



SunLine Transit Agency American Fuel Cell Bus Progress Report

Data Period Focus: January 2017–July 2019

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Introduction

This report presents results of the American Fuel Cell Bus (AFCB) project, a deployment of fuel cell electric buses (FCEBs) operating in the Coachella Valley area of California. The prototype AFCB, which was developed as part of the Federal Transit Administration's (FTA's) National Fuel Cell Bus Program, was put in revenue service in mid-December 2011. This report is focused on the upgraded design buses, which include two FCEBs delivered in June/July of 2014, one delivered in February 2015, and five delivered in 2018. The project team is collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service.

The goal of this evaluation is to compare the FCEB performance to that of conventional technology and to track progress over time toward meeting the technical targets set by DOE and FTA. NREL collects data on five 2016 model year compressed natural gas (CNG) buses as a baseline comparison at SunLine. The baseline buses for previous reports were 2008 model year CNG buses. NREL ended the data collection on those buses because they were reaching end of life. Previous reports are available online.^{1,2,3} This final report on the AFCBs updates the data through July 2019.

¹ American Fuel Cell Bus Project: First Analysis Report, FTA Report No. 0047, www.nrel.gov/hydrogen/assets/pdfs/fta_report_no_0047.pdf

² American Fuel Cell Bus Project: Second Report, NREL TP-5400-64344, www.nrel.gov/docs/fy15osti/64344.pdf

³ American Fuel Cell Bus Project: Third Report, NREL TP-5400-67209, www.nrel.gov/docs/fy17osti/67209.pdf

Results Summary

Bus fleets: This evaluation includes eight 40-ft FCEBs built by Eldorado National – California (ENC) with a BAE systems hybrid propulsion system and a Ballard fuel cell system. The baseline buses are five New Flyer 40-ft CNG buses.

Bus use: The FCEBs are operated on several SunLine routes at an average speed of 17.0 mph. SunLine randomly dispatched the five CNG buses with most time split between Line 111, Line 14, and Line 30. Based on the dispatching information, the CNG buses operated at a similar average speed (17.2 mph) as the fuel cell buses did during the evaluation period.

Fuel economy: The FCEBs had an average fuel economy of 5.50 miles per kilogram of hydrogen, which equates to 6.22 mpdge. The CNG buses had an average fuel economy of 3.44 mpgge, which equates to 3.85 mpdge. The FCEB fuel economy was 1.6 times higher than that of the CNG buses.

mpdge = miles per diesel gallon equivalent
mpgge = miles per gasoline gallon equivalent

Results Summary (continued)

Fuel cost: The average monthly cost for hydrogen at SunLine varies based on total hydrogen dispensed and station maintenance costs. During the data period, the monthly hydrogen costs ranged from \$3.70/kg to more than \$21.00/kg. The average cost of hydrogen was \$7.25/kg. The CNG fuel cost for the data period was \$0.96 per gge. The FCEBs had an average fuel cost of \$1.32 per mile. The fuel cost for the CNG buses averaged \$0.28 per mile.

Availability: The per-bus availability for the FCEBs ranged from 60% to 89%. The average availability for the FCEBs was 73%. The average availability for the new CNG buses was 87%. Most unavailable time for the FCEBs was due to general bus-related problems followed by propulsion system issues. Most downtime for the CNG buses was for general bus-related maintenance.

Results Summary (continued)

Maintenance cost: The cost to maintain the buses in the data period was \$0.56/mi for the FCEBs and \$0.23/mi for the CNG buses. The FCEB cost has increased over what was reported previously. Several factors contributed to the high maintenance cost for the FCEBs:

- The older FCEBs (FC4, FC5, and FC6) are out of warranty, resulting in higher parts costs. Overall cost for the older FCEBs was \$0.71/mi compared to \$0.37/mi for the newer buses.
- Work affecting costs for the FCEBs during the data period includes:
 - Radiator and cooling fans
 - Suspension issues
 - Brake relines
 - Low voltage batteries.
- Cost per mile for several months during the early part of the data period were high because two of three buses were not operated, accumulating little to no miles.
- Cooling system costs were primarily for labor to check and fill reservoirs as needed in SunLine's hot climate.

Results Summary (continued)

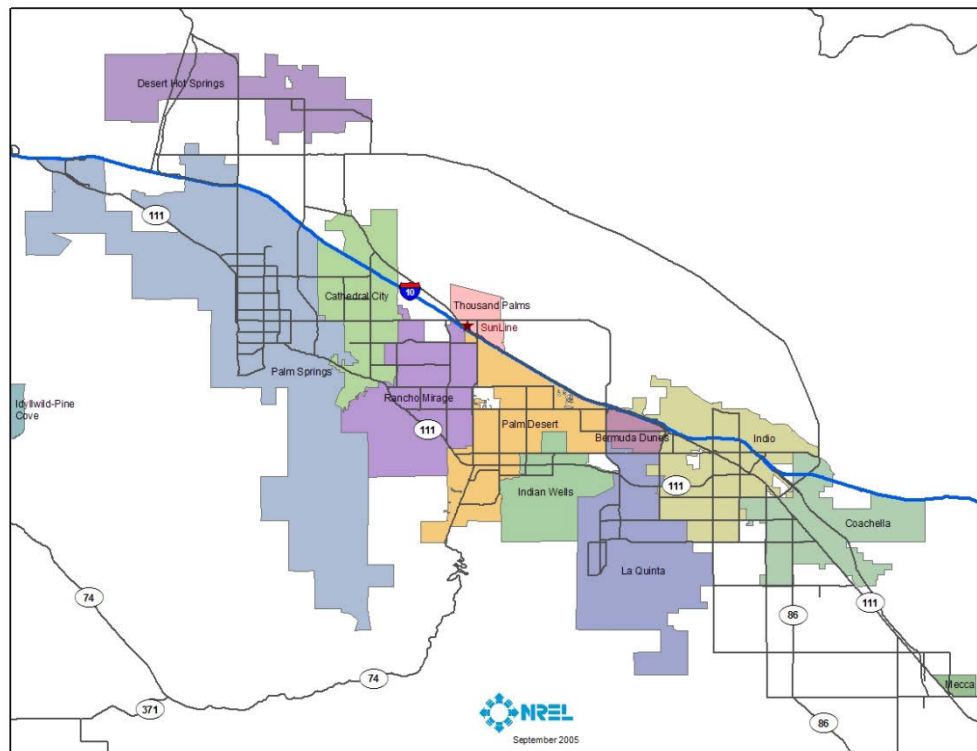
- **Future analysis:** This is the final report on this generation of the AFCB design. NREL will shift data collection to the newer design FCEBs. These buses include those shown in the table.

Project	Funding Program	# Buses	Description	In Service Start
Battery Dominant Fuel Cell Hybrid Bus	FTA—National Fuel Cell Bus Program	1	Battery-dominant FCEB based on AFCB platform with a smaller fuel cell	Q1 2018
New Flyer/Hydrogenics FCEB	California Energy Commission—Alternative and Renewable Fuel and Vehicle Technology Program	1	New Flyer Xcelsior bus, Siemens hybrid drive system with Hydrogenics fuel cell system	Q4 2019
SunLine FCEBs and Fueling Station Deployment	California Air Resources Board	5	New Flyer Xcelsior bus, Siemens ELFA hybrid drive system with Ballard fuel cell system	Q2 2019

Fleet Profile

SunLine Transit Agency provides public transit services to Southern California's Coachella Valley. Headquartered in Thousand Palms, California, SunLine's service area covers more than 1,100 square miles, including nine member cities and a portion of Riverside County.

SunLine operates 15 fixed routes—including three trunk lines and 12 local routes—one commuter route from Palm Desert to Riverside, and one express route between Desert Hot Springs and Palm Desert. The current bus fleet consists of 86 fixed route buses: 62 CNG buses, 20 FCEBs, and 4 battery electric buses.



