Long Beach Transit
Battery Electric Bus Progress Report
Data Period Focus: Jan. 2019 through Jun. 2019

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January 2020

NREL/PR-5400-73740

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Introduction

This report summarizes results of a battery electric bus (BEB) evaluation at Long Beach Transit (LBT), located in Southern California. Long Beach Transit is collaborating with the California Air Resources Board (CARB) 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. NREL completed a previous report funded by the Federal Transit Administration that documented results from January 2018 through December 2018. 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 another written report on the Long Beach Transit fleet covering all of 2019.

Results Summary

Bus fleets: This evaluation includes 10 BYD 40-ft battery electric buses (BEB) and 8 Gillig 40-ft compressed natural gas (CNG) buses.

Bus use: The BEBs are operated on an 8-mile circulator route (Passport) that travels around the Waterfront area between the Queen Mary and Downtown Long Beach. The average speed for this route is approximately 8 mph. The CNG buses are randomly dispatched on all routes out of the operations facility. The average speed for the CNG buses is around 11 mph. This difference in duty cycle effects the comparison of mileage, fuel economy, and costs per mile between fleets. LBT provided data from a selection of buses previously operated on the Passport route for a closer comparison.

Bus out of service time: Beginning in late 2018, the BEBs experienced issues with the high voltage batteries. LBT and BYD worked through a schedule to remove each bus from service and send it to the manufacturing plant for warranty work. When a bus was at BYD, it was considered "not planned" for service. The buses were cycled through the schedule to allow LBT to meet the Passport service using the BEBs. Each bus operated at least one month during the 2019 data period.

Results Summary (continued)

Bus availability: Availability in the first half of 2019 was 75.3% for the BEBs and 84.6% for the CNG buses. All but 2 of the buses were returned to BYD for warranty work during the data period. These buses were not out at the same time or for the full data period. These buses were considered unplanned during this time. One bus was offsite for more than 4 months. Most unavailable time for the BEBs and the CNG buses was due to general bus-related problems.

Availability to meet Passport service: LBT's primary goal was to use the BEBs to meet the required service on the Passport route. During the early stage of deployment, that required 6 buses for weekdays and 8 for weekends. LBT has regular service changes three times per year where they reassess the needs for each route. At the last service change in June, the Passport route required 4 buses on weekdays and 7 on weekends. NREL analyzed the data to determine the percent of time the BEBs succeeded in meeting this required service. Since January 2018, the BEBs met service 79% of the time. During the first half of 2019, the BEBs met required service 80% of time.

Results Summary (continued)

Energy use/equivalent fuel economy: NREL has collected miles and energy use from the LBT data on each bus. Energy use/equivalent fuel economy in the first half of 2019 was 1.93 kWh/mi (19.54 mpdge) for the BEB fleet and 3.38 mpgge (3.88 mpdge) for the CNG bus fleet. The BEB energy equivalent fuel economy is 5 times that of the CNG buses as they are currently operated by LBT. NREL collected data on CNG buses previously operating on the Passport route that showed an average fuel economy of 3.26 mpdge. The BEB fuel economy is approximately 6 times that of the CNG buses in the same service.

Fuel cost: Based on energy purchased in the first half of 2019, the BEB fleet had a fuel cost of $0.41/mi (at $0.20/kWh) and the CNG fleet had a fuel cost of $0.40/mi (at $1.54/dge). The cost per unit of energy/fuel is the average for the data period of January 2019–June 2019. To compare cost between buses in the same service, NREL estimated the cost per mile for the CNG buses if operated only on the Passport route. LBT provided data on CNG buses operated on the Passport route prior to the agency switching to BEBs. On this route, CNG buses averaged 3.26 mpdge. This lower fuel economy would increase the cost of the CNG buses to an overall average of $0.47/mi, compared to $0.53/mi for the BEB fleet for the full evaluation period.

Results Summary (continued)

Maintenance cost: The BEBs are still under warranty. The LBT maintenance staff handle the scheduled service and aid the manufacturer technicians with unscheduled repair. Cost to maintain the buses in the first half of 2019 was $0.43/mi for the BEBs and $0.52/mi for the CNG buses. The BEB maintenance cost is 17% lower than that of the CNG buses.

- **Scheduled labor:** LBT reports that the scheduled labor for the BEBs is artificially high because some minor repairs have been handled during scheduled maintenance and not separated out in the work orders. This results in higher scheduled maintenance cost and lower unscheduled maintenance.
- **High voltage battery issue:** Beginning in mid-2018, the buses developed a battery balancing issue. Several factors contributed to the problem: (1) these buses were some of the first ones produced by BYD at its U.S. plant and the initial commissioning was not adequate, and (2) LBT's planned use of the buses at 60–70 miles per day was too conservative because the batteries were not allowed to discharge below a certain state of charge. BYD's first solution was to do a full rebalance of the batteries. This did not solve the problem. BYD offered to replace all the batteries with its newest generation batteries. The upgraded battery pack (344 kWh) has more energy than the previous version (295 kWh), which allows LBT to meet its service with about 40% state of charge on the batteries each day. The agency reports that the buses are performing well.

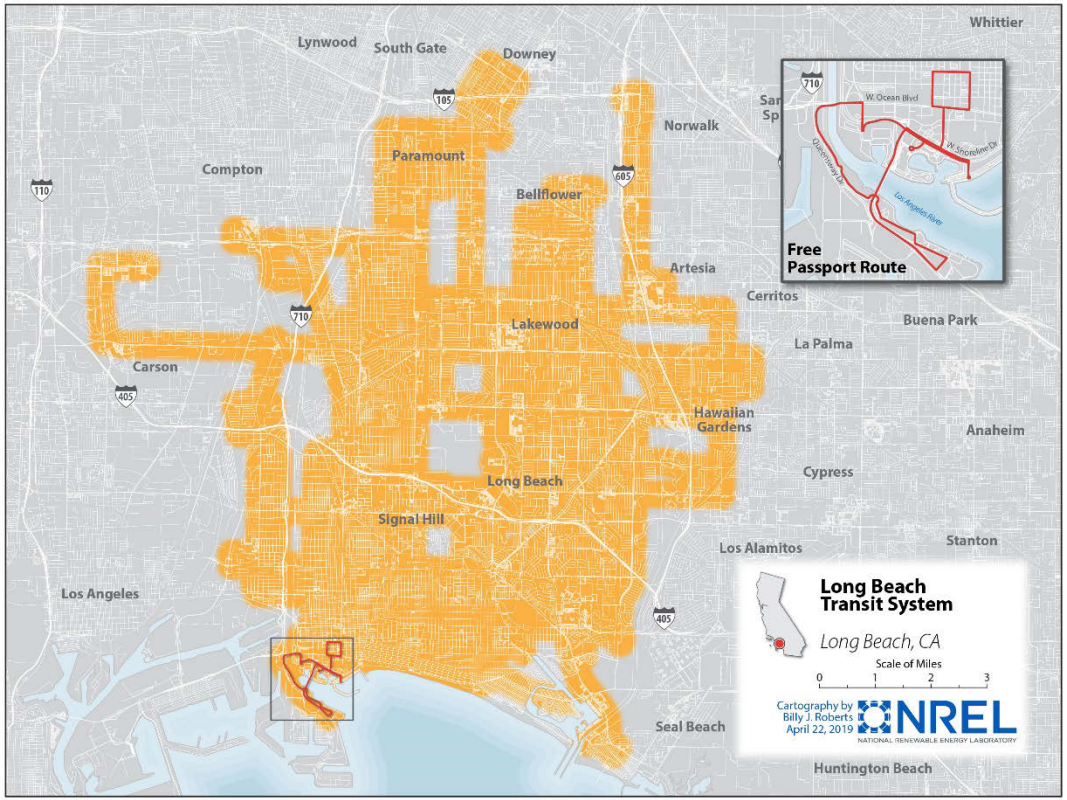
Results Summary (continued)

Future analysis: NREL's current work for CARB covers data collection and analysis on the LBT BEB fleet in comparison to the CNG baseline fleet through the end of 2019. NREL will publish a written report summarizing the full data period through the end of 2019.

Fleet Profile

Long Beach Transit (LBT) provides public transit service in a 98-square-mile area of southern California. LBT operates a variety of fixed-route bus service and demand-responsive “Dial-A-Lift” paratransit service to several communities within the LBT service area. LBT contracts with a third-party provider for its complementary paratransit services within three-quarters of a mile of any fixed route bus service.

LBT’s current fleet of 249 buses serves 36 fixed routes. The agency has a commitment to clean technologies and operates low emission compressed natural gas (CNG) and gasoline hybrid buses. The bus fleet comprises approximately 50% CNG buses, 35% gasoline hybrids, 10% standard diesels, and 4% battery electric buses.



Evaluation Buses: Specifications

Vehicle System	BEB	CNG
Number of buses	10	8
Bus manufacturer	BYD	Gillig
Model year	2015	2014
Bus purchase cost[a]	$1,02,550	$546,314
Length/width/height	40 ft/100 in./137 in.	40 ft/104 in./135 in.
GVWR/curb weight	43,431 lb/31,960 lb	41,600 lb/30,820 lb
Passenger capacity	34 seats, 2 wheelchair positions, 26 standees	38 seats, 2 wheelchair positions, 34 standees
Motor or engine	2 BYD traction motors, 90 kW	CNG engine, Cummins, ISL G280 280 hp @ 2,000 rpm
Energy storage (BEB) Fuel capacity (CNG)	Ferro type Lithium Iron, 324 kWh (original) 360 kWh (ESS upgrade)	8 SCI cylinders, 25,304 scf at 3,600 psi
Charging equipment	50 kW WAVE induction charging system	N/A
Accessories	Electric	Mechanical
Emissions equipment	N/A	3-way catalyst
Transmission/retarder	Regenerative braking	N/A

[a] Includes bus, on-board WAVE charging system, LBT equipment (such as cameras, radio, bike rack), spare parts, training, and diagnostic equipment.

BYD BEB

Gillig CNG

Photos by Leslie Eudy, NREL

Infrastructure Description

LBT set up dedicated charging stations for the 10 BEBs along one wall of its facility. Each bus has a parking space with an 80-kW charger mounted at the front. The buses are parked in these spaces when not in service. The system uses software to manage charging to help reduce electric costs. LBT's utility rate schedule has tiered rates that drop to the lowest cost at 10 p.m. The software schedules the charging to begin at 10:15 p.m. with four buses charging simultaneously. Once those buses are charged, the system cycles through the remaining buses. LBT built the system to handle up to 30 BEBs with the capability to charge up to 40 BEBs total to allow for scale up of its BEB fleet.

To supplement charging, LBT installed an inductive charger at one stop on the Passport Route. The charging system, built by WAVE, is expected to extend the range of the buses. The WAVE installation was introduced as a pilot project to test the capabilities of the on-route charging system. At this time, LBT has not needed to use the charging system as the BEBs are meeting the required range.

WAVE charging system at the Convention Center

Plug-in chargers at the LBT Facility

Data Summary: Jan.–Jun. 2019

Data Item	BEB	CNG
Number of buses	12	8
Data period	1/2019–6/2019	1/2019–6/2019
Number of months	6	6
Total mileage in data period	80,851	175,703
Average odometer	37,494	170,042
Average monthly mileage per bus	1,348	3,661
Availability (85% is target)	75	85
Fuel consumption for BEBs (kWh/mile) or fuel economy for CNG buses (mpgge[a])	1.93	3.38
Fuel economy (mpdge[b])	19.54	3.88
Average speed, including stops (mph)	8	11
Miles between roadcalls (MBRC[c])—bus	4,035	12,277
MBRC[c]—propulsion system only	10,089	20,462
MBRC[c]—ESS[d] only	48,425	—
Total maintenance cost ($/mile)[e]	0.43	0.52
Maintenance—propulsion system only ($/mile)	0.04	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

Route Assignments

LBT uses the BEBs to fully electrify the Passport route, which is a free circulator service that travels around the Waterfront area between the Queen Mary and Downtown Long Beach. The 8-mile route operates each day, with six buses required for weekday service and eight for weekends. In February 2019, LBT reconfigured the route to require four buses on weekdays and seven on weekends. Average speed for the Passport route is approximately 8 mph.

The CNG buses are randomly dispatched on all routes out of the depot including commuter routes. Based on scheduled times, the overall average speed for LBT is around 11 mph.

