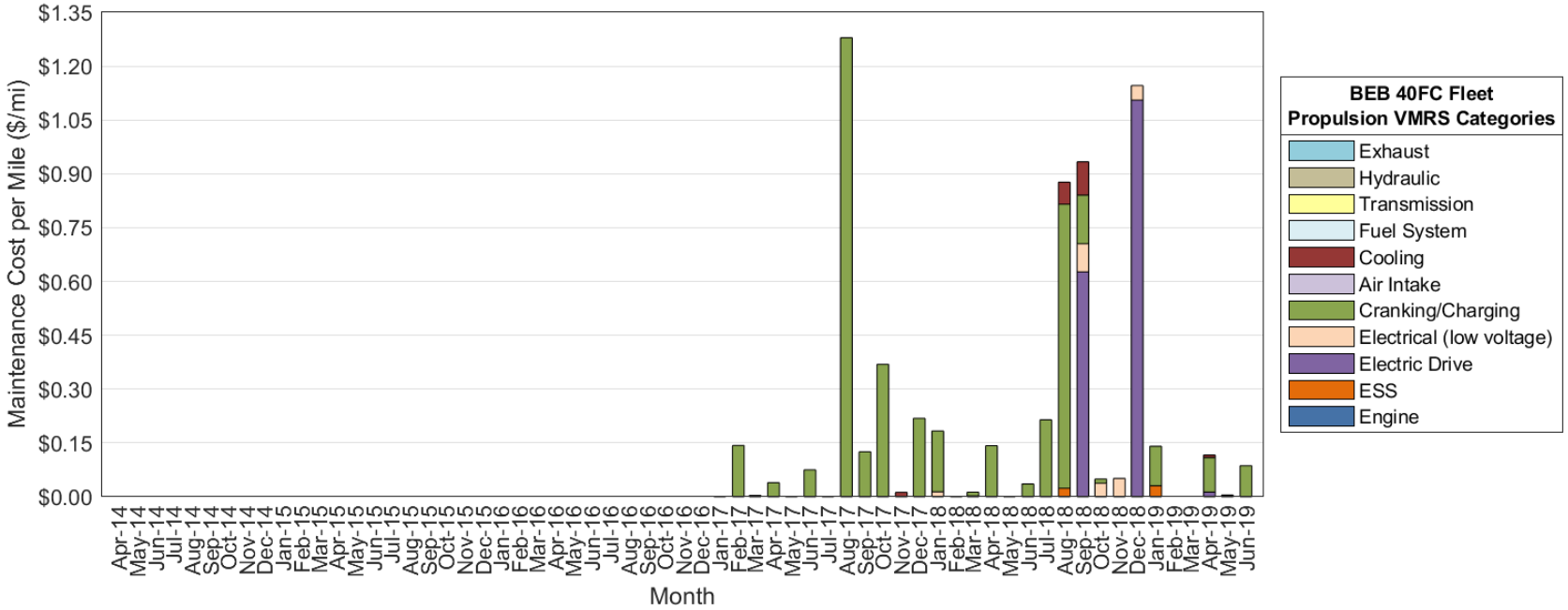
- CNG bus maintenance cost shows an increase over time as the buses age and pass the warranty period.
- During the high-cost months, multiple buses reached the mileage for a major PM.
- Multiple buses had brake relines.
- Higher propulsion system costs in the first half of 2019 were due to tune-ups on multiple buses, exhaust issues, cooling system, and engine control module failures.