Evaluation Buses: Specifications

Vehicle System	AFCB	CNG
Number of buses	8	5
Bus manufacturer/model	ENC, Axess	New Flyer, Xcelsior
Model year	2014, 2018	2016
Bus purchase cost	\$2.1 million–\$2.4 million	\$550,000
Length/width/height	40 ft/102 in./140 in.	40 ft/102 in./130.8 in.
Curb weight	43,420 lb	42,540 lb
Passenger capacity	37 seated or 31 seated with two wheelchairs; 19 standees	39 seated with no wheelchairs
Hybrid system	BAE Systems, series hybrid propulsion system, HDS 200 Series E, 200 kW peak	N/A
Fuel cell or engine	Ballard FCvelocity-HD6, 150 kW	Cummins Westport ISL G 280 hp @ 2,200 rpm
Energy storage	A123, Nanophosphate Li-ion; 200 kW, 11 kWh	N/A
Accessories	Electric (APS3)	Mechanical
Fuel capacity	Gaseous hydrogen, 8 Luxfer-Dynetek cylinders, 50 kg at 350 bar	125 dge

Evaluation Buses



AFCB Bus In-Service/
Data Clean Point

Bus	Clean Point	Odometer July 31, 2019
FC4	Jul 2014	143,685
FC5	Dec 2014	127,779
FC6	May 2015	94,959
FC8	May 2018	29,764
FC9	Apr 2018	29,849
FC10	Jun 2018	28,195
FC11	Oct 2018	16,777
FC12	Oct 2018	18,991

CNG buses were in service
beginning in January 2017

Infrastructure Description

To support the early adoption of FCEBs, SunLine built a station that produced hydrogen onsite through a natural gas reformer. This station supplied hydrogen for the buses and to the public for light-duty vehicles. This hydrogen fueling station has aged and cannot produce enough hydrogen to operate all of SunLine's FCEBs. At maximum capacity, SunLine estimated it could supply up to eight buses. As the fleet has grown, FCEB operation has been limited by the ability to provide fuel.

SunLine is building a new CNG and hydrogen station that will meet the demands of its fleet. A Proton OnSite electrolyzer will produce 900 kg of hydrogen per day. The new station will include hydrogen dispensers in line with the CNG fueling island, which will allow the FCEBs to be handled the same as the CNG bus fleet. As of this report, the station is complete and in the commissioning process.

Data Summary: January 2017–July 2019

Data Item	FCEB	CNG
Number of buses	8	5
Data period	1/17–7/19	1/17–7/19
Number of months	31	31
Total mileage in data period	268,778	813,575
Average odometer	61,250	164,855
Average monthly mileage per bus	1,791	5,249
Total fuel cell power plant hours	22,310	—
Availability (85% is target)	73	87
Fuel economy (FCEB mi/kg or CNG mpgge)	5.50	3.44
Fuel economy (mpdge)	6.22	3.85
Average speed (mph)	17.0	17.2
Miles between roadcalls (MBRC) – bus ^b	4,398	15,350
MBRC – propulsion system only ^b	7,442	33,899
MBRC – fuel cell system only ^b	17,916	—
Total maintenance cost (\$/mile) ^c	0.56	0.23
Maintenance cost – propulsion system only (\$/mile)	0.28	0.08

^a CNG bus operation not typical of SunLine’s overall fleet. SunLine reports a typical CNG bus will operate ~45,000 miles per year (3,750 miles per month).

^b MBRC for the FCEB data cumulative from the clean point of July 2014 through July 2019.

^c Work order maintenance cost.

Route Assignments

SunLine's service consists of 15 fixed routes and one commuter route to Riverside. In general, SunLine's buses are randomly dispatched on its local routes. The overall system average speed is 17.7 mph (not including the commuter route). The table summarizes the route use for the FCEBs and the CNG baseline buses during the evaluation period. SunLine operated the FCEBs primarily on Line 24 (30.3%), Line 111 (18.9%), Line 30 (17.7%), and Line 32 (16.2%). The overall average speed for the AFCBs was 17.0 mph.

SunLine randomly dispatched the five CNG buses with 82% of the time split among Line 111, Line 30, and Line 14. Based on the dispatching information, the CNG buses operated at a similar average speed (17.2 mph) as the fuel cell buses did during the evaluation period.

Route	Percent of Time	Average Speed (mph)
FCEB		
24	30.3	16.4
111	18.9	17.8
30	17.7	15.6
32	16.2	19.1
Average	—	17.0
CNG		
111	56.1	17.8
30	13.7	15.6
14	12.2	16.6
Average	—	17.2

Fleet Average Monthly Miles by Bus

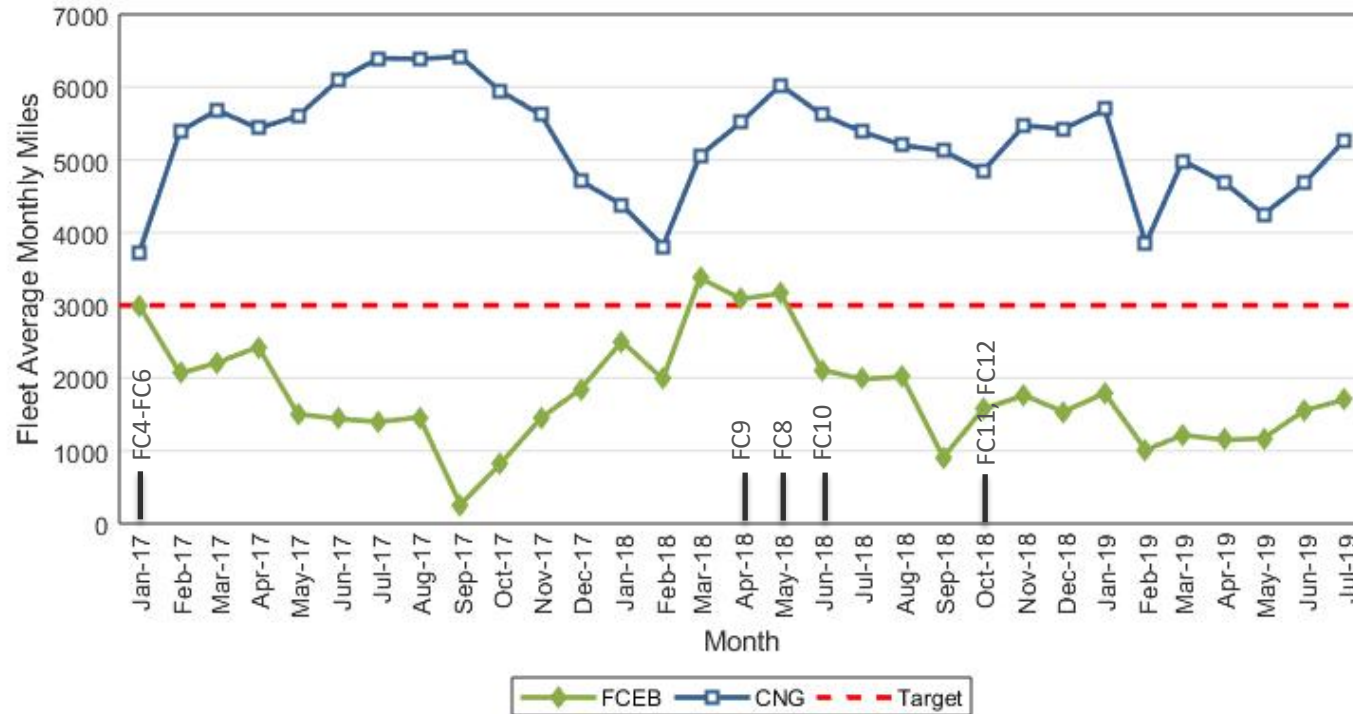
Bus	Miles	Bus Months	Average Monthly Mileage
FC4	56,092	31	1,809
FC5	55,179	31	1,780
FC6	38,115	31	1,230
FC8	28,330	15	1,889
FC9	29,749	16	1,859
FC10	26,745	14	1,910
FC11	16,777	10	1,678
FC12	17,791	10	1,779
FCEB Fleet	268,778	158	1,701

Bus	Miles	Months	Average Monthly Mileage
622	152,561	31	4,921
623	168,581	31	5,438
624	160,271	31	5,170
625	167,190	31	5,393
626	164,972	31	5,322
CNG Fleet	813,575	155	5,249

The first three FCEBs were in service the entire data period. The newer buses (FC8–FC12) were phased in after delivery beginning in April 2019. The CNG buses used for the baseline comparison are the newest in SunLine’s fleet and have been used at a much higher rate than the agency’s other CNG buses. SunLine reports its typical CNG mileage accumulation is closer to 3,700 miles per month. The mileage for the FCEBs over the last year is artificially low because the existing station cannot produce enough hydrogen to fuel each bus daily. The average monthly mileage for the FCEBs during the data period was 68% lower than that of the CNG buses.