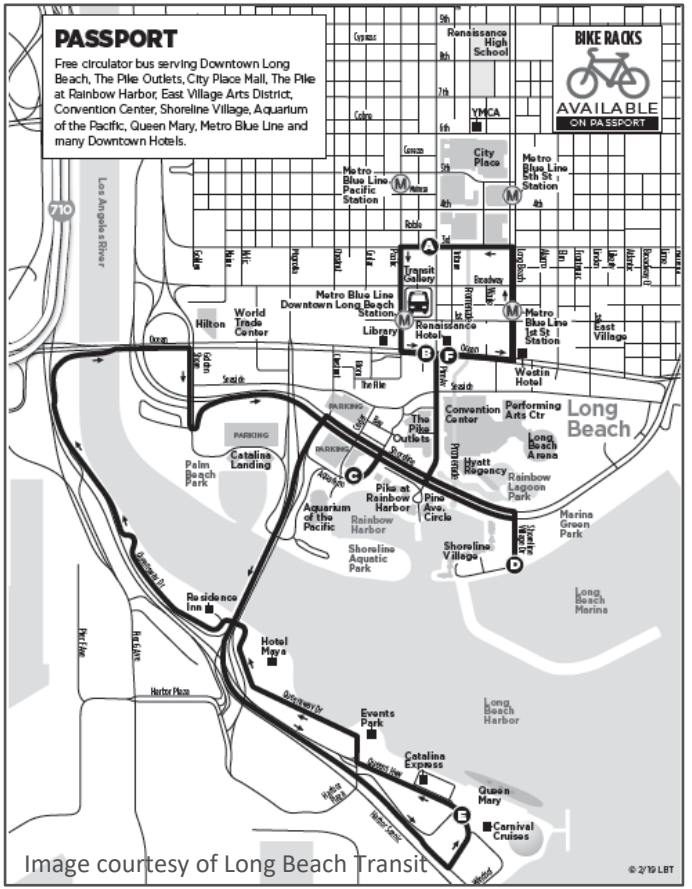
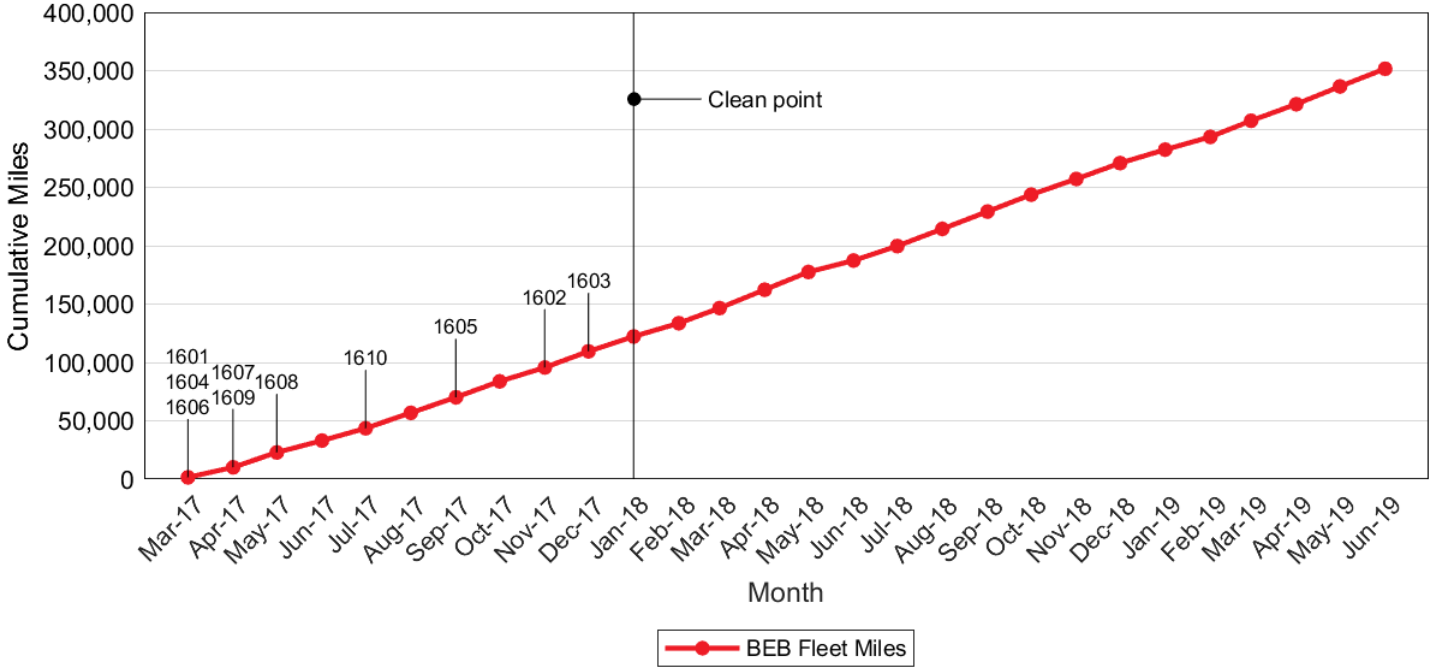


Image courtesy of Long Beach Transit

BEB Fleet Total Miles



Bus numbers indicate the month in which each bus started service

- LBT received its first bus in late 2016 and phased the fleet into service through 2017. By January 2018, all buses were in service. January 2018 was selected as the clean point for the evaluation and analysis.

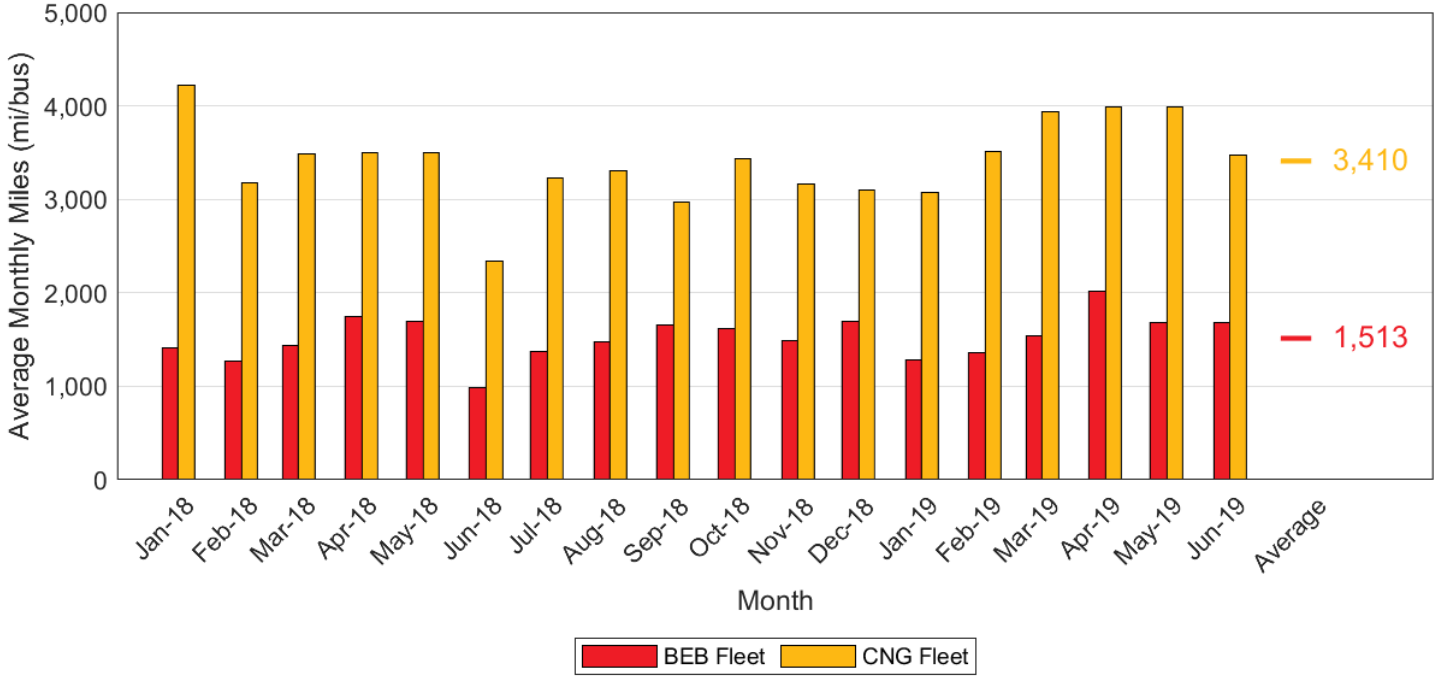
Fleet Average Monthly Miles by Bus: Jan.–Jun. 2019

Bus ID	Miles	Months	Average Monthly Mileage
1601	9,805	6	1,634
1602	6,710	6	1,118
1603	9,757	6	1,626
1604	7,981	6	1,330
1605	10,593	6	1,766
1606	8,511	6	1,419
1607	12,346	6	2,058
1608	4,819	6	803
1609	1,990	6	332
1610	8,339	6	1,390
BEB Fleet	**80,851**	**60**	**1,348**

Bus ID	Miles	Months	Average Monthly Mileage
1521	23,426	6	3,904
1522	25,093	6	4,182
1523	20,911	6	3,485
1524	25,287	6	4,215
1525	24,706	6	4,118
1526	12,930	6	2,155
1527	21,494	6	3,582
1528	21,857	6	3,643
CNG Fleet	**175,704**	**48**	**3,661**

The monthly miles for the buses is based on the planned service. Random dispatch results in faster mileage accumulation compared to that of the Passport route. Also, the Passport route does not require all 10 buses. The average monthly mileage for the first half of 2019 for the BEBs is even lower than typical because of planned downtime. During the data period, all but 2 of the BEBs were temporarily removed from service for warranty work at BYD. (Each bus operated at least one month during the data period.) If these non-planned months were removed from the analysis, monthly average miles for the BEBs would be closer to 2,000.

Fleet Average Monthly Miles



- Average shown for the entire data period

Availability Analysis

Availability, which is a measure of reliability, is presented as the percentage of days the buses are actually 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 just 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 both morning and afternoon pull-out. Transit agencies typically have a target of 85% availability for their fleets to allow for time to handle scheduled and unscheduled maintenance. For the Long Beach Transit CNG fleet, the buses are planned to operate every day, including weekends. The BEBs are primarily operated on the Passport Route.

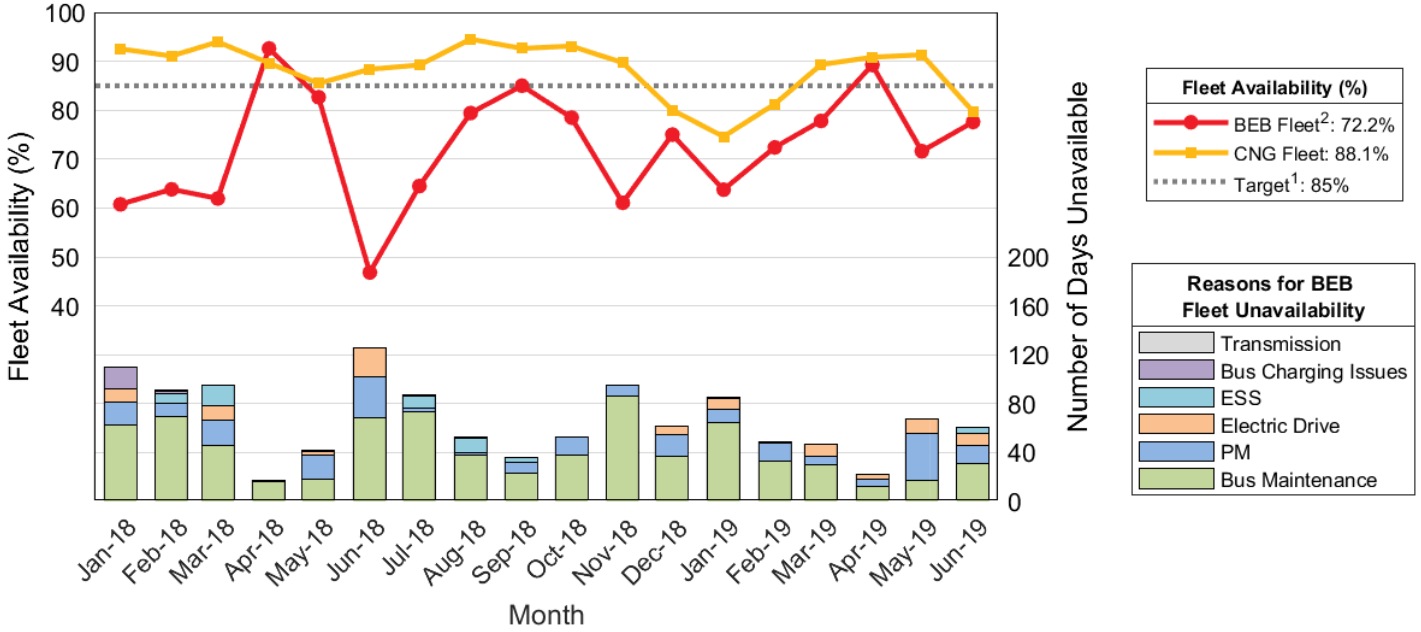
NREL presents availability as a monthly average trend and as overall availability. Unavailable time is separated into several categories to show the primary reason for downtime. For Long Beach Transit, all 10 BEBs are not required to meet the Passport service. The service typically requires 4–6 buses on weekdays and 7–8 on weekends. NREL also presents the monthly and overall percent that the BEBs met that service.