Propulsion System Maintenance Cost by Subsystem: BEB 35FC Fleet



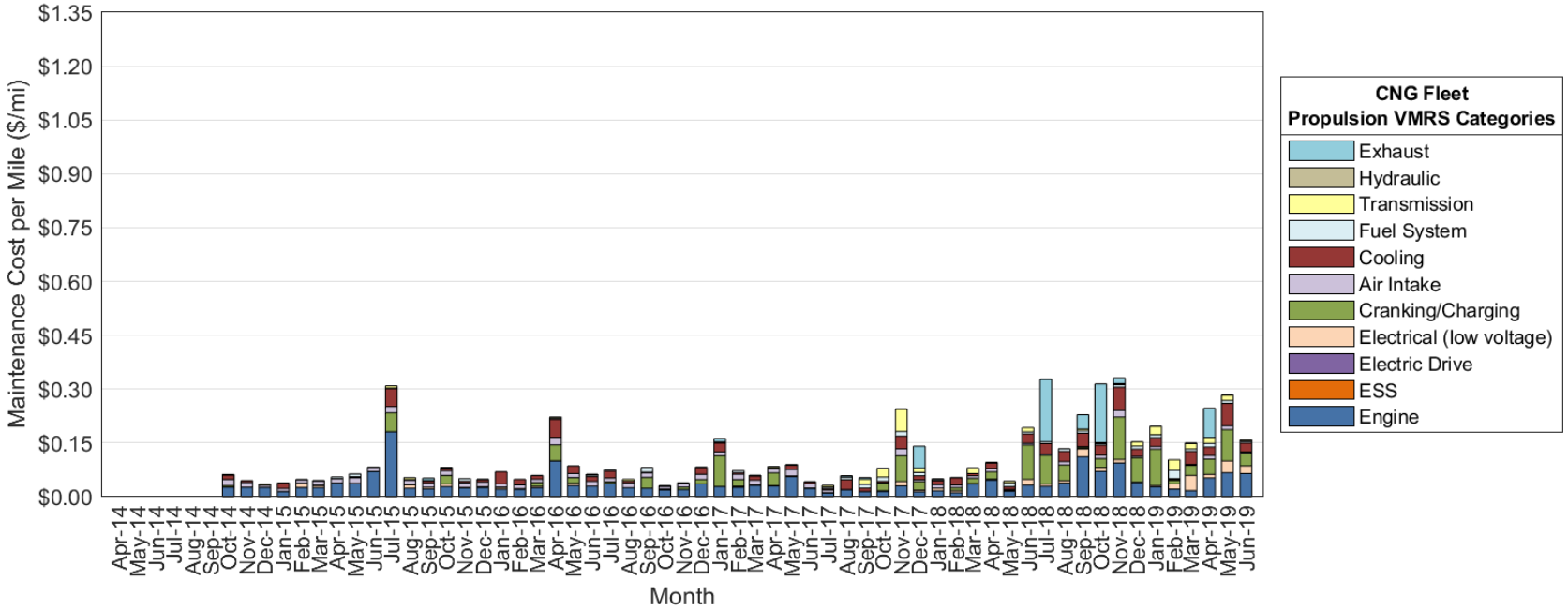
- Low-voltage battery replacements fall into the cranking/charging category.
- Electric drive issues include replacement of DC-DC converters on two buses and a traction motor (high parts cost).
- Extended labor hours for diagnosis/repair were required in some cases (electrical system, suspension, traction motor).

Propulsion System Maintenance Cost by Subsystem: BEB 40FC Fleet



- Mileage was low for both buses during the first half of 2019.
- Both buses in the BEB 40FC fleet had low-voltage battery changeouts.

Propulsion System Maintenance Cost by Subsystem: CNG Fleet



- Increased costs in the first half of 2019 fall into several categories:
  - Exhaust system—turbocharger
  - Cranking/charging—low-voltage batteries
  - Engine—tune-ups and electronic control module failures.