The FCEBs averaged 8 hours in service each day but achieved as many as 18 hours in a single day.

Fleet Average Monthly Miles



- Buses FC4 through FC6 were in service the entire data period. In service dates for the remaining buses are marked on the graph.
- Over the last year, the FCEB operation was artificially low because of limited hydrogen supply.

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 for special events, or they may have been available but just not used. Buses unavailable for service may have had issues with the propulsion system (fuel cell system, electric drive system), general bus maintenance, or undergoing scheduled maintenance. 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. For SunLine, NREL calculates availability based on the planned service days, which are typically every weekday. Weekends and holidays are included in the calculation only if the bus operated in service on those days. If a bus does not operate on the weekend or on a holiday, it is not counted as unavailable. This strategy applies to both the FCEBs and the CNG buses. SunLine provides a monthly activity sheet for the FCEBs and CNG buses that lists each bus, the use if available, and a general reason for unavailability.

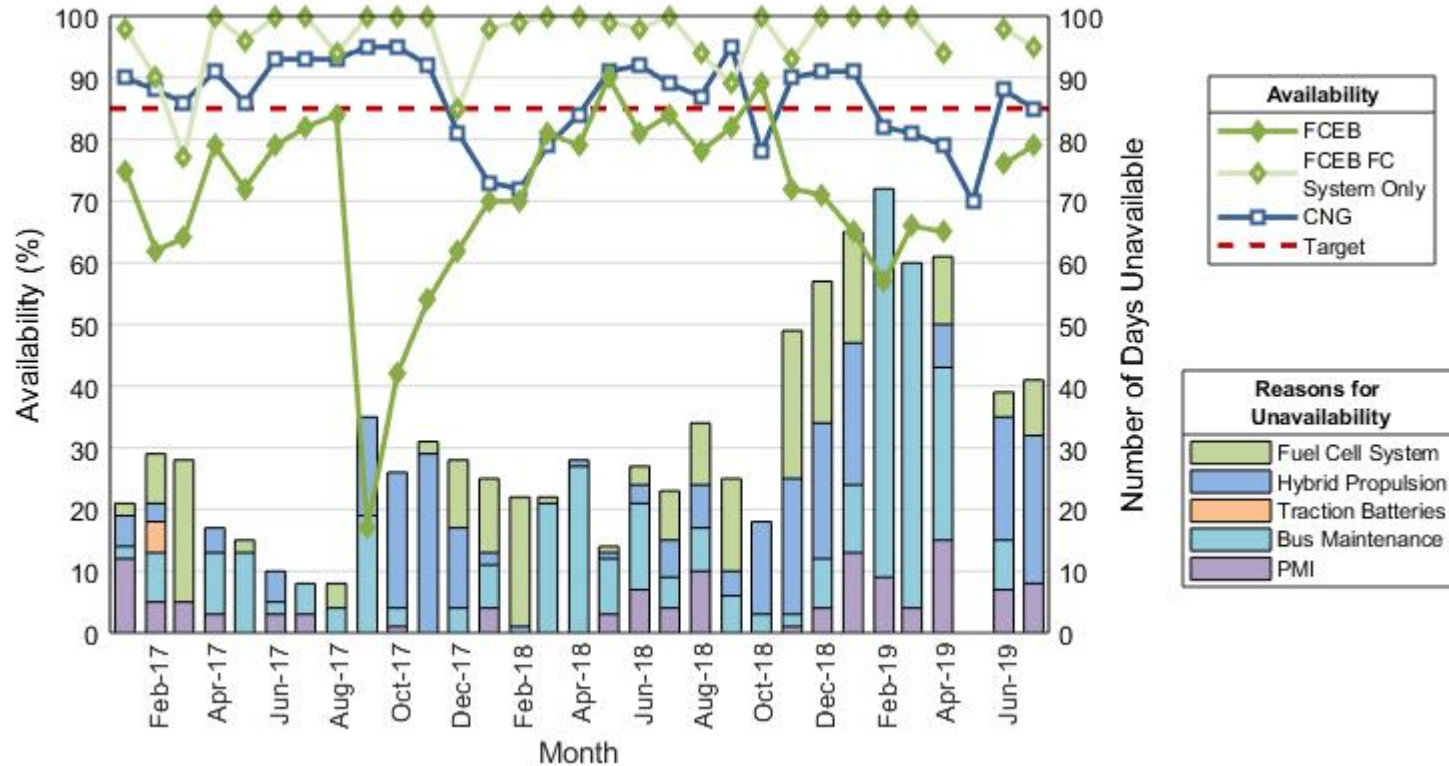
NREL presents availability as a monthly average trend and as overall availability. Unavailable time is separated into several categories to show the primary reason for downtime.

Availability Summary – Data Period

Category	FCEB # Days	FCEB %	CNG # Days	CNG %
Planned work days	3,472		4,216	
Days available	2,534	73	3,651	87
Days unavailable	938	27	565	13
Fuel cell system	212	6.1	—	—
CNG engine	—	—	73	1.7
Hybrid propulsion	255	7.3	—	—
Traction batteries	5	0.1	—	—
Preventive maintenance	121	3.5	173	4.1
General bus maintenance	345	9.9	319	7.6

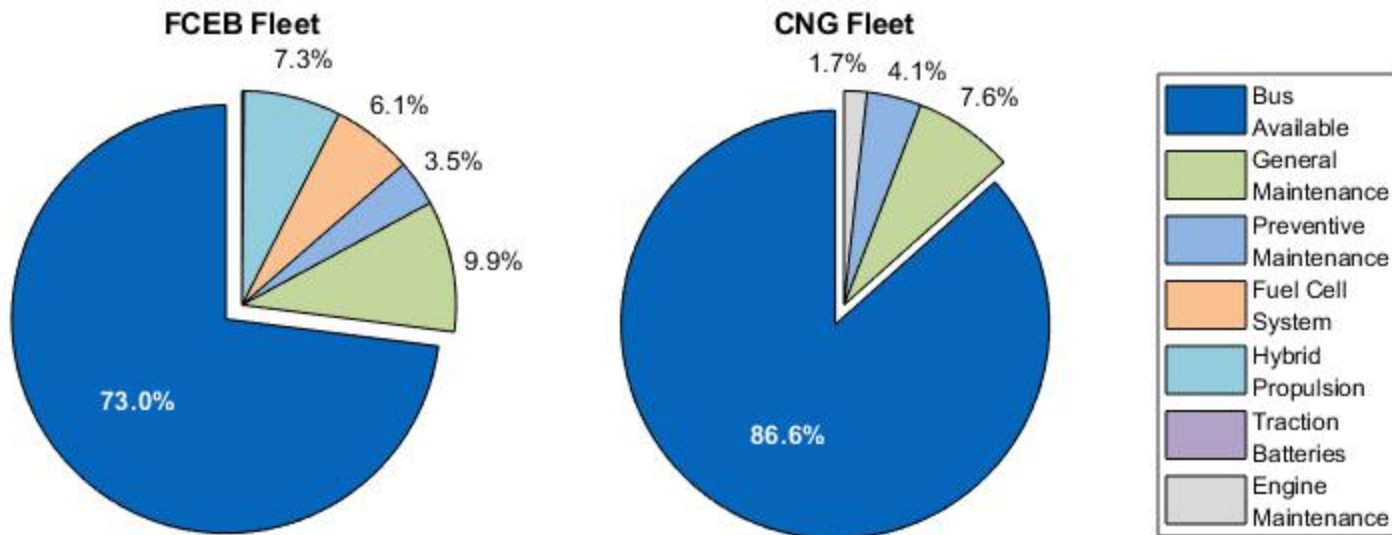
- The per-bus availability for the FCEBs during the data period ranged from 60% to 89%. Downtime for two of the older buses lowered the overall average. The newer buses (FC8–FC12) averaged 83% availability.
- The fuel-cell-system availability was 97%.
- General bus maintenance was the reason for most of the unavailable time for the FCEBs, followed by hybrid propulsion issues.
- General bus maintenance was the reason for most of the unavailable time for the CNG buses, followed by preventive maintenance.