Availability Summary: Jan.–Jun. 2019

Category	BEB Fleet (# Days)	BEB Fleet (% of total)	CNG Fleet (# Days)	CNG Fleet (% of total)
Planned work days	1,337		1,445	
Days available	1,006	75.2	1,222	84.6
Unavailable	331	24.8	223	15.4
ESS	7	0.5	—	—
CNG engine	—	—	54	3.7
Electric drive	44	3.3	—	—
Charging issues	0	0.0	—	—
Preventive maintenance	92	6.9	55	3.8
General bus maintenance	189	14.1	100	6.9
Transmission	0	0.0	15	1.0

- The per-bus availability for the BEBs ranged from a low of 56% to a high of 89%.
- The BEBs were not planned for service during the time when they were returned to BYD for warranty updates.
- Most unavailable time for the BEB and CNG bus fleets was attributed to general bus issues.
- General bus maintenance includes everything that doesn't fall into one of the other categories.

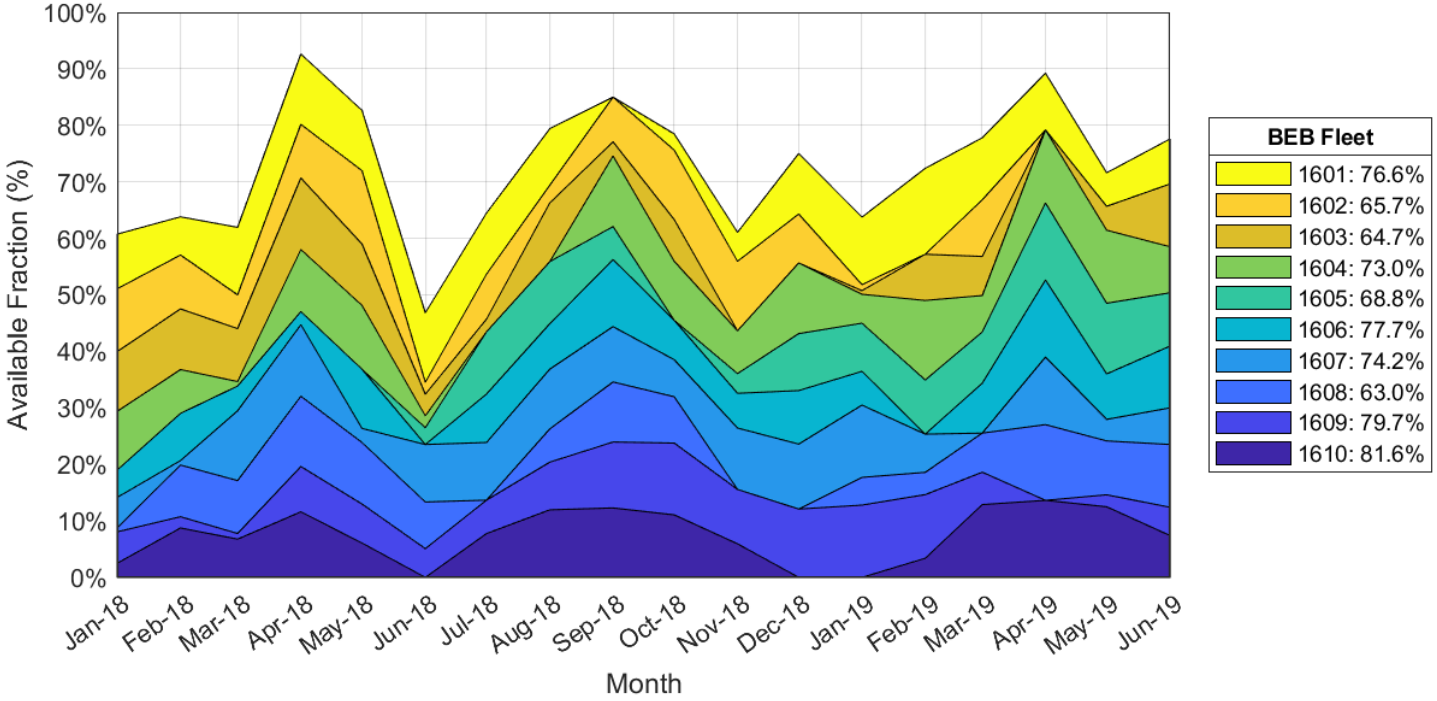
Monthly Availability



1. Target of 85% fleet availability is a general expectation for most transit agencies
2. BEB Fleet excludes days when BEBs were offsite for warranty work and were considered not planned for service

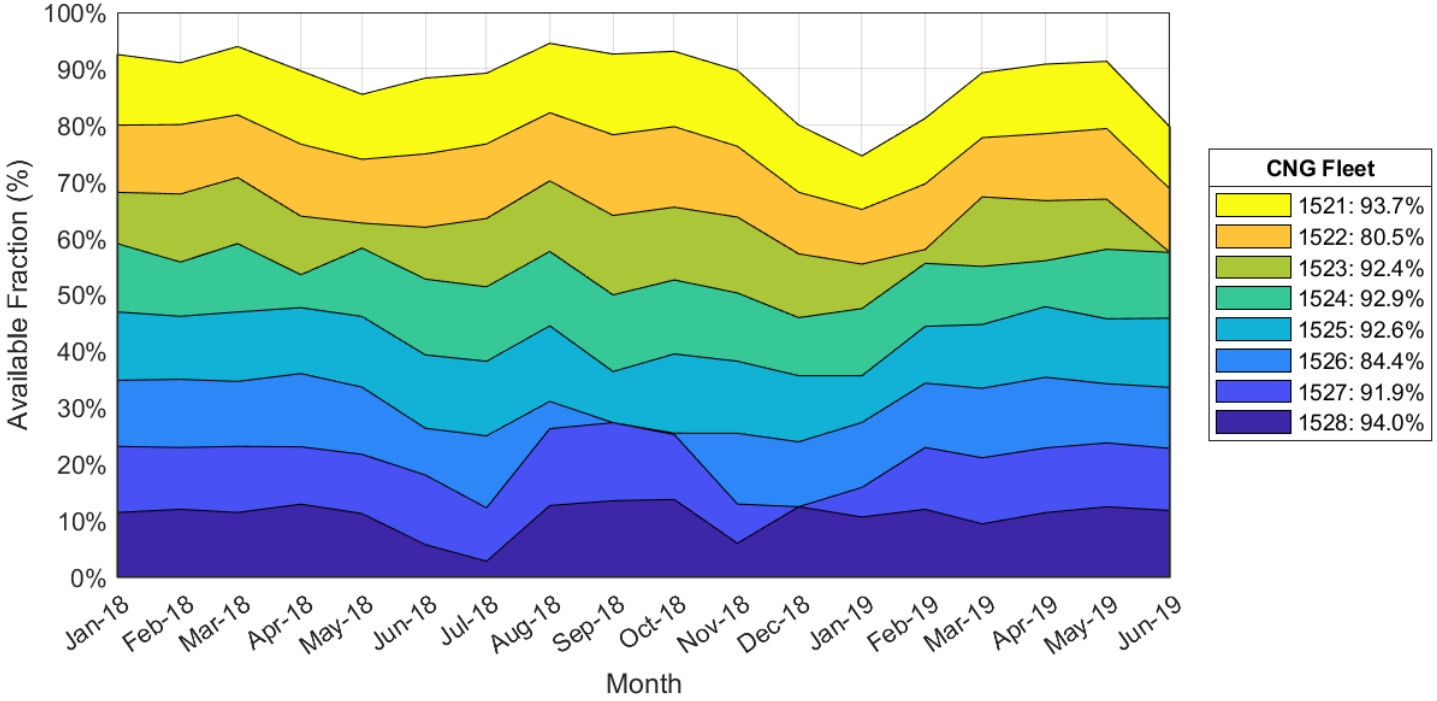
- The chart traces monthly availability for each fleet (red and gold lines), with unavailable time for the BEBs separated out by category (stacked bars).
- Multiple buses were out of service in June 2018: 3 buses were at BYD, other buses had bus issues (farebox, doors).

Monthly Availability by Bus: BEBs



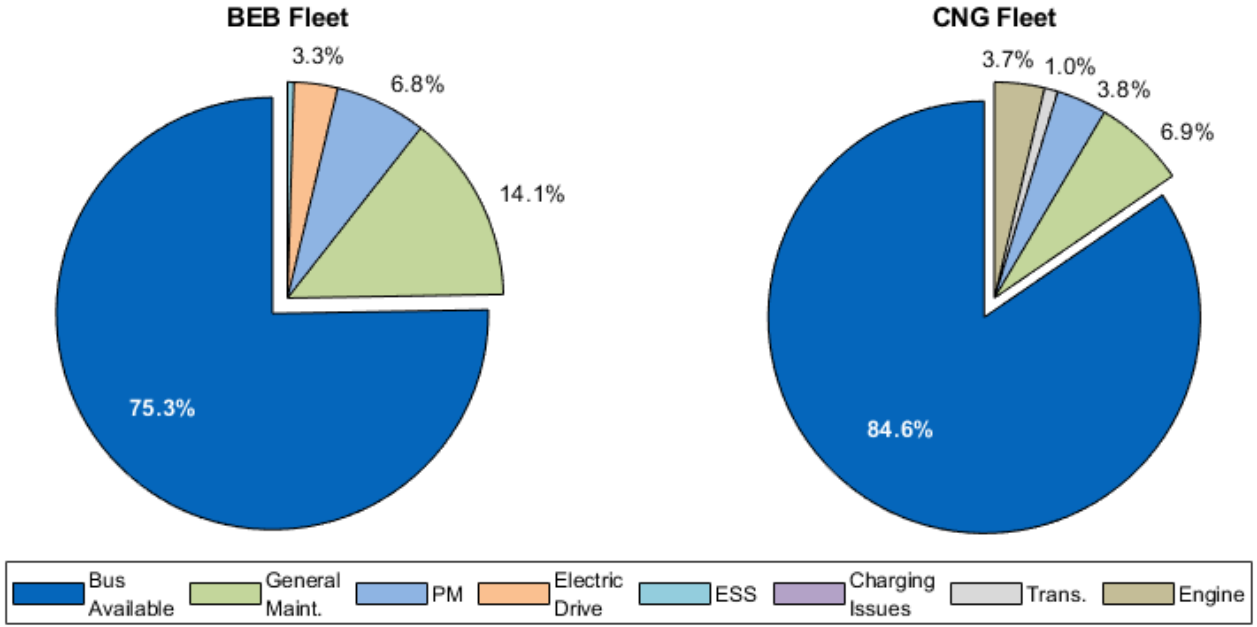
- The stacked area chart shows the monthly contribution of each bus toward the total BEB fleet availability.
- The availability of each BEB during the entire data period is displayed in the legend.

Monthly Availability by Bus: CNG Buses



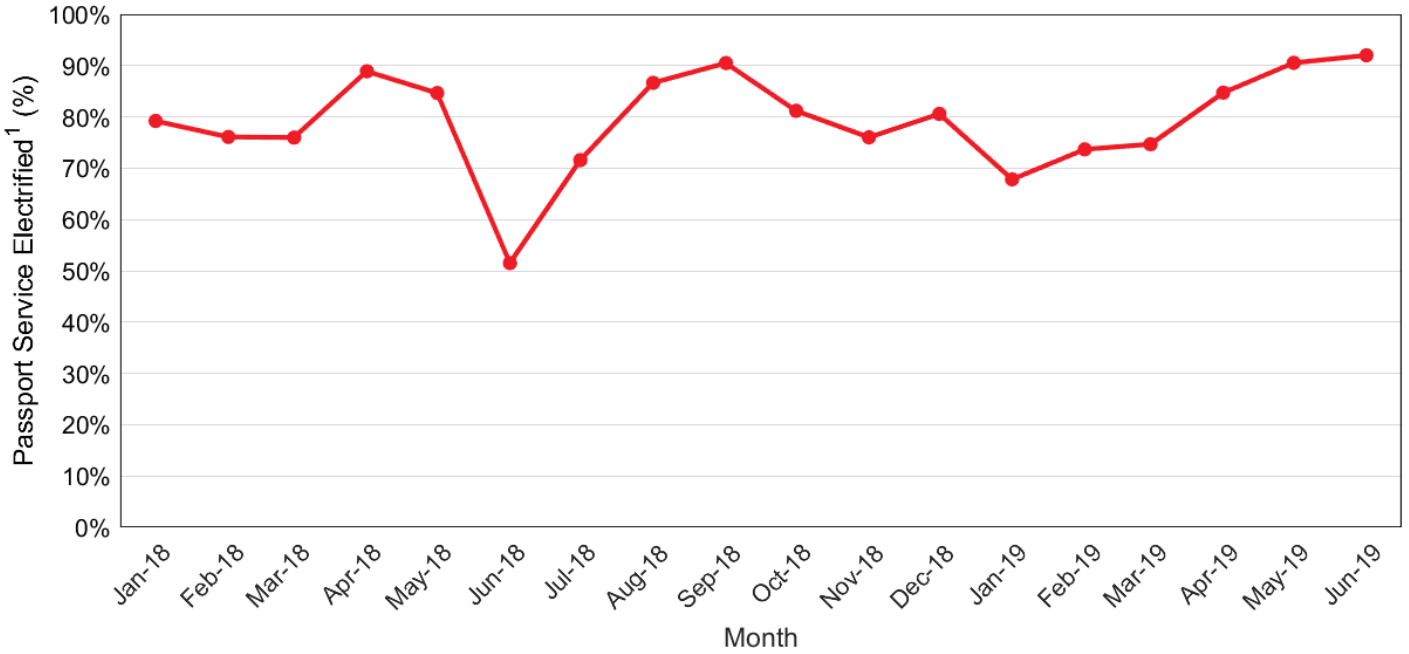
- The stacked area chart shows the monthly contribution of each bus toward the total CNG fleet availability.
- The availability of each CNG bus during the entire data period is displayed in the legend.