Propulsion-Related Maintenance Costs by Subsystem: Jan.–Jun. 2019

Maintenance System		BEB 35FC	BEB 40FC	CNG
Mileage		132,319	20,524	235,197
Total Propulsion-Related Systems (Roll-Up of All Systems)	Parts cost ($)	35,647.53	1,712.87	27,429.67
	Labor hours	351.0	16.1	299.4
	Total cost ($)	53,199.53	2,518.87	42,401.17
	Total cost ($) per mile Without battery changeouts	**0.402** **0.319**	**0.123** **0.032**	**0.180** **0.161**
Exhaust System Repairs	Parts cost ($)	0.00	0.00	2,515.16
	Labor hours	0.0	0.0	12.2
	Total cost ($)	0.00	0.00	3,124.16
	Total cost ($) per mile	**0.000**	**0.000**	**0.013**
Fuel System Repairs	Parts cost ($)	0.00	0.00	1,468.47
	Labor hours	0.0	0.0	14.8
	Total cost ($)	0.00	0.00	2,207.97
	Total cost ($) per mile	**0.000**	**0.000**	**0.009**
Powerplant System Repairs (ESS for BEBs)	Parts cost ($)	56.34	0.00	4,879.40
	Labor hours	19.1	2.8	86.2
	Total cost ($)	1,012.34	138.50	9,186.90
	Total cost ($) per mile	**0.008**	**0.007**	**0.039**
Electric Propulsion System Repairs	Parts cost ($)	28,394.41	0.00	0.00
	Labor hours	64.5	2.6	0.0
	Total cost ($)	31,619.41	131.00	0.00
	Total cost ($) per mile	**0.239**	**0.006**	**0.000**

Propulsion-Related Maintenance Costs by Subsystem: Jan.–Jun. 2019

Maintenance System		BEB 35FC	BEB 40FC	CNG
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)	Parts cost ($)	6,396.97	1,706.67	12,249.33
	Labor hours	219.6	3.5	79.5
	Total cost ($)	17,377.97	1,882.17	16,222.83
	Total cost ($) per mile	**0.131**	**0.092**	**0.069**
Air Intake System Repairs	Parts cost ($)	15.50	6.20	1,243.31
	Labor hours	0.0	0.0	2.3
	Total cost ($)	15.50	6.20	1,358.81
	Total cost ($) per mile	**0.000**	**0.000**	**0.006**
Cooling System Repairs	Parts cost ($)	553.31	0.00	3,284.71
	Labor hours	5.5	7.2	65.7
	Total cost ($)	827.31	361.00	6,570.21
	Total cost ($) per mile	**0.006**	**0.018**	**0.028**
Transmission System Repairs	Parts cost ($)	231.00	0.00	1,789.29
	Labor hours	42.3	0.0	38.8
	Total cost ($)	2,347.00	0.00	3,730.29
	Total cost ($) per mile	**0.018**	**0.000**	**0.016**
Hydraulic System Repairs	Parts cost ($)	0.00	0.00	0.00
	Labor hours	0.0	0.0	0.0
	Total cost ($)	0.00	0.00	0.00
	Total cost ($) per mile	**0.000**	**0.000**	**0.000**

Low-Voltage Battery Maintenance Analysis

Foothill Transit continues to have issues with the low-voltage (LV) batteries. The tables summarize the LV battery changeout data from the BEB and CNG buses. The BEBs are averaging 8.9 changeouts per bus at approximately 12,000 miles between changeout. The CNG buses average 1.6 changeouts per bus at more than 165,000 miles. One issue is that the accessories (farebox, cameras, etc.) continually draw power from these batteries. If the master switch is not turned off at the end of operation, the accessories continue to draw power from the LV batteries. The CNG buses are equipped with an auto shutoff for the accessories; the BEBs are not.

BEB	LV Battery Changeouts	Accumulated Miles	Miles between Changeout	Data Period
2004	5	104,750	20,950	0
2005	7	116,513	16,645	1
2006	9	124,538	13,838	3
2007	6	120,706	20,118	1
2008	10	112,893	11,289	2
2009	8	126,819	15,852	0
2010	5	115,963	23,193	0
2011	9	123,759	13,751	1
2012	8	121,809	15,226	1
2013	8	89,738	11,217	1
2014	8	124,854	15,607	0
2015	19	103,694	5,458	0
2016	13	55,907	4,301	4
2017	9	58,035	6,448	1
Total	**124**	**1,499,977**	**12,097**	**15**
Per Bus	**8.9**			**1.1**

Proterra is aware of the issue and is developing an auto shutoff to address the problem. New designs will include this feature. Proterra is also working on a retrofit for buses already in service.