Monthly Availability



- In September 2017, two of the three buses were out of service for the entire month.

Overall Availability—Data Period



Downtime for two of the older buses lowered the overall average. The newer buses (FC8–FC12) averaged 83% availability.

Fuel Economy Analysis

SunLine provides individual fueling records for the FCEBs and CNG buses. CNG is typically dispensed in units of gge. NREL uses these records to calculate the CNG fuel economy in mpgge as well as mpdge. Hydrogen is tracked in kilograms; 1 kg of hydrogen has essentially the same energy content as a gallon of gasoline. To compare the fuel economy of the FCEBs to that of the baseline buses, NREL converted kg hydrogen to dge using a conversion factor of 1.13 kg/dge.

Hydrogen fuel costs at SunLine consist of the cost of natural gas for the reformer, the cost for maintenance of the station equipment, and capital cost amortization. SunLine performs maintenance of the station equipment, including parts and labor. The average monthly cost for hydrogen at SunLine varies based on total hydrogen dispensed and station maintenance costs. During the data period for the report, the agency has seen costs from as low as \$3.67/kg to more than \$21.62/kg. The average cost of hydrogen during the evaluation period was \$7.25/kg. The CNG fuel cost for the data period was \$0.96 per gge.

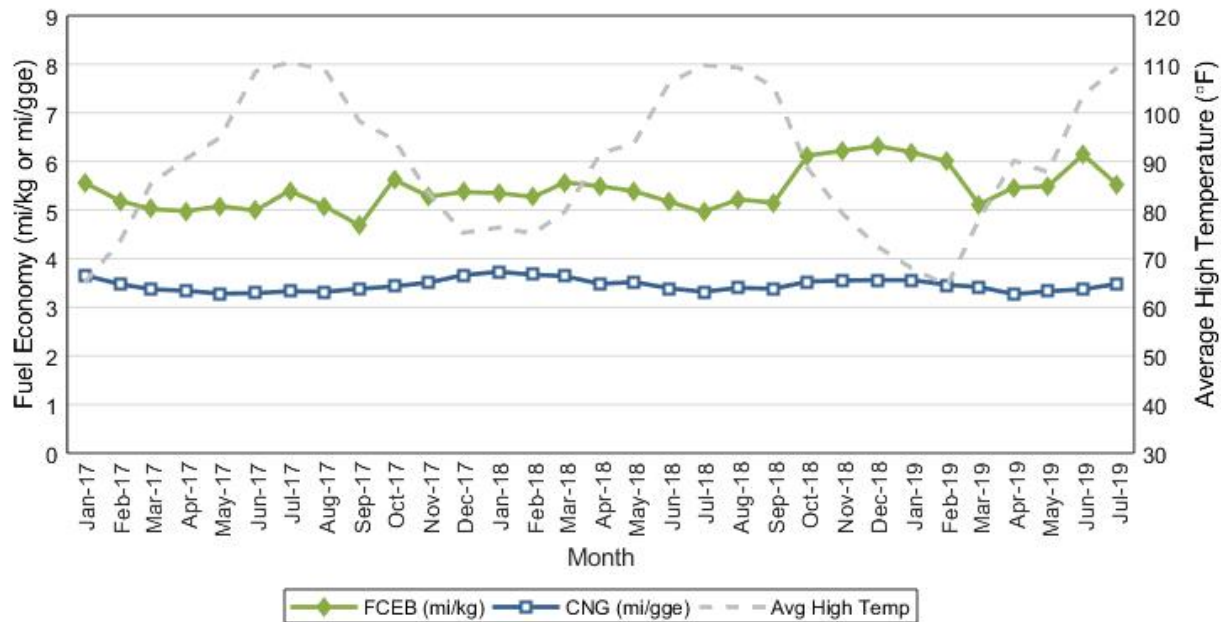
Fuel Economy by Bus—Data Period

Bus	Miles	Hydrogen (kg)	mi/kg	Diesel gallon Equiv.	Fuel economy (mpdge)
FC4	52,884	9,372.5	5.64	8,294.3	6.38
FC5	53,105	10,130.9	5.24	8,965.4	5.92
FC6	34,348	6,909.1	4.97	6,114.3	5.62
FC8	26,222	4,804.9	5.46	4,252.1	6.17
FC9	29,131	5,298.3	5.50	4,688.8	6.21
FC10	25,897	4,302.2	6.02	3,807.2	6.80
FC11	16,435	2,623.9	6.26	2,322.1	7.08
FC12	17,166	2,922.1	5.87	2,585.9	6.64
FCEB Fleet	255,188	46,364.0	5.50	41,030.1	6.22

Bus	Miles	CNG (gge)	Miles per gge	CNG (dge)	Fuel Economy (mpdge)
624	151,213	44,404.8	3.41	39,742.3	3.80
625	167,610	48,729.4	3.44	43,612.8	3.84
626	159,354	46,070.4	3.46	41,233.0	3.86
627	164,790	49,056.1	3.36	43,905.2	3.75
628	163,608	46,085.3	3.55	41,246.4	3.97
CNG Total	806,575	234,345.9	3.44	209,739.6	3.85

- FCEB fuel economy is 1.6 times that of the CNG buses.
- Fuel cost for the evaluation period is as follows:
 - \$1.32 per mile for the FCEBs (hydrogen at \$7.25/kg)
 - \$0.28 per mile for the CNG buses (CNG at \$0.96/gge).