Overall Fleet Availability: Jan.–Jun. 2019



1. Data period for availability analysis: Jan 2019 - Jun 2019
2. Data labels omitted for pie slices representing < 1.0%

Percent of Time BEBs Met Passport Service



1. Fraction of scheduled service for Passport route fulfilled by BEBs rather than CNG buses

- Passport route does not require all 10 BEBs to meet service.
- Overall, LBT met the Passport service with the BEBs 79% of the time.

Fuel Use/Fuel Economy Analysis

LBT provides individual charging records for each BEB. Records come from the BYD data logging system and daily LBT maintenance logs. These data were provided to NREL for calculating energy use of the buses in kWh per mile. LBT's CNG buses are typically fueled once each day. The agency provided individual fueling records for the CNG buses. CNG consumption was reported in units of diesel gallon equivalent (dge).

To compare the BEBs to the baseline buses, NREL converted the electrical energy from kWh to diesel gallon equivalent (dge) using the following conversion factor. CNG is typically tracked in units of gasoline gallon equivalent (gge); therefore, CNG fuel energy was converted from dge to gge for reference.

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

Btu: British thermal units; LHV: lower heating value

Fuel Economy by Bus: Jan.–Jun. 2019

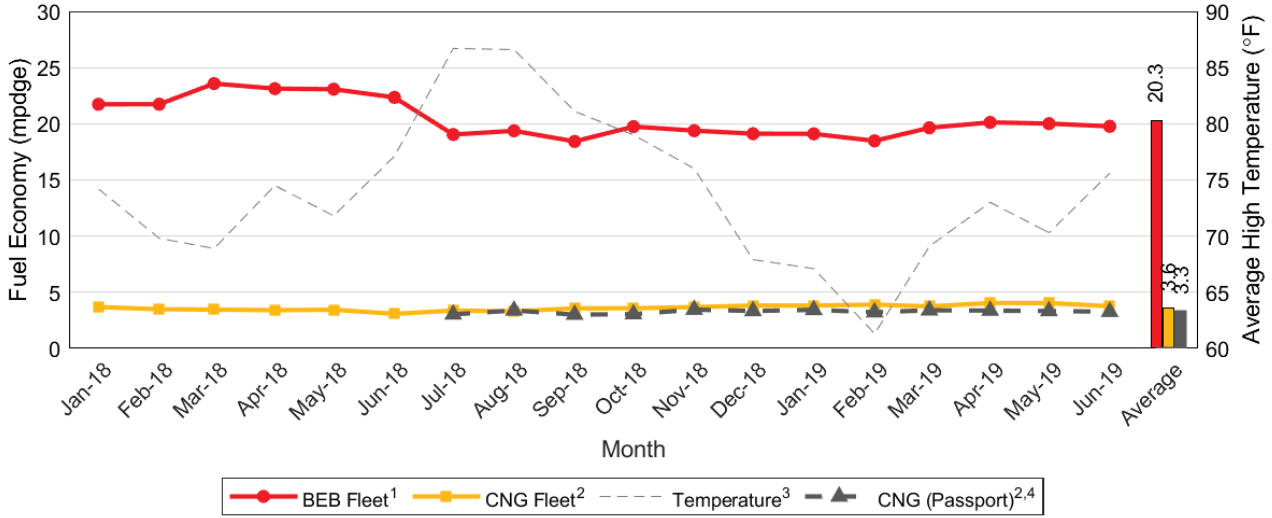
Bus ID	Miles	Energy[a] (kWh)	kWh/mi	Diesel Gallon Equiv.	Fuel economy (mpdge)
1601	8,601	16,494.1	1.92	438.3	19.63
1602	6,031	10,839.1	1.80	288.0	20.94
1603	7,802	14,512.1	1.86	385.6	20.23
1604	6,858	14,354.9	2.09	381.4	17.98
1605	10,199	19,353.5	1.90	514.2	19.83
1606	7,173	13,327.3	1.86	354.1	20.26
1607	11,458	21,802.1	1.90	579.3	19.78
1608	3,679	7,640.8	2.08	203.0	18.12
1609	1,745	3,506.6	2.01	93.2	18.73
1610	6,989	13,993.0	2.00	371.8	18.80
BEB Fleet	**70,535**	**135,823.5**	**1.93**	**3,608.9**	**19.54**

Bus ID	Miles	CNG (gge)	mpgge	Diesel Gallon Equiv.	Fuel economy (mpdge)
1521	22,772	6,687.1	3.41	5,835.0	3.90
1522	20,792	5,858.4	3.55	5,111.8	4.07
1523	20,513	6,241.0	3.29	5,445.7	3.77
1524	24,693	7,877.1	3.13	6,873.3	3.59
1525	23,686	6,789.0	3.48	5,931.7	3.99
1526	11,680	3,381.6	3.45	2,950.6	3.96
1527	20,927	5,920.6	3.53	5,166.1	4.05
1528	21,410	6,417.8	3.34	5,600.0	3.82
CNG Fleet	**166,473**	**48,181.6**	**3.38**	**42,914.1**	**3.88**

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

- The BEB fuel economy is 5 times that of the CNG buses, as operated on current routes.
- Previous data show the CNG buses had a fuel economy around 3.26 mpdge on the Passport route. The BEB fuel economy is 6 times that of the CNG buses in the same service.

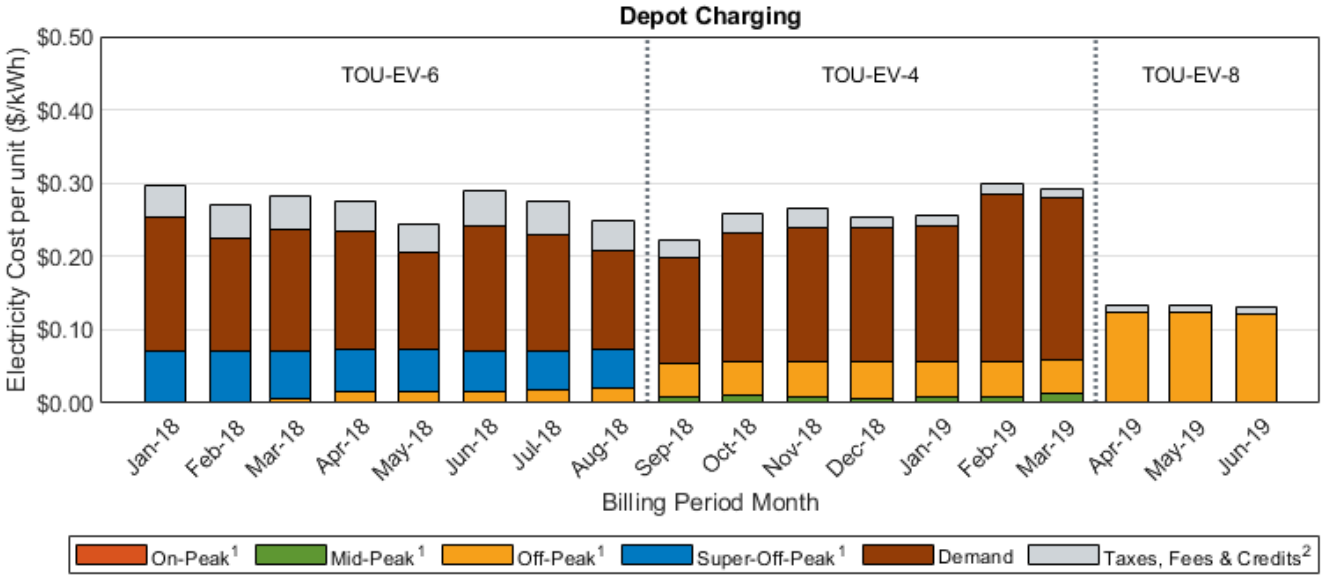
Fleet Average Monthly Fuel Economy



1. BEB electrical energy converted from kWh to diesel gallon equivalent (dge): 37.64 kWh/dge
2. CNG fuel energy reported in diesel gallon equivalent (dge)
3. Average high temperatures at Long Beach Daugherty Airport; data acquired from: *https://www.ncdc.noaa.gov/*
4. 1200-series CNG buses operating on Passport route (Sep 2015 - Aug 2016)

	Overall		Jan.–Jun. 2019	
Fleet	**kWh/mi, mpgge**	**mpdge**	**kWh/mi, mpgge**	**mpdge**
BEB	1.85	20.31	1.93	19.54
CNG	3.17	3.63	3.38	3.88
CNG on Passport	2.84	3.26	–	–

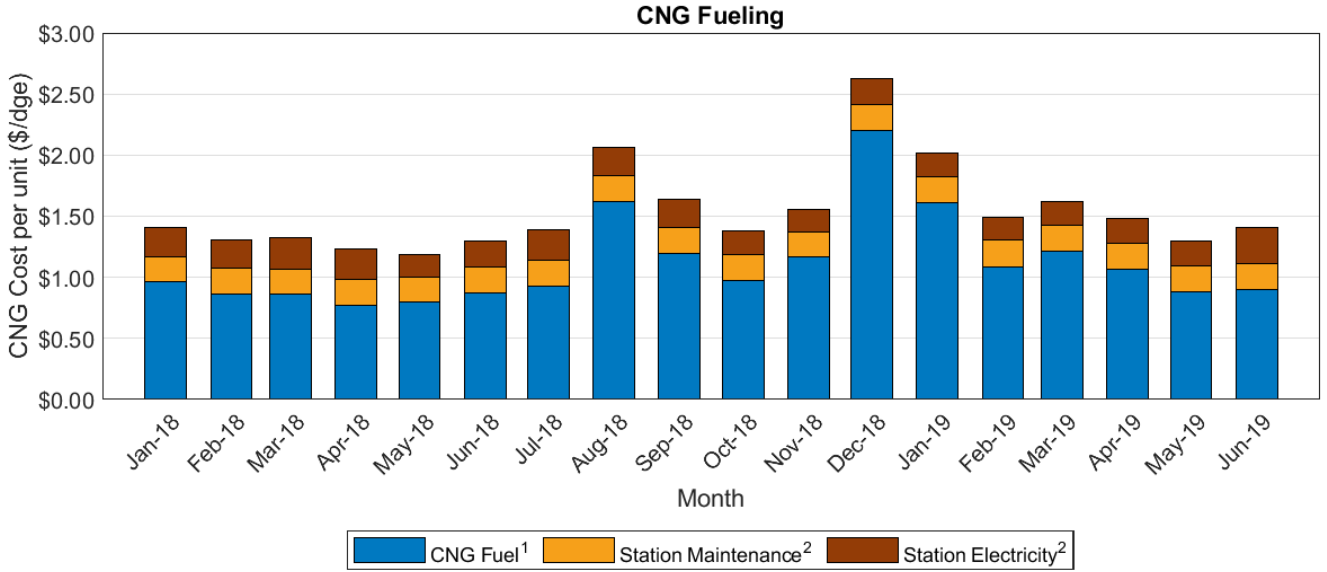
Monthly Electric Utility Costs: Depot



1. On-, Mid-, Off-, and Super-Off-Peak charge categories include respective costs for delivery and generation
2. Taxes, Fees & Credits category includes all remaining utility bill items (costs & credits)

- Costs are based on utility billing periods, not calendar months.
- Average rate under each rate structure: TOU-EV-6 = $0.27/kWh; TOU-EV-4 = $0.26/kWh; TOU-EV-8 = $0.13/kWh.