CNG Bus	LV Battery Changeouts	Accumulated Miles	Miles between Changeout
2200	3	261,604	87,201
2201	0	264,110	
2202	0	268,634	
2203	3	269,193	89,731
2204	2	261,998	130,999
2205	1	271,376	271,376
2206	0	278,091	
2207	4	278,946	69,737
Total	**13**	**2,153,952**	**165,689**
Per Bus	**1.63**		

Contacts

NREL
Leslie Eudy
Phone: 303-275-4412
Email: leslie.eudy@nrel.gov

Foothill Transit
Roland Cordero
Phone: 626-931-7246
Email: rcordero@foothilltransit.org

California Air Resources Board
Yachun Chow
Phone: 919-322-7450
Email: yachun.chow@arb.ca.gov

Proterra
Mike Finnern
Phone: 864-214-0393
Email: mfinnern@Proterra.com

Acronyms and Abbreviations

BEB	battery electric bus
Btu	British thermal unit
CNG	compressed natural gas
dge	diesel gallon equivalent
ESS	energy storage system
FC	fast charge
ft	feet
gge	gasoline gallon equivalent
GVWR	gross vehicle weight rating
hp	horsepower
HVAC	heating, ventilation, and air conditioning
in.	inches
kW	kilowatts
kWh	kilowatt hours
lb	pounds
LHV	lower heating value
LV	low voltage
MBRC	miles between roadcalls
mi	miles
mpdge	miles per diesel gallon equivalent
mpgge	miles per gasoline gallon equivalent
mph	miles per hour
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PM	preventive maintenance
PMI	preventive maintenance inspection
psi	pounds per square inch
PTC	Pomona Transit Center
scf	standard cubic feet
VMRS	Vehicle Maintenance Reporting Standards

Acknowledgments

Produced under direction of the California Air Resources Board by the National Renewable Energy Laboratory (NREL) under Work for Others Agreement number FIA-17-1847.

Appendix:
Fleet Summary Statistics

Fleet Summary Statistics

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Number of vehicles	12	12	2	2	8	8
Period used for fuel and oil analysis	4/14–6/19	1/19–6/19	1/17–6/19	1/19–6/19	10/14–6/19	1/19–6/19
Total number of months in period	63	6	30	6	57	6
Fuel and oil analysis base fleet mileage	1,539,813	132,319	40,917	11,053	1,925,673	201,374
Period used for maintenance analysis	1/15–6/19	1/19–6/19	1/17–6/19	1/19–6/19	10/14–6/19	1/19–6/19
Total number of months in period	54	6	30	6	57	6
Maintenance analysis base fleet mileage	1,386,035	132,319	113,943	20,524	2,153,952	221,895
Availability	85	63	82	89	96	93
Fleet fuel/energy usage in kWh (BEB) or gge (CNG)	3,328,111	269,651	88,420	22,214	504,617	55,196
Roadcalls	285	31	16	2	85	13
Total MBRC	5,555	4,268	7,121	10,262	25,341	17,069
Propulsion roadcalls	114	20	6	2	55	10
Propulsion MBRC	13,887	6,616	18,990	10,262	39,163	22,190
Fleet kWh/mile (BEB) or mpgge (CNG)	2.16	2.04	2.16	2.01	3.82	3.65
Representative fleet mpg (energy equiv.)	17.41	18.47	17.42	18.73	4.37	4.18
Energy cost per kWh or CNG cost per gge	0.179	0.172	0.179	0.172	0.99	1.19
Fuel cost per mile	0.45	0.39	0.45	0.39	0.26	0.33
Total scheduled repair cost per mile	0.08	0.06	0.08	0.04	0.12	0.10
Total unscheduled repair cost per mile	0.34	0.63	0.39	0.58	0.16	0.31
Total maintenance cost per mile	0.42	0.68	0.47	0.62	0.28	0.41
Total operating cost per mile	***0.86***	***1.07***	***0.91***	***1.01***	***0.54***	***0.74***

Maintenance Cost Summary

Maintenance Cost Summary

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Fleet mileage	1,386,035	132,319	113,943	20,524	2,153,952	221,895
Total parts cost	286,122.90	51,146.01	20,159.79	4,916.32	314,458.27	47,661.72
Total labor hours	5,829.5	783.3	667.0	157.2	5,613.6	857.4
Average labor cost (@ $50.00 per hour)	291,472.50	39,166.50	33,351.50	7,861.50	280,681.00	42,871.50
Total maintenance cost	577,595.40	90,312.51	53,511.29	12,777.82	595,139.27	90,533.22
Total maintenance cost per bus	48,132.95	7,526.04	26,755.65	6,388.91	74,392.41	11,316.65
Total maintenance cost per mile	**0.417**	**0.683**	**0.470**	**0.623**	**0.276**	**0.408**
without low-voltage battery cost	***0.368***	***0.599***	***0.376***	***0.532***	***0.270***	***0.389***