Fleet Average Monthly Fuel Economy



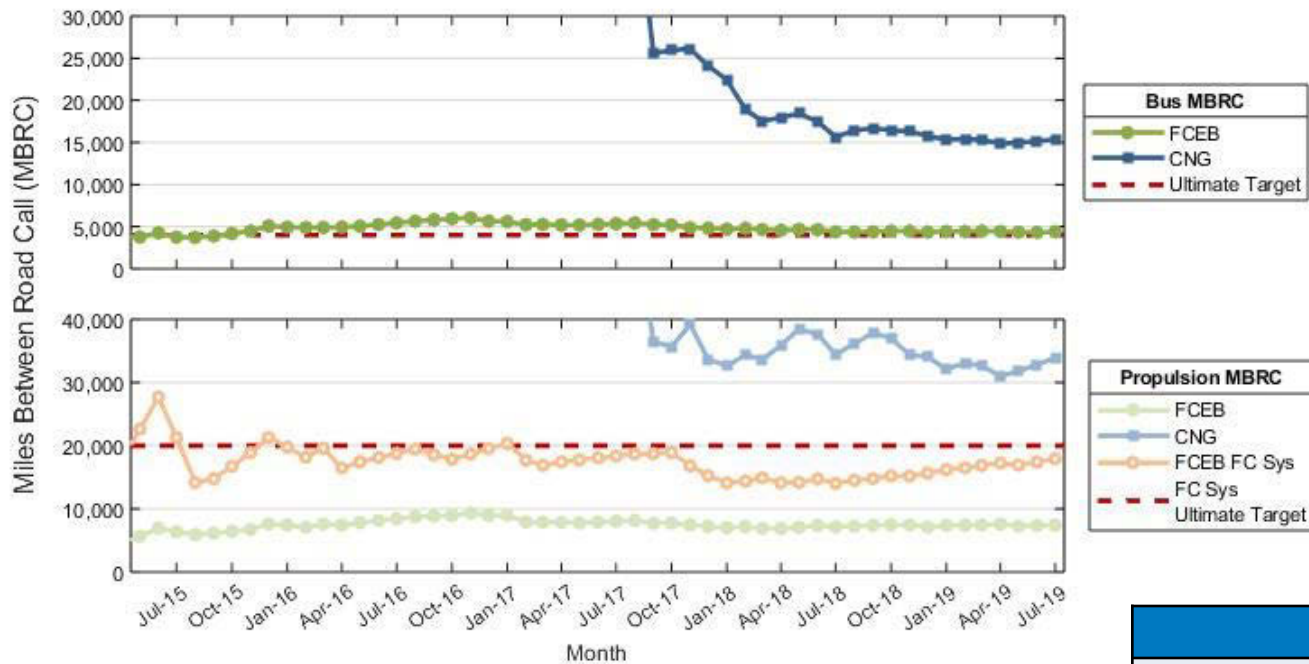
	Jan 2017 – Jul 2019	
Bus	mi/kg, mpgge	mpgde
FCEB	5.50	6.22
CNG	3.44	3.85

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, this is not considered a roadcall. The analysis described here includes only roadcalls that were caused by “chargeable” failures. Chargeable roadcalls include systems that can physically disable the bus from operating on route, such as interlocks (doors, air system), engine, or things that are deemed to be safety issues if operation of the bus continues. They do not include roadcalls for things such as problems with radios, fareboxes, or destination signs.

The transit industry measures reliability as mean distance between failures, also documented as MBRC. NREL tracks MBRC by total roadcalls, propulsion-related roadcalls, and fuel cell (FC) system-related roadcalls. Total roadcalls includes all chargeable roadcalls. “Propulsion-related roadcall” is a subset of total roadcalls and includes all roadcalls due to propulsion-related systems including the FC system (or engine for a conventional bus), electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, transmission systems, and hydraulics. The FC system-related roadcalls, a subset of the propulsion-related roadcalls, and MBRC are included for the FCEBs.

Cumulative MBRC



- The upper chart shows cumulative MBRC for all chargeable roadcalls.
- The lower chart shows MBRC for propulsion-related roadcalls and FC system-related roadcalls.

	FCEB	CNG
Bus MBRC	4,398	15,350
Propulsion MBRC	7,442	33,899
FC system MBRC	17,916	N/A

Maintenance Analysis

NREL collects all work orders for the evaluation buses to calculate a maintenance cost per mile. Costs for accident-related repairs 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. This does not reflect an average rate for SunLine. 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 which systems have the most costs for each technology.

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

SunLine staff handle most of the maintenance on the FCEBs. Ballard has a technician stationed at SunLine that is available to provide needed service to SunLine and other transit agencies in the area that operate FCEBs.

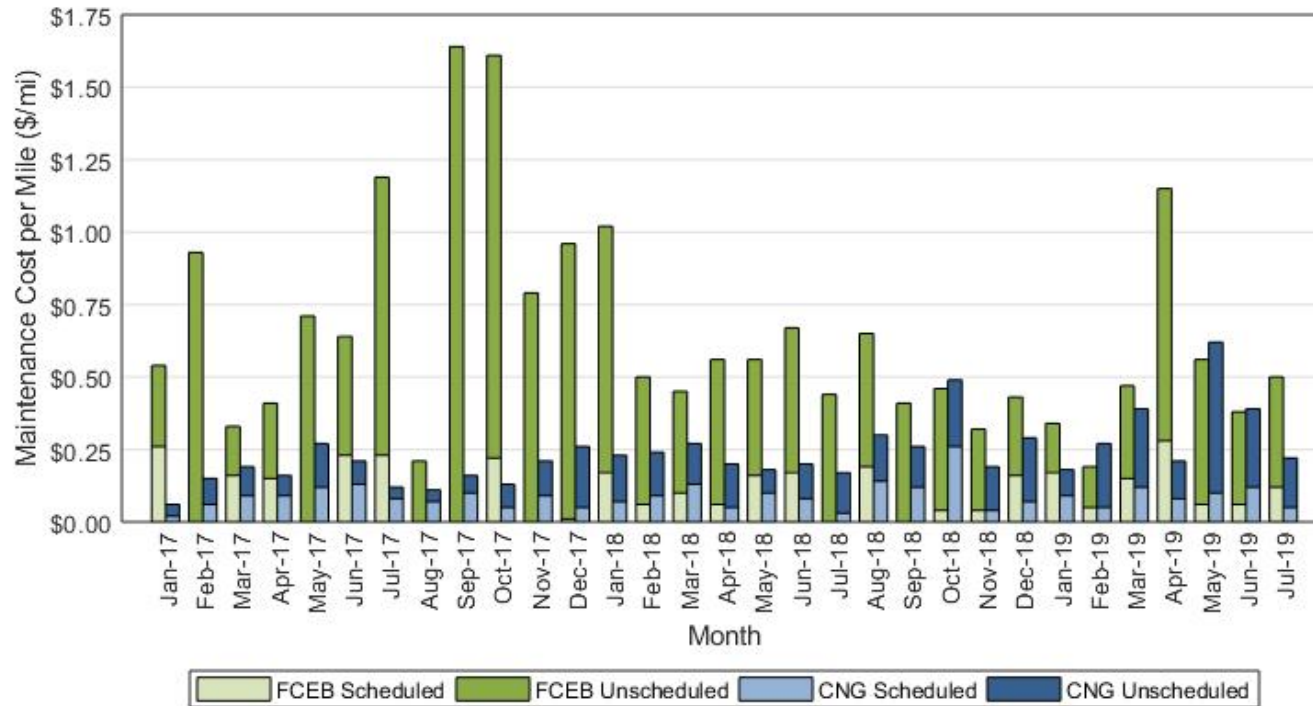
Maintenance Analysis Results—Data Period

Bus	Mileage	Parts (\$)	Labor hours	Scheduled Cost per Mile (\$)	Unscheduled Cost per Mile (\$)	Total Cost per Mile (\$)
FC4	56,092	6,625	523.0	0.11	0.47	0.58
FC5	55,179	6,302	597.1	0.10	0.51	0.66
FC6	38,115	5,210	630.0	0.10	0.86	0.96
FC8	28,330	1,324	161.5	0.09	0.24	0.33
FC9	29,749	1,704	310.0	0.12	0.46	0.58
FC10	26,745	716	133.5	0.08	0.19	0.28
FC11	16,777	864	70.0	0.09	0.17	0.26
FC12	17,791	1,854	90.5	0.22	0.13	0.36
FCEB Fleet	268,778	24,601	2,515.6	0.11	0.45	0.56

Bus	Mileage	Parts (\$)	Labor hours	Scheduled Cost per Mile (\$)	Unscheduled Cost per Mile (\$)	Total Cost per Mile (\$)
622	152,561	13,495	494.8	0.09	0.17	0.25
623	168,581	11,759	565.3	0.09	0.14	0.24
624	160,271	10,344	453.8	0.09	0.12	0.21
625	167,190	8,678	474.0	0.08	0.12	0.19
626	164,972	17,284	552.0	0.10	0.17	0.27
CNG Fleet	813,575	61,561	2,539.8	0.08	0.09	0.23