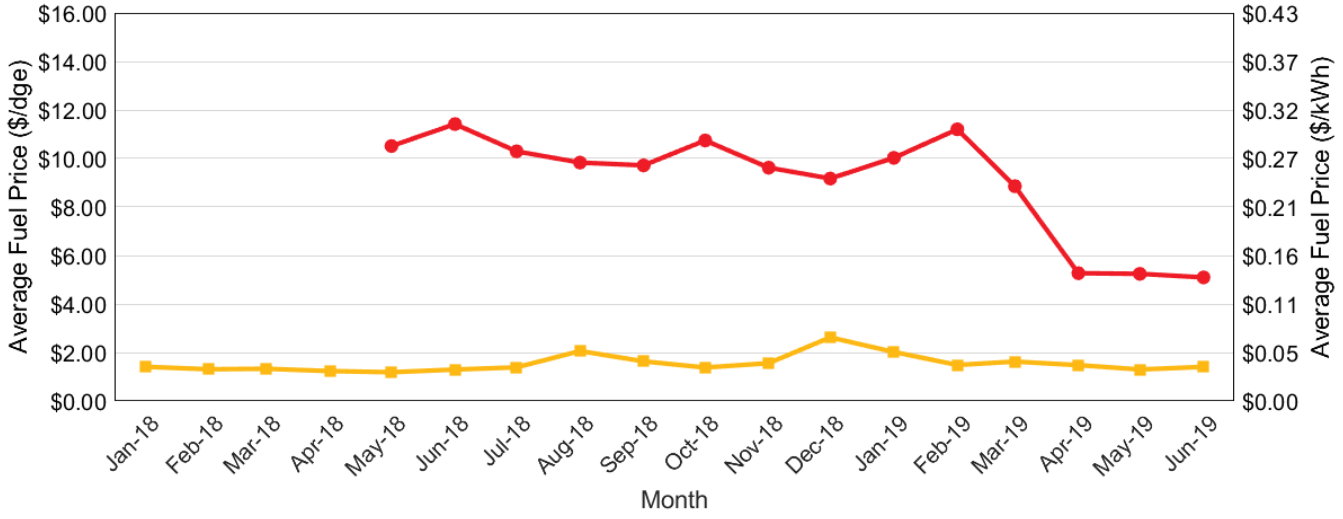
Monthly CNG Cost per gge



1. CNG Fuel represents the commodity cost for CNG
2. Station Maintenance and Station Electricity represent the O&M cost for the CNG station

- CNG prices increased in August 2018 and December 2018 due to temporary disruptions in regional CNG supply.

Monthly Average Fuel Price

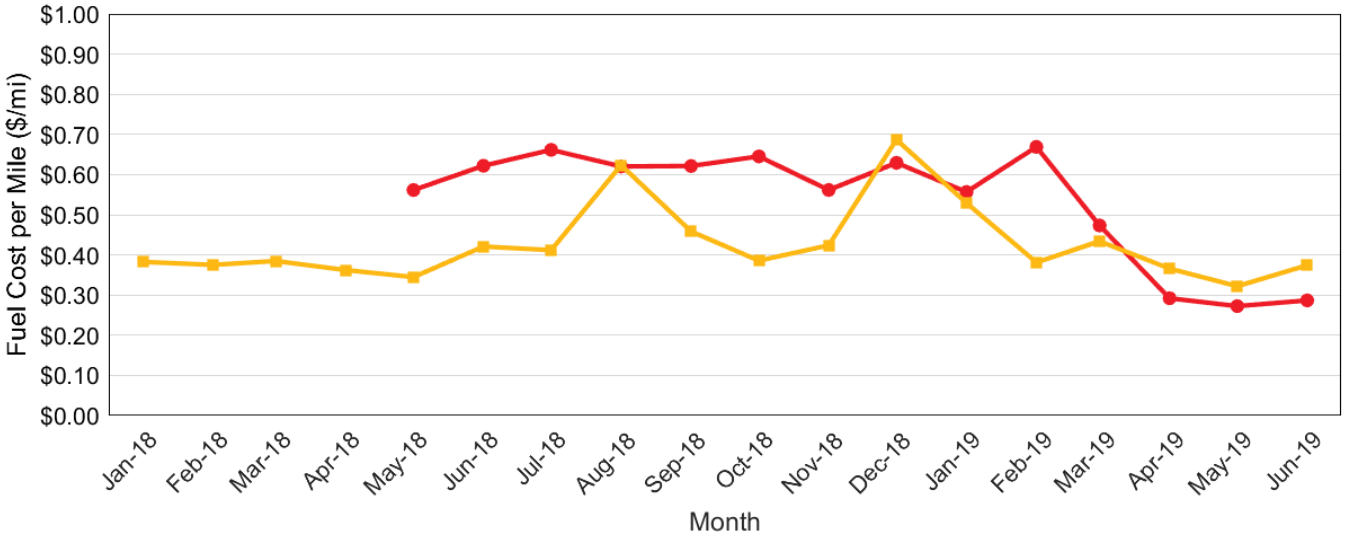


	Electricity Price[1]	CNG Price[2]
Data period average	$9.00/dge	$1.53/dge

1. BEB electrical energy converted from kWh to diesel gallon equivalent (dge): 37.64 kWh/dge
2. CNG fuel energy reported in diesel gallon equivalent (dge)

- Electricity prices decreased with recent change to TOU-EV-8 utility rate structure.
- CNG cost includes price of fuel, transmission, and operations and maintenance cost for station.
- On average, electricity cost is more than 6 times the cost of CNG.

Monthly Fuel Cost Per Mile



	BEB Fleet	CNG Fleet
Fleet average fuel cost/mi	$0.53/mi	$0.42/mi
Average fuel price	$0.24/kWh	$1.33/gge

- The per-mile fuel costs are impacted by the unit price of each fuel as well as the fuel economy of the buses.
- Lower electricity costs during the end of the data period results in cost parity between the BEB and diesel buses.

Fuel Cost Per Mile

The operating duty cycle of a bus has a significant effect on fuel economy and therefore cost. LBT has fully electrified the Passport Route with the BYD buses. The baseline CNG buses are randomly dispatched on the other routes from the depot. For a better comparison to baseline buses in the same service, NREL collected data from 8 CNG buses operated on the Passport Route prior to delivery of the BEBs. On the Passport Route, the average fuel economy for the CNG buses was 3.26 mpdge.

During the first half of 2019, LBT paid an average of $1.35/gge ($1.54/dge) for CNG. The average cost of electricity during the time period was $0.20/kWh ($7.38/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 the Passport Route. The lower fuel economy on the Passport route would increase the CNG fuel cost to an overall average of $0.47/mi, compared to $0.53/mi for the BEBs.

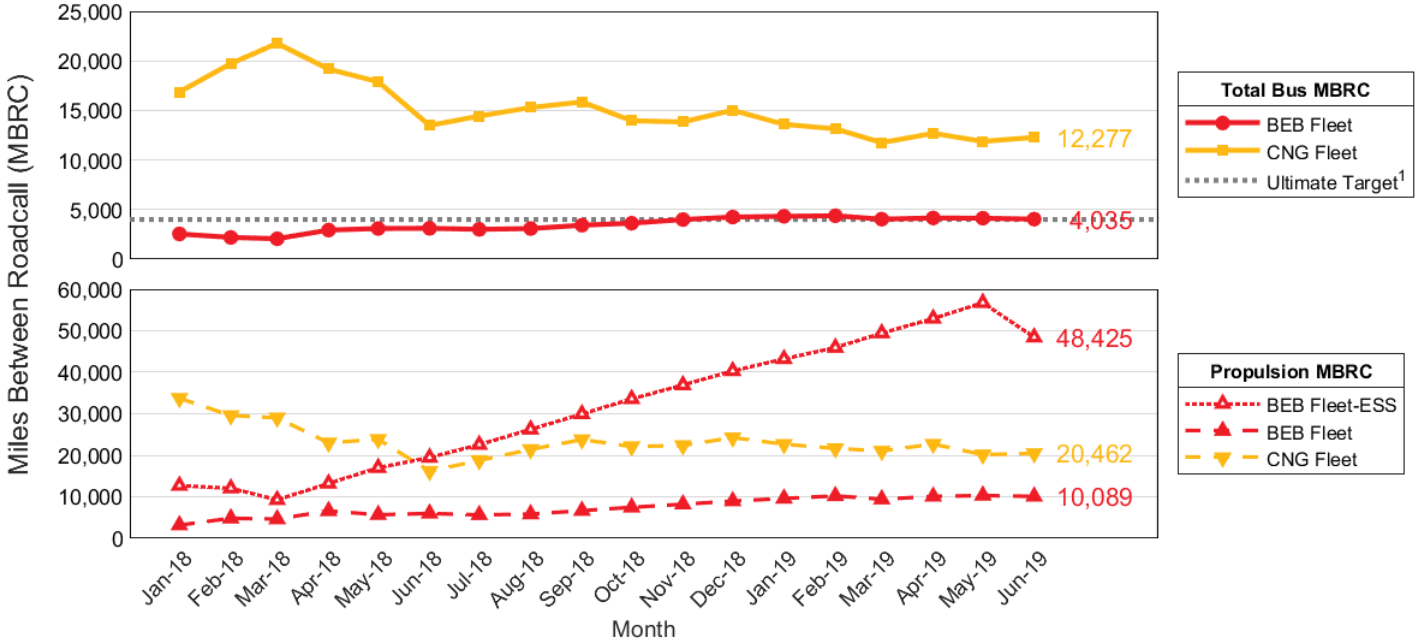
	Average Service Speed (mph)	Fuel Economy (mpdge)	Overall Fuel $/mi	Data Period Fuel $/mi
BEB	8	20.31	0.53	0.41
CNG	11	3.63	0.42	0.40
CNG on Passport	8	3.26	0.47	0.47

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: 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.

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, are 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 Long Beach 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.

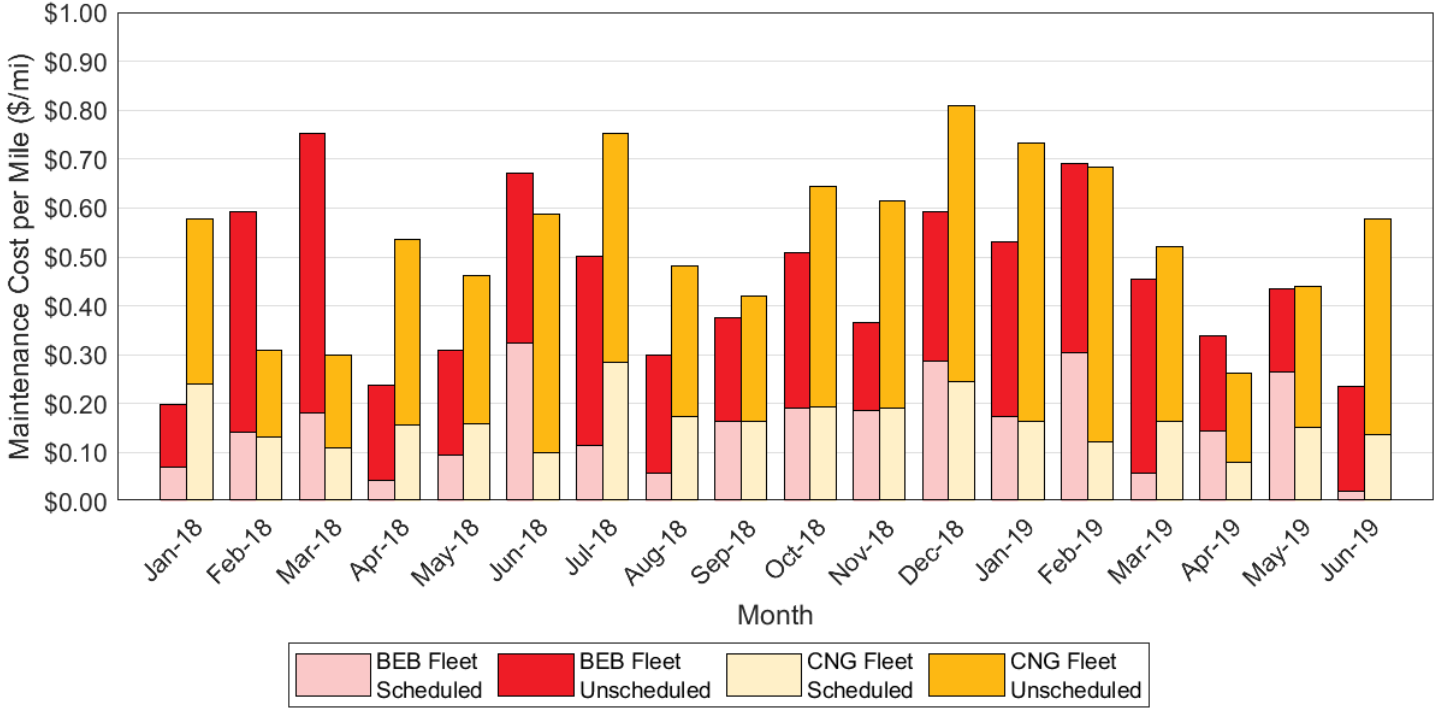
Maintenance Analysis Results: Jan.–Jun. 2019