Propulsion System Maintenance Cost Summary

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)						
Parts cost	117,879.96	35,647.53	8,936.19	1,712.87	164,912.22	27,429.67
Labor hours	1,424.63	351.04	175.68	16.12	1,389.13	299.43
Average labor cost	71,231.50	17,552.00	8,784.00	806.00	69,456.50	14,971.50
Total cost (for system)	189,111.46	53,199.53	17,720.19	2,518.87	234,368.72	42,401.17
Total cost (for system) per bus	15,759.29	4,433.29	8,860.10	1,259.44	29,296.09	5,300.15
Total cost (for system) per mile	**0.136**	**0.402**	**0.156**	**0.123**	**0.109**	**0.191**
without low-voltage battery cost	***0.088***	***0.319***	***0.062***	***0.032***	***0.102***	***0.172***

Maintenance Cost by Vehicle System

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Exhaust System Repairs (ATA VMRS 43)						
Parts cost	0.00	0.00	0.00	0.00	18,670.19	2,515.16
Labor hours	0.0	0.0	0.0	0.0	60.3	12.2
Average labor cost	0.00	0.00	0.00	0.00	3,014.50	609.00
Total cost (for system)	0.00	0.00	0.00	0.00	21,684.69	3,124.16
Total cost (for system) per bus	0.00	0.00	0.00	0.00	2,710.59	390.52
Total cost (for system) per mile	**0.000**	**0.000**	**0.000**	**0.000**	**0.010**	**0.014**
Fuel System Repairs (ATA VMRS 44)						
Parts cost	0.00	0.00	0.00	0.00	4,918.88	1,468.47
Labor hours	0.0	0.0	0.0	0.0	90.4	14.8
Average labor cost	0.00	0.00	0.00	0.00	4,518.00	739.50
Total cost (for system)	0.00	0.00	0.00	0.00	9,436.88	2,207.97
Total cost (for system) per bus	0.00	0.00	0.00	0.00	1,179.61	276.00
Total cost (for system) per mile	**0.000**	**0.000**	**0.000**	**0.000**	**0.004**	**0.010**
Power Plant (Engine) Repairs (ATA VMRS 45)						
Parts cost	56.34	56.34	0.00	0.00	56,287.01	4,879.40
Labor hours	66.4	19.1	3.8	2.8	419.6	86.2
Average labor cost	3,317.50	956.00	188.50	138.50	20,977.50	4,307.50
Total cost (for system)	3,373.84	1,012.34	188.50	138.50	77,264.51	9,186.90
Total cost (for system) per bus	281.15	84.36	94.25	69.25	9,658.06	1,148.36
Total cost (for system) per mile	**0.002**	**0.008**	**0.002**	**0.007**	**0.036**	**0.041**