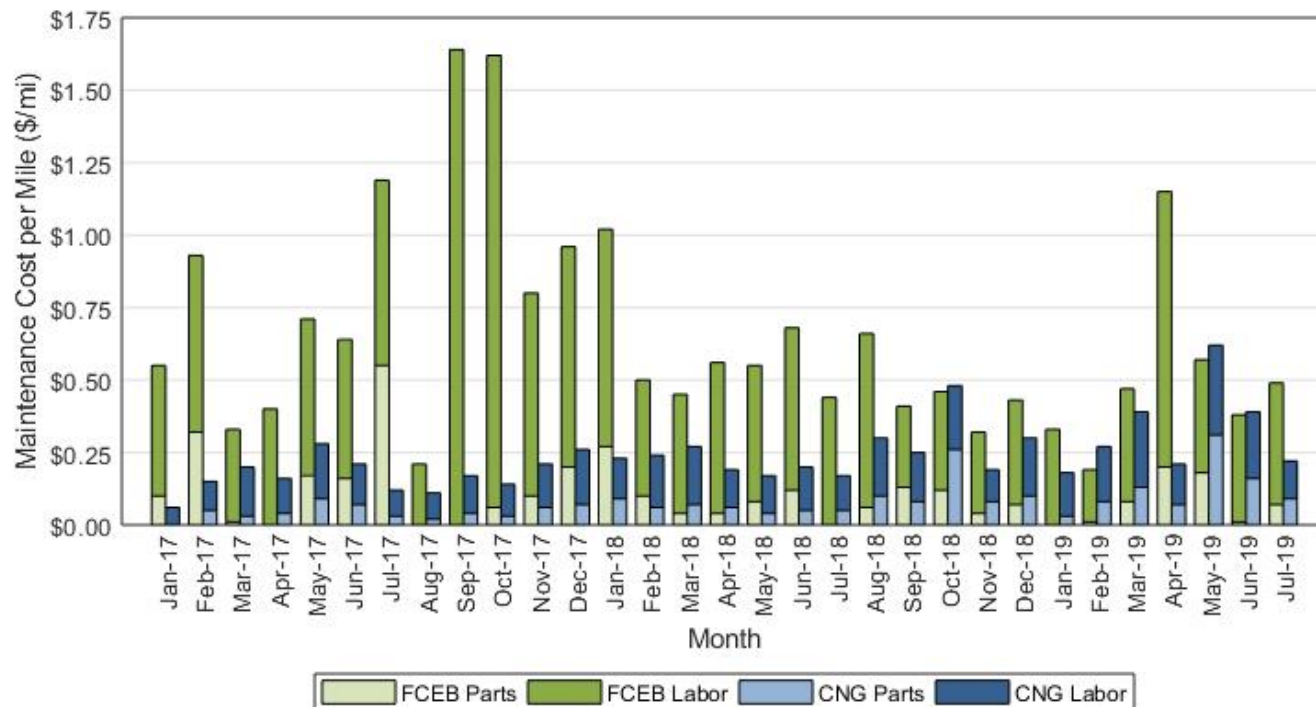
- The older FCEBs (FC4, FC5, and FC6) are out of warranty, resulting in higher parts costs. Overall cost for the older FCEBs was \$0.71/mi compared to \$0.37/mi for the newer buses.
- The MY2016 CNG buses are also out of warranty for most components.
- Work affecting costs for the FCEBs during the data period includes:
 - Radiator and cooling fans
 - Suspension issues
 - Brake relines
 - Low-voltage batteries.
- Work affecting costs for the CNG buses includes:
 - Radiator
 - Radius rods
 - Brake relines
 - Voltage regulators
 - Low-voltage batteries.

Scheduled and Unscheduled Maintenance Cost



- During July 2017, unscheduled costs included a brake service on one FCEB and suspension issues with another.
- September and October 2017 costs were high due to low miles on all three buses in service.
- Labor for one FCEB with cooling system leaks affected the cost from October through December 2017.

Parts and Labor Maintenance Cost



- Much of the costs for the FCEBs is for labor.

Maintenance Cost by System

The vehicle systems include the following:

- Propulsion-related systems—Repairs for exhaust, fuel, engine, electric motors, fuel cell modules, battery modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, hydraulics, and transmission
- Cab, body, and accessories—Includes body, glass, and paint repairs following accidents; cab and sheet metal repairs on seats and doors; and accessory repairs such as hubodometers and radios
- PMI (preventive maintenance inspections)—Labor for preventive maintenance
- Brakes
- Frame, steering, and suspension
- Heating, ventilation, and air conditioning (HVAC)
- Lighting
- Axles, wheels, and drive shaft
- Air system, general
- Tires.


Maintenance Cost per Mile by System

System	FCEB		CNG	
	Cost per Mile (\$)	Percent of Total (%)	Cost per Mile (\$)	Percent of Total (%)
Propulsion-related	0.277	49	0.082	35
Cab, body, and accessories	0.088	16	0.050	22
PMI	0.112	20	0.056	24
Brakes	0.024	4	0.021	9
Frame, steering, and suspension	0.028	5	0.014	6
HVAC	0.016	3	0.002	1
Lighting	0.005	1	0.001	0
Air, general	0.000	0	0.000	0
Axles, wheels, and drive shaft	0.003	0	0.000	0
Tires	0.006	1	0.006	2
Total	0.559	100	0.232	100

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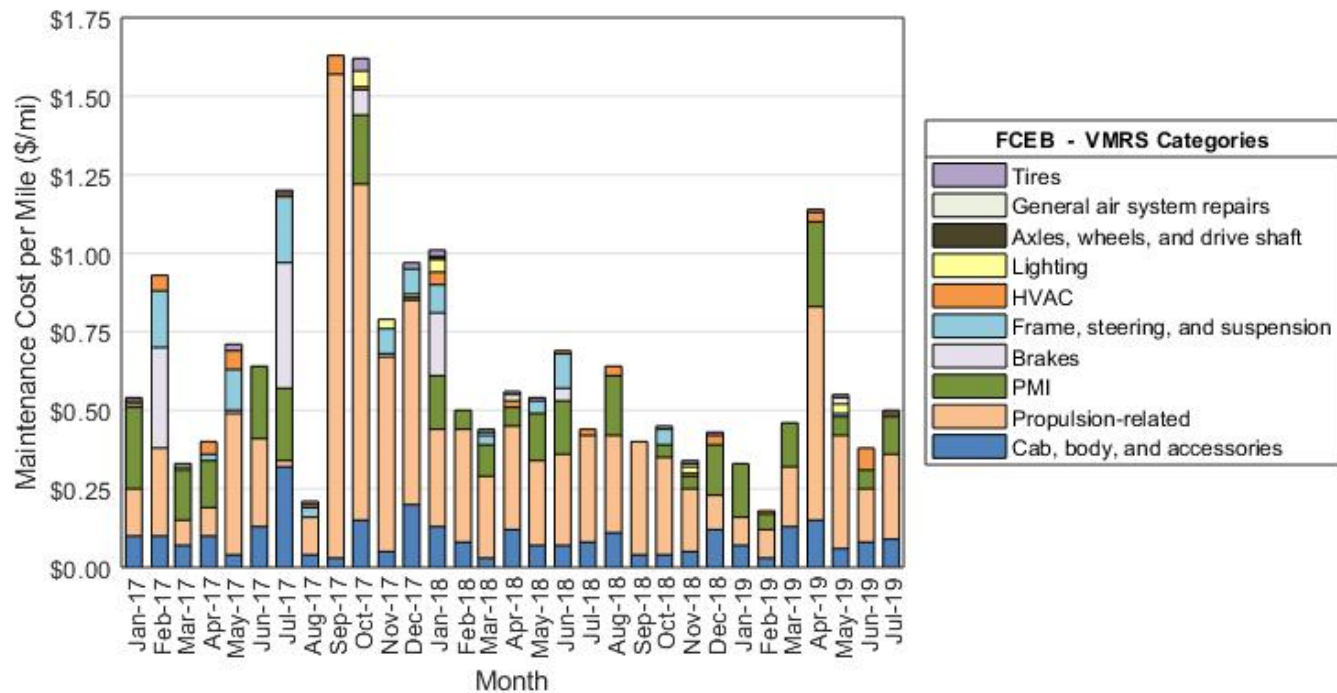
 Highest cost