Bus ID	Mileage	Parts ($)	Labor Hours	Scheduled Cost ($/mi)	Unscheduled Cost ($/mi)	Total Cost ($/mi)
1601	9,805	$1,323.29	76.5	$0.19	$0.34	$0.53
1602	6,710	$84.94	54.5	$0.17	$0.25	$0.42
1603	9,757	$126.70	91.0	$0.12	$0.36	$0.48
1604	7,981	$292.32	37.3	$0.09	$0.18	$0.27
1605	10,593	$95.91	74.0	$0.23	$0.13	$0.36
1606	8,511	$141.32	50.5	$0.09	$0.23	$0.31
1607	12,346	$488.72	81.8	$0.10	$0.27	$0.37
1608	4,819	$566.52	41.0	$0.04	$0.50	$0.54
1609	1,990	$660.11	23.0	$0.60	$0.31	$0.91
1610	8,339	$909.84	75.5	$0.23	$0.33	$0.56
BEB Fleet	**80,851**	**$4,689.67**	**605.1**	**$0.16**	**$0.28**	**$0.43**

Bus ID	Mileage	Parts ($)	Labor Hours	Scheduled Cost ($/mi)	Unscheduled Cost ($/mi)	Total Cost ($/mi)
1521	23,426	$9,068.14	155.0	$0.21	$0.51	$0.72
1522	25,093	$3,776.93	161.5	$0.10	$0.38	$0.47
1523	20,911	$4,549.24	107.5	$0.11	$0.36	$0.47
1524	25,287	$3,389.24	158.5	$0.13	$0.31	$0.45
1525	24,706	$5,178.54	153.0	$0.14	$0.38	$0.52
1526	12,930	$4,893.78	76.5	$0.09	$0.59	$0.67
1527	21,494	$7,075.73	106.3	$0.17	$0.41	$0.58
1528	21,857	$3,043.76	101.5	$0.13	$0.25	$0.37
CNG Fleet	**175,703**	**$40,975.36**	**1,019.8**	**$0.14**	**$0.39**	**$0.52**

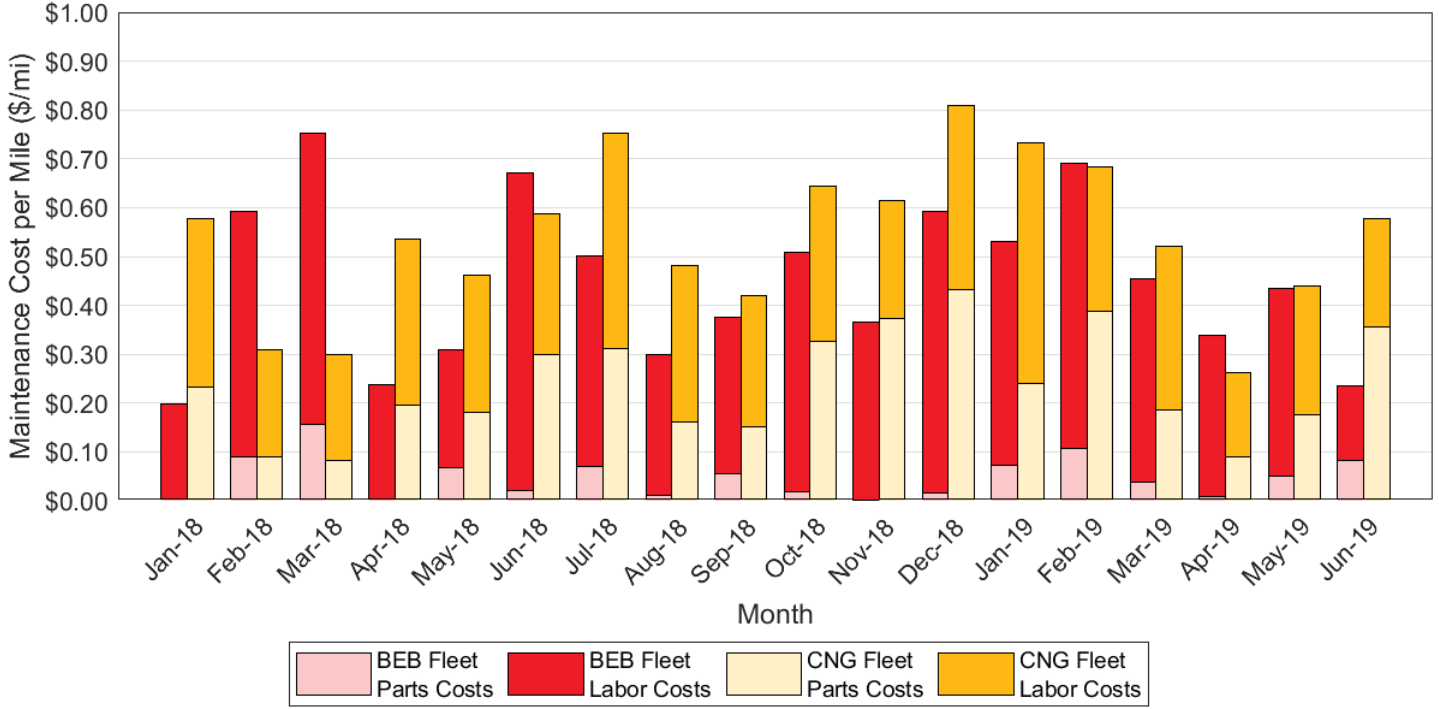
- The BEBs are still under warranty—warranty-related costs are not included in the analysis.
- The overall cost per mile for the BEBs is 17% lower than that of the CNG buses.
- LBT reports that some minor repairs for the BEBs were handled during scheduled maintenance—this would result in higher scheduled maintenance cost and lower unscheduled maintenance.

Monthly Scheduled and Unscheduled Maintenance Cost



- For the BEBs, some unscheduled maintenance was included in scheduled maintenance because minor repairs found during PMs were not separated in the work order. As a result, the split between scheduled and unscheduled costs are shifted.
- Scheduled maintenance for the CNG buses is higher during months when multiple buses reach the mileage target for a major PM.

Monthly Parts and Labor Maintenance Cost



- The majority of costs for the BEBs was for labor to troubleshoot and repair issues. Most parts are currently covered under warranty.

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

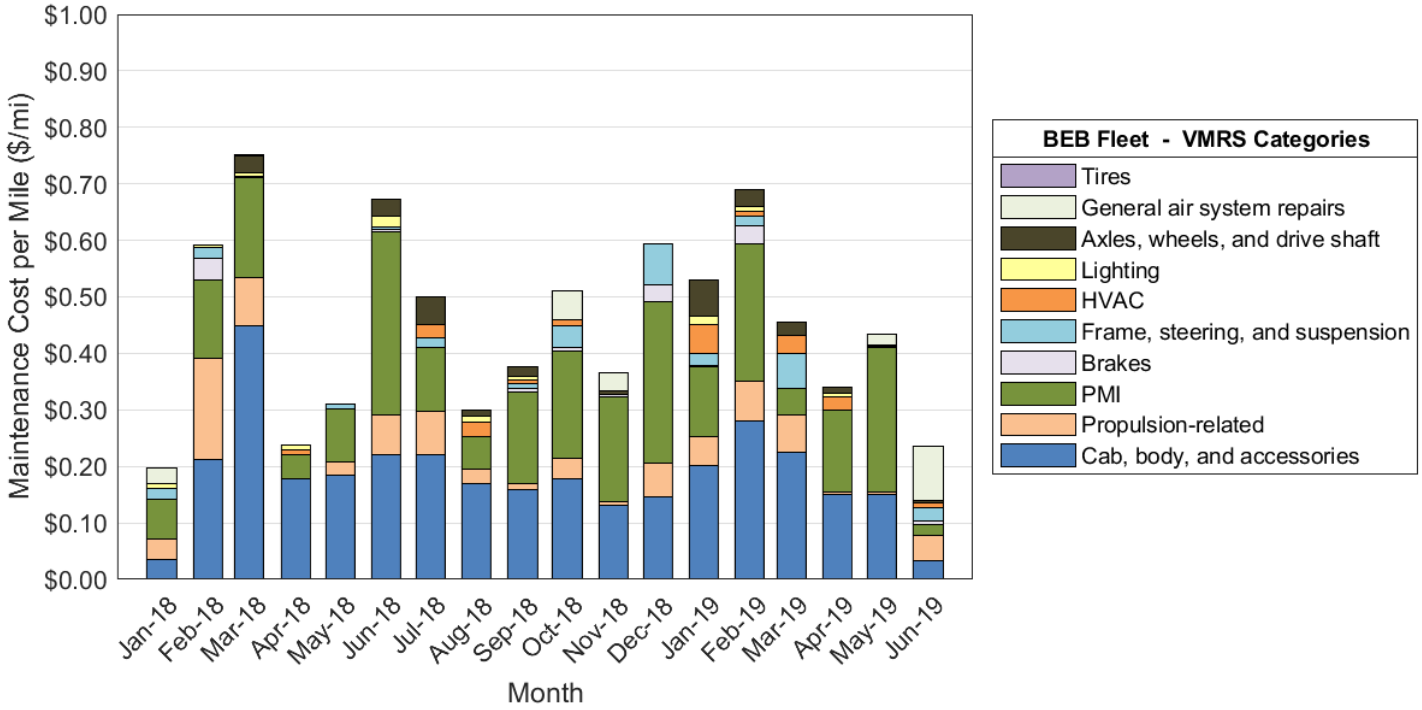
System	BEB		CNG	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Propulsion-related	0.04	8.6	0.17	31.9
Cab, body, and accessories	0.17	38.4	0.17	32.1
PMI	0.14	31.1	0.07	13.8
Brakes	0.01	1.4	0.01	2.5
Frame, steering, and suspension	0.02	4.8	0.04	7.2
HVAC	0.02	4.5	0.02	3.8
Lighting	0.00	1.0	0.00	0.5
General air system repairs	0.02	4.7	0.01	1.9
Axles, wheels, and drive shaft	0.02	4.5	0.02	4.4
Tires	0.00	0.0	0.00	0.0
Total	***0.43***	***100***	***0.52***	***100***

Color coding:

- Highest cost
- Second highest cost
- Third highest cost

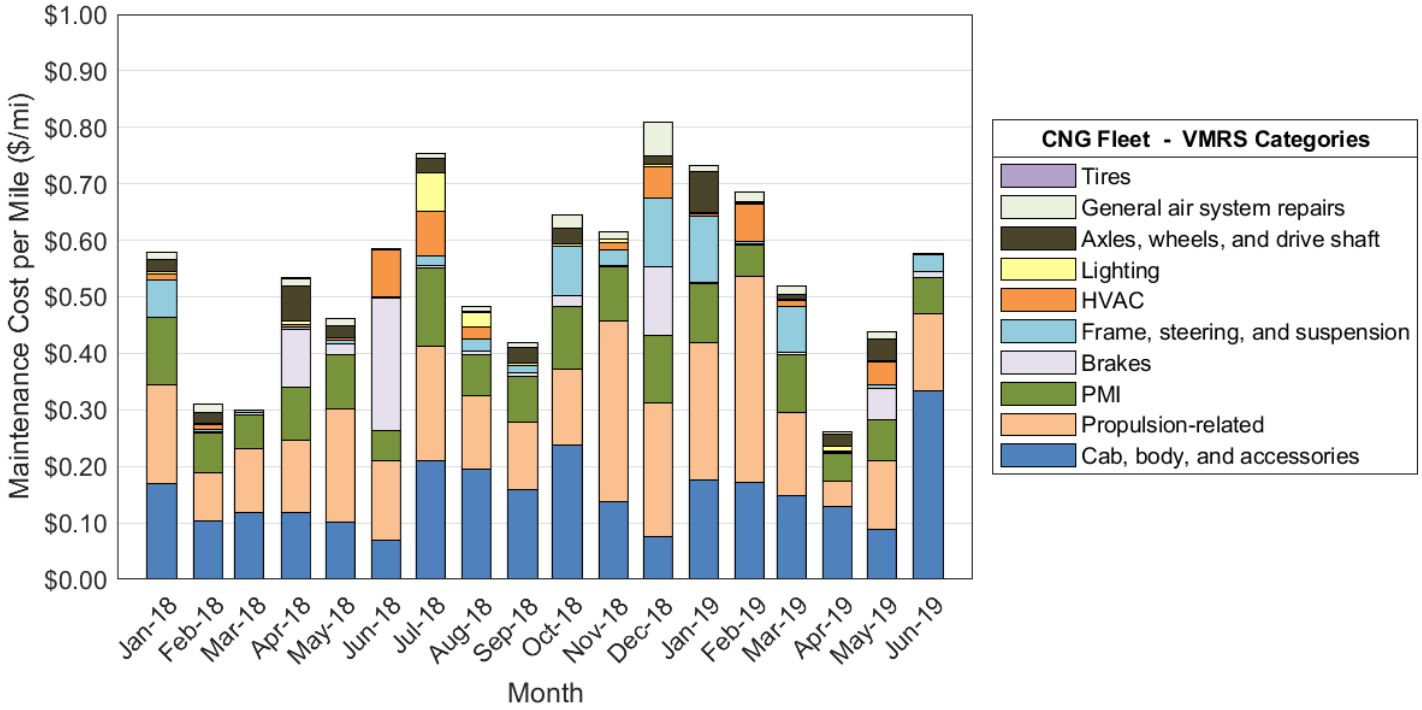
- Cab, body, and accessories repairs were the highest category for both the BEB and CNG buses.
- Cab, body, and accessories repairs for the BEBs included wheelchair ramps and windshield wipers.
- PMI labor hours for the BEBs is higher than expected because some minor repairs were included and not split out by system.
- Overall cost per mile for the BEBs was 17% lower than the CNG bus cost.