Maintenance Cost by Vehicle System

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Electric Propulsion Repairs (ATA VMRS 46)						
Parts cost	56,315.86	28,394.41	0.00	0.00	0.00	0.00
Labor hours	281.7	64.5	88.5	2.6	0.0	0.0
Average labor cost	14,084.50	3,225.00	4,424.00	131.00	0.00	0.00
Total cost (for system)	70,400.36	31,619.41	4,424.00	131.00	0.00	0.00
Total cost (for system) per bus	5,866.70	2,634.95	2,212.00	65.50	0.00	0.00
Total cost (for system) per mile	**0.051**	**0.239**	**0.039**	**0.006**	**0.000**	**0.000**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)						
Parts cost	56,370.58	6,396.97	8,899.91	1,706.67	38,465.08	12,249.33
Labor hours	803.5	219.6	67.3	3.5	400.6	79.5
Average labor cost	40,172.50	10,981.00	3,366.50	175.50	20,031.50	3,973.50
Total cost (for system)	96,543.08	17,377.97	12,266.41	1,882.17	58,496.58	16,222.83
Total cost (for system) per bus	8,045.26	1,448.16	6,133.21	941.09	7,312.07	2,027.85
Total cost (for system) per mile	**0.070**	**0.131**	**0.108**	**0.092**	**0.027**	**0.073**
Air Intake System Repairs (ATA VMRS 41)						
Parts cost	47.30	15.50	6.20	6.20	20,595.26	1,243.31
Labor hours	3.9	0.0	0.0	0.0	9.8	2.3
Average labor cost	195.00	0.00	0.00	0.00	488.00	115.50
Total cost (for system)	242.30	15.50	6.20	6.20	21,083.26	1,358.81
Total cost (for system) per bus	20.19	1.29	3.10	3.10	2,635.41	169.85
Total cost (for system) per mile	**0.000**	**0.000**	**0.000**	**0.000**	**0.010**	**0.006**

Maintenance Cost by Vehicle System

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Cooling System Repairs (ATA VMRS 42)						
Parts cost	3,373.11	553.31	30.08	0.00	18,877.55	3,284.71
Labor hours	82.7	5.5	16.1	7.2	308.6	65.7
Average labor cost	4,133.50	274.00	805.00	361.00	15,431.00	3,285.50
Total cost (for system)	7,506.61	827.31	835.08	361.00	34,308.55	6,570.21
Total cost (for system) per bus	625.55	68.94	417.54	180.50	4,288.57	821.28
Total cost (for system) per mile	**0.005**	**0.006**	**0.007**	**0.018**	**0.016**	**0.030**
Hydraulic System Repairs (ATA VMRS 65)						
Parts cost	0.00	0.00	0.00	0.00	0.00	0.00
Labor hours	1.5	0.0	0.0	0.0	0.0	0.0
Average labor cost	75.00	0.00	0.00	0.00	0.00	0.00
Total cost (for system)	75.00	0.00	0.00	0.00	0.00	0.00
Total cost (for system) per bus	6.25	0.00	0.00	0.00	0.00	0.00
Total cost (for system) per mile	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
General Air System Repairs (ATA VMRS 10)						
Parts cost	32,093.76	935.67	1,064.00	679.45	3,211.03	826.05
Labor hours	299.9	31.5	97.2	58.4	59.2	11.9
Average labor cost	14,995.50	1,574.50	4,861.00	2,922.00	2,959.50	592.50
Total cost (for system)	47,089.26	2,510.17	5,925.00	3,601.45	6,170.53	1,418.55
Total cost (for system) per bus	3,924.11	209.18	2,962.50	1,800.73	771.32	177.32
Total cost (for system) per mile	**0.034**	**0.019**	**0.052**	**0.175**	**0.003**	**0.006**

Maintenance Cost by Vehicle System

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Brake System Repairs (ATA VMRS 13)						
Parts cost	1,923.56	197.15	0.00	0.00	18,068.14	5,222.19
Labor hours	85.9	2.4	8.5	8.0	306.2	136.2
Average labor cost	4,296.50	121.50	425.50	400.50	15,308.00	6,809.00
Total cost (for system)	6,220.06	318.65	425.50	400.50	33,376.14	12,031.19
Total cost (for system) per bus	518.34	26.55	212.75	200.25	4,172.02	1,503.90
Total cost (for system) per mile	**0.004**	**0.002**	**0.004**	**0.020**	**0.015**	**0.054**
Transmission Repairs (ATA VMRS 27)						
Parts cost	1,716.77	231.00	0.00	0.00	7,098.26	1,789.29
Labor hours	185.1	42.3	0.0	0.0	99.9	38.8
Average labor cost	9,253.50	2,116.00	0.00	0.00	4,996.00	1,941.00
Total cost (for system)	10,970.27	2,347.00	0.00	0.00	12,094.26	3,730.29
Total cost (for system) per bus	914.19	195.58	0.00	0.00	1,511.78	466.29
Total cost (for system) per mile	**0.008**	**0.018**	**0.000**	**0.000**	**0.006**	**0.017**
Inspections Only—No Parts Replacements (101)						
Parts cost	0.00	0.00	0.00	0.00	0.00	0.00
Labor hours	2076.5	128.2	168.0	14.7	2376.0	184.4
Average labor cost	103,826.00	6,411.50	8,397.50	735.50	118,798.00	9,218.00
Total cost (for system)	103,826.00	6,411.50	8,397.50	735.50	118,798.00	9,218.00
Total cost (for system) per bus	8,652.17	534.29	4,198.75	367.75	14,849.75	1,152.25
Total cost (for system) per mile	**0.075**	**0.048**	**0.074**	**0.036**	**0.055**	**0.042**