 Second highest cost

 Third highest cost

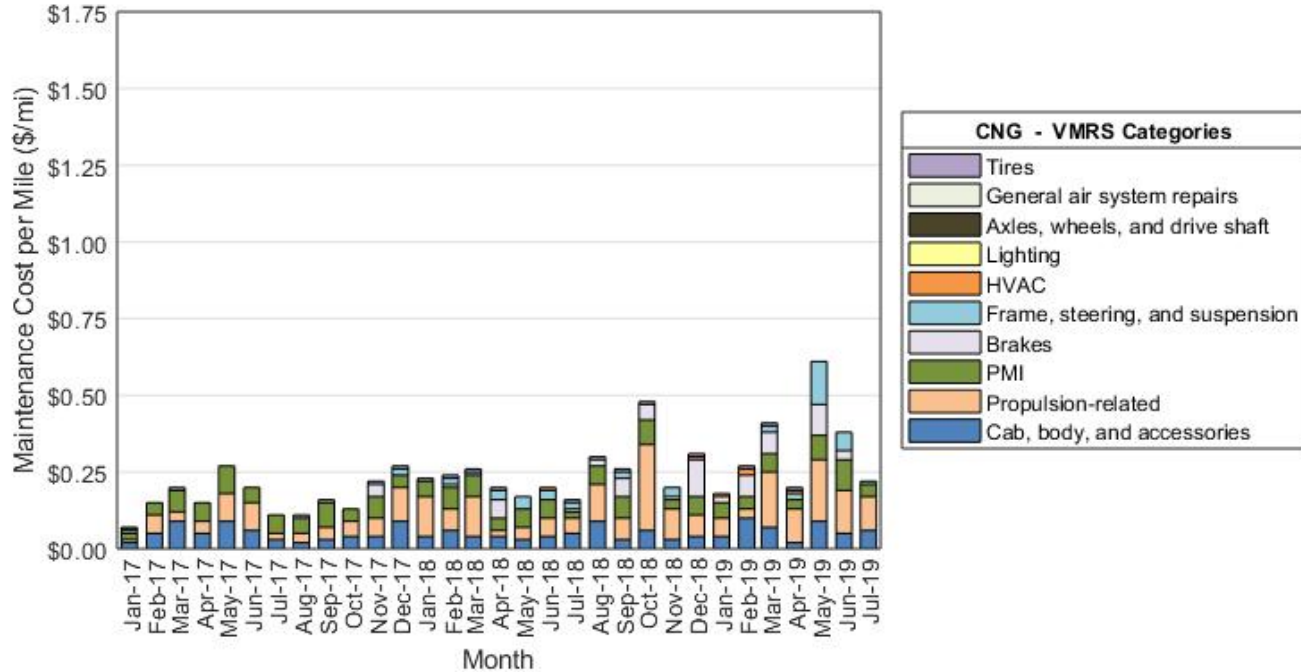
- For the FCEB and the CNG bus fleets, the systems with the highest cost were propulsion-related; PMI; and cab, body, and accessories.
- Overall costs for the FCEBs were 2.4 times that of the CNG buses. This is primarily driven by the higher cost of the older buses.

Maintenance Cost by System: FCEBs



- July 2017 costs were high due to two brake relines, suspension work (air bags), PMIs for two buses, and an issue with a farebox.
- September and October 2017 costs were high due to low mileage for the buses.
- The primary propulsion-related issues were labor for cooling system issues, low-voltage batteries, fuel cell balance of plant components, and energy storage system issues.

Maintenance Cost by System: CNG Buses



- Maintenance costs for the CNG buses were primarily parts and labor for scheduled PMIs and tune-ups.
- High costs in October 2018 were for a transmission replacement and a voltage regulator.
- May 2019 costs included issues with suspension, charging system, brake reline, and a windshield replacement.

Propulsion-Related Maintenance Costs by Subsystem

Maintenance System		FCEB	CNG	Maintenance System		FCEB	CNG
Mileage		268,778	813,575	Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)	Parts cost (\$)	10,768.07	9,862.33
Total Propulsion-Related Systems (Roll-Up of All Systems)	Parts cost (\$)	11,516.18	38,980.11		Labor hours	189.3	93.5
	Labor hours	1,256.8	548.8		Total cost (\$)	20,230.57	14,537.33
	Total cost (\$)	74,353.68	66,417.61		Total cost (\$) per mile	0.075	0.018
	Total cost (\$) per mile	0.277	0.082	Air Intake System Repairs	Parts cost (\$)	38.50	2,229.73
Exhaust System Repairs	Parts cost (\$)	0.00	1,033.72		Labor hours	0.0	1.5
	Labor hours	0.0	0.0		Total cost (\$)	38.50	2,304.73
	Total cost (\$)	0.00	1,033.72		Total cost (\$) per mile	0.000	0.003
	Total cost (\$) per mile	0.000	0.001	Cooling System Repairs	Parts cost (\$)	31.93	4,837.67
Fuel System Repairs	Parts cost (\$)	23.68	1,914.47		Labor hours	628.0	92.5
	Labor hours	12.3	3.3		Total cost (\$)	31,431.93	9,462.67
	Total cost (\$)	636.18	2,076.97		Total cost (\$) per mile	0.117	0.012
	Total cost (\$) per mile	0.002	0.003	Transmission System Repairs	Parts cost (\$)	0.00	4,468.32
Powerplant System Repairs (Fuel Cell System for FCEBs)	Parts cost (\$)	32.30	14,580.84		Labor hours	0.0	15.5
	Labor hours	272.5	342.5		Total cost (\$)	0.00	5,243.32
	Total cost (\$)	13,657.30	31,705.84		Total cost (\$) per mile	0.000	0.006
	Total cost (\$) per mile	0.051	0.039	Hydraulic System Repairs	Parts cost (\$)	0.00	53.03
Electric Propulsion System Repairs	Parts cost (\$)	621.70	0.00		Labor hours	0.0	0.0
	Labor hours	154.8	0.0		Total cost (\$)	0.00	53.03
	Total cost (\$)	8,359.20	0.00		Total cost (\$) per mile	0.000	0.000
	Total cost (\$) per mile	0.031	0.000				

Summary of Challenges and Lessons Learned

- SunLine acquired its AFCB fleet in several small orders. Each version was slightly different, which made it challenging for maintenance staff. Reliability has improved with each version.
- Fuel availability has been the biggest challenge—the original station was not capable of providing enough hydrogen for the larger fleet, so FCEBs were not able to fuel each day. The new station will alleviate that issue; however, the transition has taken longer than anticipated.
- Careful planning for building a hydrogen station should include potential delays. SunLine experienced early issues in contracting with partners. The agency also has had construction delays.
- Agencies should operate zero-emission buses like the rest of the fleet.
- Bus efficiency is highly variable based on operator driving style. SunLine is developing a driver training course for the most efficient operation.
- Zero-emission buses currently need more attention, SunLine has had issues keeping good technicians in a tight job market.
- Technical issues with the buses included problems with cooling pumps and air compressors. These were solved by working with the component suppliers to identify and correct the root cause or to change the component.
- Propulsion system issues included labor for cooling system issues (daily checks for fluid levels), low-voltage batteries, fuel cell balance of plant components, and energy storage system issues
- Successful deployments require support from all levels of an agency, beginning with upper management.