Maintenance Cost by System: BEB Fleet



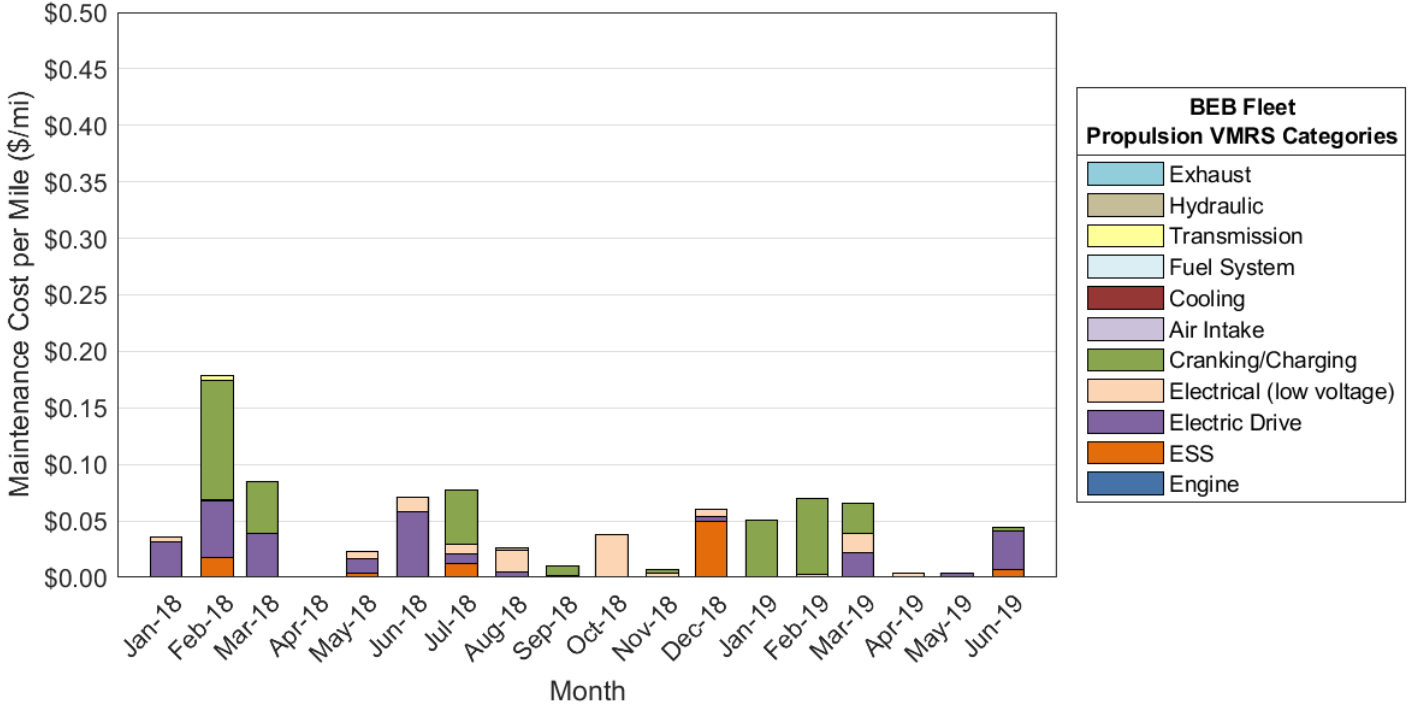
- Costs for cab, body, and accessories made up the largest percent of maintenance, followed by labor hours for PMs.

Maintenance Cost by System: CNG Fleet



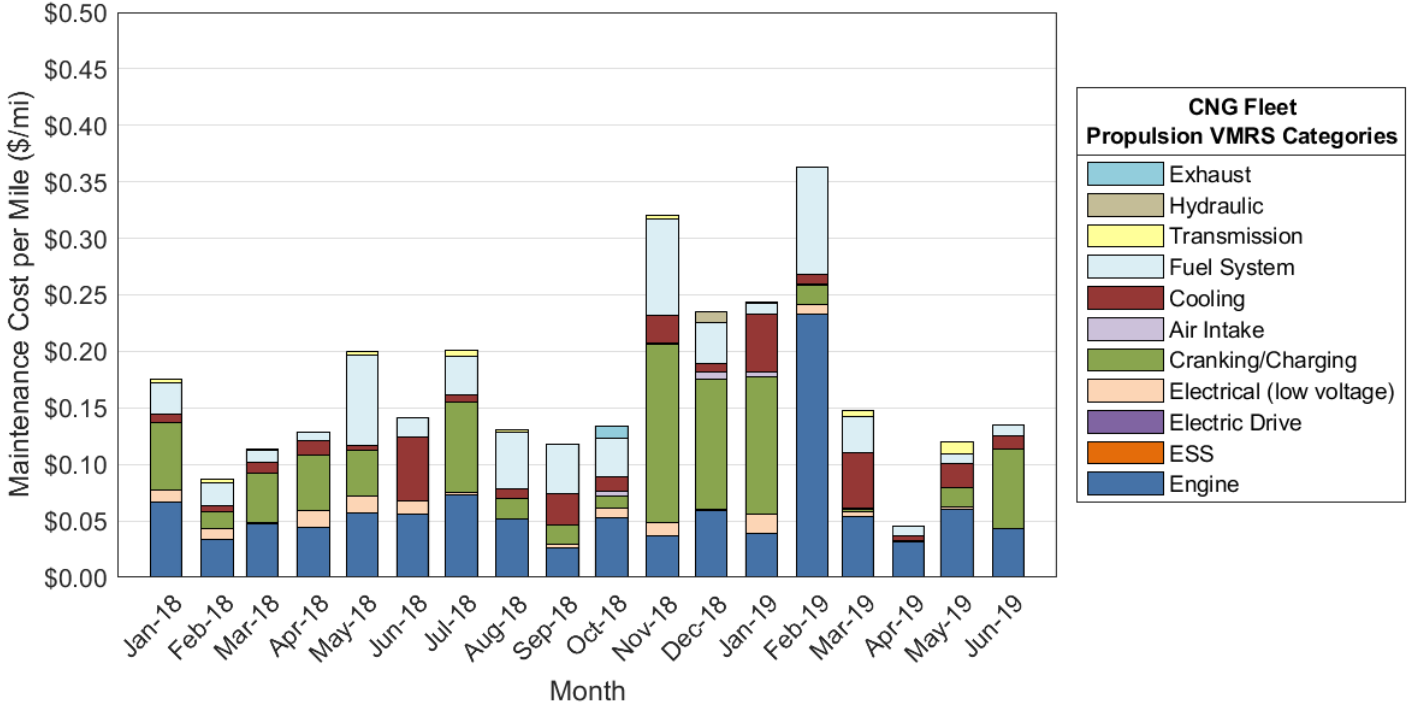
- Costs for cab, body, and accessories made up the largest percent of maintenance, followed by propulsion-related maintenance.

Propulsion System Maintenance Cost by Subsystem: BEB Fleet



- Cranking/charging costs were high due to the replacement of the low voltage batteries.
- Electric drive costs were primarily labor.

Propulsion System Maintenance Cost by Subsystem: CNG Fleet



- Engine costs included scheduled service and tune-ups.
- Cranking/charging included costs for low voltage batteries and spark plugs.

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

Maintenance System		BEB	CNG
Mileage		80,851	175,703
Total Propulsion-Related Systems (Roll-Up of All Systems)	Parts cost ($)	1,617.51	18,538.24
	Labor hours	28.5	226.5
	Total cost ($)	3,042.51	29,863.24
	Total cost ($) per mile	**0.04**	**0.17**
Exhaust System Repairs	Parts cost ($)	0.00	28.48
	Labor hours	0.0	0.0
	Total cost ($)	0.00	28.48
	Total cost ($) per mile	**0.00**	**0.00**
Fuel System Repairs	Parts cost ($)	0.00	4,190.08
	Labor hours	0.0	10.0
	Total cost ($)	0.00	4,690.08
	Total cost ($) per mile	**0.00**	**0.03**
Powerplant System Repairs (ESS for BEBs)	Parts cost ($)	0.00	7,612.15
	Labor hours	2.0	110.0
	Total cost ($)	100.00	13,112.15
	Total cost ($) per mile	**0.00**	**0.07**
Electric Propulsion System Repairs	Parts cost ($)	152.50	0.00
	Labor hours	14.5	0.0
	Total cost ($)	877.50	0.00
	Total cost ($) per mile	**0.01**	**0.00**

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

Maintenance System		BEB	CNG
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)	Parts cost ($)	1,465.01	4,065.99
	Labor hours	12.0	61.5
	Total cost ($)	2,065.01	7,140.99
	Total cost ($) per mile	**0.03**	**0.04**
Air Intake System Repairs	Parts cost ($)	0.00	118.77
	Labor hours	0.0	0.0
	Total cost ($)	0.00	118.77
	Total cost ($) per mile	**0.00**	**0.00**
Cooling System Repairs	Parts cost ($)	0.00	2,010.99
	Labor hours	0.0	44.5
	Total cost ($)	0.00	4,235.99
	Total cost ($) per mile	**0.00**	**0.02**
Transmission System Repairs	Parts cost ($)	0.00	511.78
	Labor hours	0.0	0.5
	Total cost ($)	0.00	536.78
	Total cost ($) per mile	**0.00**	**0.00**
Hydraulic System Repairs	Parts cost ($)	0.00	0.00
	Labor hours	0.0	0.0
	Total cost ($)	0.00	0.00
	Total cost ($) per mile	**0.00**	**0.00**

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Acronyms and Abbreviations

BEB	battery electric bus
Btu	British thermal unit
CARB	California Air Resources Board
CNG	compressed natural gas
dge	diesel gallon equivalent
ESS	energy storage system
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
LBT	Long Beach Transit
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
PM	preventive maintenance
PMI	preventive maintenance inspection
psi	pounds per square inch
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 All data	BEB Data Period	CNG All data	CNG Data Period
Number of vehicles	10	10	8	8
Period used for fuel and oil analysis	1/2018–6/2019	1/2019–6/2019	1/2018–6/2019	1/2019–6/2019
Total number of months in period	18	6	18	6
Fuel and oil analysis base fleet mileage	214,662	70,535	449,469	166,473
Period used for maintenance analysis	1/18–6/19	1/19–6/19	1/18–6/19	1/19–6/19
Total number of months in period	18	6	18	6
Maintenance analysis base fleet mileage	242,126	80,851	491,085	175,703
Average monthly miles per vehicle	1,345	1,348	3,410	3,661
Availability	72	75	88	85
Fleet fuel/energy usage in BEB kWh/CNG gge	397,751.26	135,823.50	141,994.95	49,181.57
Roadcalls	60	22	40	19
Total MBRC	4,035	3,675	12,277	9,248
Propulsion roadcalls	24	6	24	11
Propulsion MBRC	10,089	13,475	20,462	15,973
Fleet kWh/mile (BEB) or miles/gge (CNG)	1.85	1.93	3.17	3.38
Representative fleet MPG (energy equiv)	20.31	19.54	3.63	3.88
Energy cost per kWh / CNG cost per dge	0.24	0.20	1.53	1.54
Fuel cost per mile	0.53	0.41	0.42	0.40
Total scheduled repair cost per mile	0.15	0.16	0.17	0.14
Total unscheduled repair cost per mile	0.29	0.28	0.37	0.39
Total maintenance cost per mile	0.44	0.43	0.53	0.52
Total operating cost per mile	***0.97***	***0.84***	***0.95***	***0.92***

Maintenance Cost Summary

Maintenance Cost Summary

	BEB All Data	BEB Data Period	CNG All Data	CNG Data Period
Fleet mileage	242,126	80,851	491,085	175,703
Total parts cost	11,407.30	4,689.67	114,615.66	40,975.37
Total labor hours	1,883.0	605.0	2,948.1	1,019.8
Average labor cost (@ $50.00 per hour)	94,150.00	30,250.00	147,405.00	50,990.00
Total maintenance cost	105,557.30	34,939.67	262,020.66	91,965.37
Total maintenance cost per bus	10,555.73	3,493.97	32,752.58	11,495.67
Total maintenance cost per mile	***0.44***	***0.43***	***0.53***	***0.52***

Propulsion System Maintenance Cost Summary

	BEB All data	BEB 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	3,955.18	1,617.51	54,868.58	18,538.24
Labor hours	133.5	28.5	543.5	226.5
Average labor cost	6,675.00	1,425.00	27,175.00	11,325.00
Total cost (for system)	10,630.18	3,042.51	82,043.58	29,863.24
Total cost (for system) per bus	1,063.02	304.25	10,255.45	3,732.91
Total cost (for system) per mile	**0.04**	**0.04**	**0.17**	**0.17**