Maintenance Cost by Vehicle System

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)						
Parts cost	28,113.21	3,098.87	2,230.11	0.00	41,705.96	7,290.08
Labor hours	1218.9	141.5	170.5	47.6	1038.3	150.1
Average labor cost	60,943.00	7,072.50	8,523.00	2,381.00	51,916.50	7,504.00
Total cost (for system)	89,056.21	10,171.37	10,753.11	2,381.00	93,622.46	14,794.08
Total cost (for system) per bus	7,421.35	847.61	5,376.56	1,190.50	11,702.81	1,849.26
Total cost (for system) per mile	**0.064**	**0.077**	**0.094**	**0.116**	**0.043**	**0.067**
HVAC System Repairs (ATA VMRS 01)						
Parts cost	2,335.47	974.62	158.79	82.72	9,168.67	1,205.77
Labor hours	97.0	32.8	7.0	0.0	90.5	9.0
Average labor cost	4,848.50	1,640.00	352.00	0.00	4,524.00	447.50
Total cost (for system)	7,183.97	2,614.62	510.79	82.72	13,692.67	1,653.27
Total cost (for system) per bus	598.66	217.89	255.40	41.36	1,711.58	206.66
Total cost (for system) per mile	**0.005**	**0.020**	**0.004**	**0.004**	**0.006**	**0.007**
Lighting System Repairs (ATA VMRS 34)						
Parts cost	4,199.49	894.63	243.61	71.28	539.92	77.37
Labor hours	197.5	35.9	18.9	1.2	44.7	12.8
Average labor cost	9,873.00	1,794.00	945.00	60.50	2,234.00	642.00
Total cost (for system)	14,072.49	2,688.63	1,188.61	131.78	2,773.92	719.37
Total cost (for system) per bus	1,172.71	224.05	594.31	65.89	346.74	89.92
Total cost (for system) per mile	**0.010**	**0.020**	**0.010**	**0.006**	**0.001**	**0.003**

Maintenance Cost by Vehicle System

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)						
Parts cost	4,712.86	1,892.54	188.48	0.00	8,481.79	127.38
Labor hours	180.6	40.8	0.0	0.0	84.5	3.8
Average labor cost	9,030.00	2,041.50	1.00	0.00	4,226.00	191.50
Total cost (for system)	13,742.86	3,934.04	189.48	0.00	12,707.79	318.88
Total cost (for system) per bus	1,145.24	327.84	94.74	0.00	1,588.47	39.86
Total cost (for system) per mile	**0.010**	**0.030**	**0.002**	**0.000**	**0.006**	**0.001**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)						
Parts cost	1,892.90	0.00	0.00	0.00	22,042.50	458.79
Labor hours	14.1	0.0	7.8	7.8	48.1	17.3
Average labor cost	706.50	0.00	390.00	390.00	2,404.00	864.50
Total cost (for system)	2,599.40	0.00	390.00	390.00	24,446.50	1,323.29
Total cost (for system) per bus	216.62	0.00	195.00	195.00	3,055.81	165.41
Total cost (for system) per mile	**0.002**	**0.000**	**0.003**	**0.019**	**0.011**	**0.006**
Tire Repairs (ATA VMRS 17)						
Parts cost	86,686.69	7,505.00	7,053.61	2,370.00	43,626.84	5,024.42
Labor hours	234.4	19.2	13.5	3.3	176.1	32.6
Average labor cost	11,722.00	959.00	672.50	166.00	8,804.50	1,631.00
Total cost (for system)	98,408.69	8,464.00	7,726.11	2,536.00	52,431.34	6,655.42
Total cost (for system) per bus	8,200.72	705.33	3,863.06	1,268.00	6,553.92	831.93
Total cost (for system) per mile	**0.071**	**0.064**	**0.068**	**0.124**	**0.024**	**0.030**