Maintenance Cost by Vehicle System

	BEB All Data	BEB Data Period	CNG All Data	CNG Data Period
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	342.50	28.48
Labor hours	0	0	0	0
Average labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	342.50	28.48
Total cost (for system) per bus	0.00	0.00	42.81	3.56
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**
Fuel System Repairs (ATA VMRS 44)				
Parts cost	0.00	0.00	13,367.39	4,190.08
Labor hours	0	0	61.5	10
Average labor cost	0.00	0.00	3,075.00	500.00
Total cost (for system)	0.00	0.00	16,442.39	4,690.08
Total cost (for system) per bus	0.00	0.00	2,055.30	586.26
Total cost (for system) per mile	**0.00**	**0.00**	**0.03**	**0.03**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	0.00	0.00	17,021.28	7,612.15
Labor hours	23.5	2	220.5	110
Average labor cost	1,175.00	100.00	11,025.00	5,500.00
Total cost (for system)	1,175.00	100.00	28,046.28	13,112.15
Total cost (for system) per bus	117.50	10.00	3,505.79	1,639.02
Total cost (for system) per mile	**0.00**	**0.00**	**0.06**	**0.07**

Maintenance Cost by Vehicle System

	BEB All data	BEB Data Period	CNG All data	CNG Data Period
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	188.39	152.50	0.00	0.00
Labor hours	63.5	14.5	0.0	0.0
Average labor cost	3,175.00	725.00	0.00	0.00
Total cost (for system)	3,363.39	877.50	0.00	0.00
Total cost (for system) per bus	336.34	87.75	0.00	0.00
Total cost (for system) per mile	**0.01**	**0.01**	**0.00**	**0.00**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	3,766.79	1,465.01	18,687.85	4,065.99
Labor hours	45	12	161	61.5
Average labor cost	2,250.00	600.00	8,050.00	3,075.00
Total cost (for system)	6,016.79	2,065.01	26,737.85	7,140.99
Total cost (for system) per bus	601.68	206.50	3,342.23	892.62
Total cost (for system) per mile	**0.02**	**0.03**	**0.05**	**0.04**
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	0.00	0.00	436.49	118.77
Labor hours	0	0	0	0
Average labor cost	0.00	0.00	0.00	0.00
Total cost (for system)	0.00	0.00	436.49	118.77
Total cost (for system) per bus	0.00	0.00	54.56	14.85
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**

Maintenance Cost by Vehicle System

	BEB All Data	BEB Data Period	CNG All Data	CNG Data Period
Cooling System Repairs (ATA VMRS 42)				
Parts cost	0.00	0.00	4,352.90	2,010.99
Labor hours	0	0	86.5	44.5
Average labor cost	0.00	0.00	4,325.00	2,225.00
Total cost (for system)	0.00	0.00	8,677.90	4,235.99
Total cost (for system) per bus	0.00	0.00	1,084.74	529.50
Total cost (for system) per mile	**0.00**	**0.00**	**0.02**	**0.02**
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0.00	0.00	148.39	0.00
Labor hours	0.5	0	2	0
Average labor cost	25.00	0.00	100.00	0.00
Total cost (for system)	25.00	0.00	248.39	0.00
Total cost (for system) per bus	2.50	0.00	31.05	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	1,572.85	1,572.85	4,816.45	994.33
Labor hours	34	3.5	29.5	15.5
Average labor cost	1,700.00	175.00	1,475.00	775.00
Total cost (for system)	3,272.85	1,747.85	6,291.45	1,769.33
Total cost (for system) per bus	327.29	174.79	786.43	221.17
Total cost (for system) per mile	**0.01**	**0.02**	**0.01**	**0.01**

Maintenance Cost by Vehicle System

	BEB All Data	BEB Data Period	CNG All Data	CNG Data Period
Brake System Repairs (ATA VMRS 13)				
Parts cost	11.62	0.00	8,818.62	1,375.44
Labor hours	32	10	109.5	19.5
Average labor cost	1,600.00	500.00	5,475.00	975.00
Total cost (for system)	1,611.62	500.00	14,293.62	2,350.44
Total cost (for system) per bus	161.16	50.00	1,786.70	293.81
Total cost (for system) per mile	**0.01**	**0.01**	**0.03**	**0.01**
Transmission Repairs (ATA VMRS 27)				
Parts cost	0.00	0.00	511.78	511.78
Labor hours	1	0	12	0.5
Average labor cost	50.00	0.00	600.00	25.00
Total cost (for system)	50.00	0.00	1,111.78	536.78
Total cost (for system) per bus	5.00	0.00	138.97	67.10
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	696	219	852.5	259.5
Average labor cost	34,800.00	10,950.00	42,625.00	12,975.00
Total cost (for system)	34,800.00	10,950.00	42,625.00	12,975.00
Total cost (for system) per bus	3,480.00	1,095.00	5,328.13	1,621.88
Total cost (for system) per mile	**0.14**	**0.14**	**0.09**	**0.07**

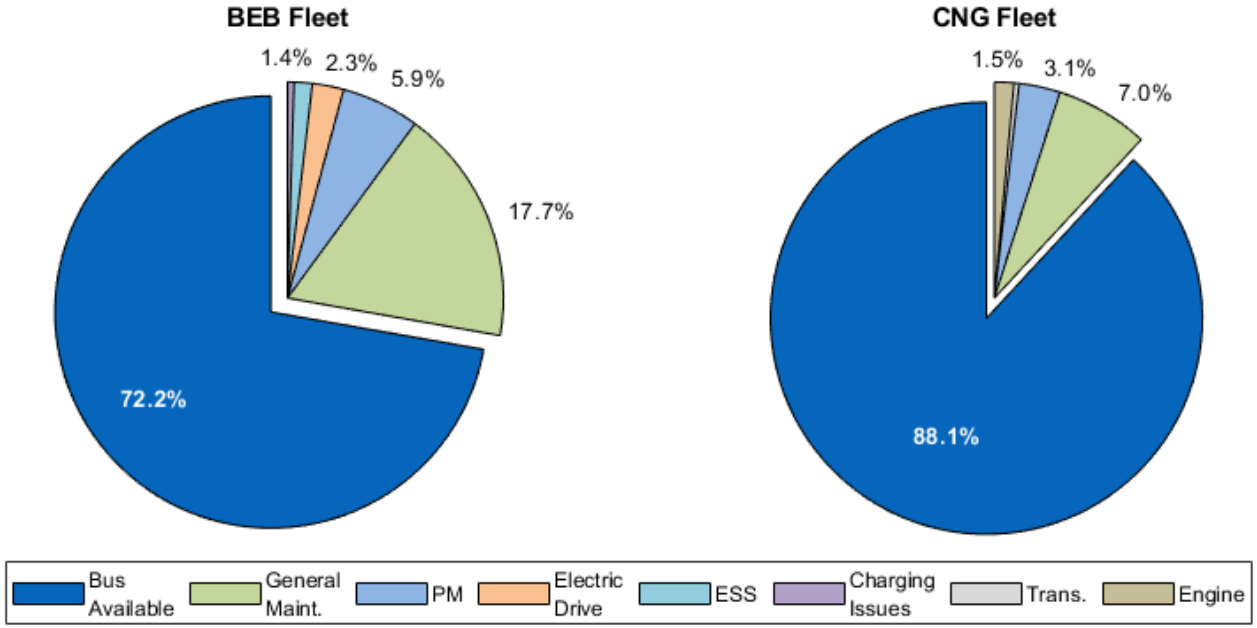
Maintenance Cost by Vehicle System

	BEB All Data	BEB 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	5,533.92	1,245.69	25,693.25	12,860.86
Labor hours	765.75	244.25	994.6	344.8
Average labor cost	38,287.50	12,212.50	49,730.00	17,240.00
Total cost (for system)	43,821.42	13,458.19	75,423.25	30,100.86
Total cost (for system) per bus	4,382.14	1,345.82	9,427.91	3,762.61
Total cost (for system) per mile	**0.18**	**0.17**	**0.15**	**0.17**
HVAC System Repairs (ATA VMRS 01)				
Parts cost	56.62	43.08	5,349.31	2,160.28
Labor hours	50.75	30.75	100	28
Average labor cost	2,537.50	1,537.50	5,000.00	1,400.00
Total cost (for system)	2,594.12	1,580.58	10,349.31	3,560.28
Total cost (for system) per bus	259.41	158.06	1,293.66	445.04
Total cost (for system) per mile	**0.01**	**0.02**	**0.02**	**0.02**
Lighting System Repairs (ATA VMRS 34)				
Parts cost	163.15	162.94	2,118.51	201.61
Labor hours	21	4	32.5	5.5
Average labor cost	1,050.00	200.00	1,625.00	275.00
Total cost (for system)	1,213.15	362.94	3,743.51	476.61
Total cost (for system) per bus	121.32	36.29	467.94	59.58
Total cost (for system) per mile	**0.01**	**0.00**	**0.01**	**0.00**

Maintenance Cost by Vehicle System

	BEB All Data	BEB Data Period	CNG All Data	CNG Data Period
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	87.00	20.64	11,863.54	4,339.96
Labor hours	83	33.5	103.5	49
Average labor cost	4,150.00	1,675.00	5,175.00	2,450.00
Total cost (for system)	4,237.00	1,695.64	17,038.54	6,789.96
Total cost (for system) per bus	423.70	169.56	2,129.82	848.75
Total cost (for system) per mile	**0.02**	**0.02**	**0.03**	**0.04**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	26.96	26.96	1,087.40	504.65
Labor hours	67	31.5	181	71.5
Average labor cost	3,350.00	1,575.00	9,050.00	3,575.00
Total cost (for system)	3,376.96	1,601.96	10,137.40	4,079.65
Total cost (for system) per bus	337.70	160.20	1,267.18	509.96
Total cost (for system) per mile	**0.01**	**0.02**	**0.02**	**0.02**
Tire Repairs (ATA VMRS 17)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	0.0	0.0	1.5	0.0
Average labor cost	0.00	0.00	75.00	0.00
Total cost (for system)	0.00	0.00	75.00	0.00
Total cost (for system) per bus	0.00	0.00	9.38	0.00
Total cost (for system) per mile	**0.00**	**0.00**	**0.00**	**0.00**

Overall Fleet Availability: Full Data Period



1. Data period for availability analysis: Jan 2018 - Jun 2019
2. Data labels omitted for pie slices representing < 1.0%

Fleet Summary Statistics: SI Units

	BEB All Data	BEB Data Period	CNG All Data	CNG Data Period
Number of vehicles	10	10	8	8
Period used for fuel and oil analysis	1/18–6/19	1/19–6/19	1/18–6/19	1/19–6/19
Total number of months in period	18	6	18	6
Fuel and oil analysis base fleet kilometers	345,456	113,512	723,331	267,905
Period used for maintenance analysis	1/18–6/19	1/19–6/19	1/18–6/19	1/19–6/19
Total number of months in period	18	6	18	6
Maintenance analysis base fleet kilometers	389,653	130,114	790,304	282,759
Average monthly kilometers per vehicle	2,165	2,169	3,052	3,277
Availability	72	75	88	85
Fleet fuel/energy usage in kWh (BEB) or L (CNG)	397,751.3	135,823.5	537,509.4	186,172.5
Roadcalls	60	22	40	19
Total KBRC	6,494	5,914	19,758	14,882
Propulsion roadcalls	24	6	24	11
Propulsion KBRC	16,236	21,686	32,929	25,705
Representative fleet L/100 km (energy equiv.)	11.58	12.03	74.31	69.49
Energy cost per kWh or CNG cost per liter	0.24	0.20	0.40	0.41
Fuel cost per kilometer	0.33	0.25	0.26	0.25
Total scheduled repair cost per km	0.09	0.10	0.10	0.08
Total unscheduled repair cost per km	0.18	0.17	0.23	0.24
Total maintenance cost per km	0.27	0.27	0.33	0.33
Total operating cost per km	***0.60***	***0.52***	***0.59***	***0.57***

Maintenance Cost Summary: SI Units

Maintenance Cost Summary

	BEB All Data	BEB Data Period	CNG All Data	CNG Data Period
Fleet kilometers	389,653	130,114	790,304	282,759
Total parts cost	11,407.30	4,689.67	114,615.66	40,975.37
Total labor hours	1,883.0	605.0	2,948.1	1,019.8
Average labor cost (@ $50.00 per hour)	94,150.00	30,250.00	147,405.00	50,990.00
Total maintenance cost	105,557.30	34,939.67	262,020.66	91,965.37
Total maintenance cost per bus	10,555.73	3,493.97	32,752.58	11,495.67
Total maintenance cost per km	***0.27***	***0.27***	***0.33***	***0.33***

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NREL/PR-5400-73740

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.