Maintenance Cost by Vehicle System

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Towing Charges						
Charge	6,285.00	0.00	285.00	0.00	2,701.20	0.00
Labor hours	0.00	0.00	0.00	0.00	1.0	0.0
Average labor cost	0.00	0.00	0.00	0.00	50.00	0.00
Total cost (for system)	6,285.00	0.00	285.00	0.00	2,751.20	0.00
Total cost (for system) per bus	523.75	0.00	142.50	0.00	343.90	0.00
Total cost (for system) per mile	**0.005**	**0.000**	**0.003**	**0.000**	**0.001**	**0.000**

Fleet Summary Statistics: SI Units

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Number of vehicles	12	12	2	2	8	8
Period used for fuel and oil analysis	4/14–6/19	1/19–6/19	1/17–6/19	1/19–6/19	10/14–6/19	1/19–6/19
Total number of months in period	63	6	30	6	57	6
Fuel and oil analysis base fleet kilometers	2,478,021	212,940	65,847	—	3,098,986	324,071
Period used for maintenance analysis	1/15–6/19	1/19–6/19	1/17–6/19	1/19–6/19	10/14–6/19	1/19–6/19
Total number of months in period	54	6	30	6	57	6
Maintenance analysis base fleet kilometers	2,230,545	212,940	183,368	33,030	3,466,355	357,096
Average monthly kilometers per vehicle	3,932	2,958	3,056	2,752	7,602	7,439
Availability	85	63	82	89	96	93
Fleet fuel/energy usage in kWh (BEB) or liter (CNG)	3,328,111	269,651	88,420	22,214	1,910,184	208,939
Roadcalls	285	31	16	2	85	13
Total KBRC	8,939	6,869	11,460	16,515	40,781	27,469
Propulsion roadcalls	114	20	6	2	55	10
Propulsion KBRC	22,348	10,647	30,561	16,512	63,025	35,710
Representative fleet kg/100 km (energy equiv.)	13.49	12.71	13.48	12.54	53.78	56.26
Energy cost per kWh or CNG cost per liter	0.18	0.17	0.18	0.17	0.26	0.32
Fuel cost per kilometer	0.28	0.29	0.28	0.29	0.16	0.20
Total scheduled repair cost per km	0.05	0.03	0.05	0.03	0.07	0.06
Total unscheduled repair cost per km	0.21	0.39	0.24	0.36	0.10	0.19
Total maintenance cost per km	0.26	0.42	0.29	0.39	0.17	0.25
Total operating cost per km	***0.54***	***0.71***	***0.57***	***0.67***	***0.33***	***0.46***

Maintenance Cost Summary: SI Units

Maintenance Cost Summary

	BEB 35FC All Data	BEB 35FC Data Period	BEB 40FC All Data	BEB 40FC Data Period	CNG All Data	CNG Data Period
Fleet kilometers	2,230,545	212,940	183,368	33,030	3,466,355	357,096
Total parts cost	286,122.90	51,146.01	20,159.79	4,916.32	314,458.27	47,661.72
Total labor hours	5,829.5	783.3	667.0	157.2	5,613.6	857.4
Average labor cost (@ $50.00 per hour)	291,472.50	39,166.50	33,351.50	7,861.50	280,681.00	42,871.50
Total maintenance cost	577,595.40	90,312.51	53,511.29	12,777.82	595,139.27	90,533.22
Total maintenance cost per bus	48,132.95	7,526.04	26,755.65	6,388.91	74,392.41	11,316.65
Total maintenance cost per km	**0.26**	**0.42**	**0.29**	**0.39**	**0.17**	**0.25**
without low-voltage battery cost	***0.23***	***0.37***	***0.23***	***0.33***	***0.17***	***0.24***

www.nrel.gov

NREL/PR-5400-73516

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the California Air Resources Board. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.