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Acronyms and Abbreviations

AFCB	American Fuel Cell Bus	kg	kilogram
CNG	compressed natural gas	kW	kilowatt
dge	diesel gallon equivalent	kWh	kilowatt-hour
DOE	U.S. Department of Energy	lb	pound
FC	fuel cell	MBRC	miles between roadcalls
FCEB	fuel cell electric bus	mi	mile
ft	feet	mpdge	miles per diesel gallon equivalent
FTA	Federal Transit Administration	mpgge	miles per gasoline gallon equivalent
gge	gasoline gallon equivalent	mph	miles per hour
GVWR	gross vehicle weight rating	NREL	National Renewable Energy Laboratory
hp	horsepower	PM	preventive maintenance
HVAC	heating, ventilation, and air conditioning	PMI	preventive maintenance inspection
in.	inch	psi	pounds per square inch

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Appendix: Fleet Summary Statistics

Fleet Summary Statistics

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Number of vehicles	8	8	5	5
Period used for fuel and oil analysis	7/14–7/19	1/17–7/19	3/12–12/16	1/17–7/19
Total number of months in period	61	31	58	31
Fuel and oil analysis base fleet mileage	462,619	255,188	1,362,268	806,575
Period used for maintenance analysis	7/14–7/19	1/17–7/19	3/12–12/16	1/17–7/19
Total number of months in period	61	31	58	31
Maintenance analysis base fleet mileage	483,731	268,778	1,369,822	813,575
Average monthly mileage per vehicle	2,307	1,791	5,235	5,249
Availability	77	73	87	87
Fleet fuel usage in kg hydrogen or gge CNG	84,780.1	46,364.0	473,649.9	234,345.9
Roadcalls	110	72	152	53
Total MBRC	4,398	3,733	9,012	15,350
Propulsion roadcalls	65	41	59	24
Propulsion MBRC	7,442	6,556	23,217	33,899
Fleet mi/kg hydrogen (1.13 kg hydrogen/gge CNG)	5.46	5.50	2.88	3.44
Representative fleet mpg (energy equiv.)	6.17	6.22	3.21	3.85
Fuel cost per kg hydrogen or gge CNG	7.49	7.25	0.95	0.96
Fuel cost per mile	1.37	1.32	0.33	0.28
Total scheduled repair cost per mile	0.09	0.11	0.09	0.09
Total unscheduled repair cost per mile	0.36	0.45	0.42	0.14
Total maintenance cost per mile	0.46	0.56	0.51	0.23
Total operating cost per mile	1.83	1.88	0.84	0.51

Maintenance Cost Summary

Maintenance Cost Summary

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Fleet mileage	483,731	268,778	1,369,822	813,575
Total parts cost	31,334.24	24,600.57	321,061.44	61,561.10
Total labor hours	3,793.1	2,515.6	7,668.5	2,539.3
Average labor cost (@ \$50.00 per hour)	189,652.50	125,777.50	383,422.50	126,966.50
Total maintenance cost	220,986.74	150,378.07	704,483.94	188,527.60
Total maintenance cost per bus	3,622.73	2,465.21	22,725.29	6,081.54
Total maintenance cost per mile	0.46	0.56	0.51	0.23

Propulsion System Maintenance Cost Summary

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	15,054.53	11,516.18	177,532.51	38,980.11
Labor hours	1,851.75	1,256.75	2,726.70	548.75
Average labor cost	92,587.50	62,837.50	136,335.00	27,437.50
Total cost (for system)	107,642.03	74,353.68	313,867.51	66,417.61
Total cost (for system) per bus	1,764.62	1,218.91	10,124.76	2,142.50
Total cost (for system) per mile	0.223	0.277	0.229	0.082

Maintenance Cost by Vehicle System

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Exhaust System Repairs (ATA VMRS 43)				
Parts cost	0.00	0.00	17,206.13	1,033.72
Labor hours	0.0	0.0	65.3	0.0
Average labor cost	0.00	0.00	3,262.50	0.00
Total cost (for system)	0.00	0.00	20,468.63	1,033.72
Total cost (for system) per bus	0.00	0.00	660.28	33.35
Total cost (for system) per mile	0.000	0.000	0.015	0.001
Fuel System Repairs (ATA VMRS 44)				
Parts cost	23.68	23.68	6,997.72	1,914.47
Labor hours	18.0	12.3	16.8	3.3
Average labor cost	900.00	612.50	837.50	162.50
Total cost (for system)	923.68	636.18	7,835.22	2,076.97
Total cost (for system) per bus	15.14	10.43	252.75	67.00
Total cost (for system) per mile	0.002	0.002	0.006	0.003
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts cost	84.92	32.30	88,883.82	14,580.84
Labor hours	530.0	272.5	2,044.8	342.5
Average labor cost	26,500.00	13,625.00	102,237.50	17,125.00
Total cost (for system)	26,584.92	13,657.30	191,121.32	31,705.84
Total cost (for system) per bus	435.82	223.89	6,165.20	1,022.77
Total cost (for system) per mile	0.055	0.051	0.140	0.039

Maintenance Cost by Vehicle System

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Electric Propulsion Repairs (ATA VMRS 46)				
Parts cost	636.70	621.70	0.00	0.00
Labor hours	222.5	154.8	0.0	0.0
Average labor cost	11,125.00	7,737.50	0.00	0.00
Total cost (for system)	11,761.70	8,359.20	0.00	0.00
Total cost (for system) per bus	192.81	137.04	0.00	0.00
Total cost (for system) per mile	0.024	0.031	0.000	0.000
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts cost	14,174.36	10,768.07	42,577.84	9,862.33
Labor hours	275.8	189.3	184.0	93.5
Average labor cost	13,787.50	9,462.50	9,200.00	4,675.00
Total cost (for system)	27,961.86	20,230.57	51,777.84	14,537.33
Total cost (for system) per bus	458.39	331.65	1,670.25	468.95
Total cost (for system) per mile	0.058	0.075	0.038	0.018
Air Intake System Repairs (ATA VMRS 41)				
Parts cost	50.16	38.50	5,013.21	2,229.73
Labor hours	4.0	0.0	1.0	1.5
Average labor cost	200.00	0.00	50.00	75.00
Total cost (for system)	250.16	38.50	5,063.21	2,304.73
Total cost (for system) per bus	4.10	0.63	163.33	74.35
Total cost (for system) per mile	0.001	0.000	0.004	0.003

Maintenance Cost by Vehicle System

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Cooling System Repairs (ATA VMRS 42)				
Parts cost	84.71	31.93	7,468.97	4,837.67
Labor hours	801.5	628.0	337.5	92.5
Average labor cost	40,075.00	31,400.00	16,872.50	4,625.00
Total cost (for system)	40,159.71	31,431.93	24,341.47	9,462.67
Total cost (for system) per bus	658.36	515.28	785.21	305.25
Total cost (for system) per mile	0.083	0.117	0.018	0.012
Hydraulic System Repairs (ATA VMRS 65)				
Parts cost	0.00	0.00	5,447.16	53.03
Labor hours	0.0	0.0	7.0	0.0
Average labor cost	0.00	0.00	350.00	0.00
Total cost (for system)	0.00	0.00	5,797.16	53.03
Total cost (for system) per bus	0.00	0.00	187.01	1.71
Total cost (for system) per mile	0.000	0.000	0.004	0.000
General Air System Repairs (ATA VMRS 10)				
Parts cost	441.86	222.45	3,655.53	49.31
Labor hours	58.8	10.0	274.0	2.8
Average labor cost	2,937.50	500.00	13,700.00	137.50
Total cost (for system)	3,379.36	722.45	17,355.53	186.81
Total cost (for system) per bus	55.40	11.84	559.86	6.03
Total cost (for system) per mile	0.007	0.003	0.013	0.000

Maintenance Cost by Vehicle System

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Brake System Repairs (ATA VMRS 13)				
Parts cost	2,938.09	2,888.52	28,391.86	7,128.61
Labor hours	71.8	70.3	190.0	192.0
Average labor cost	3,587.50	3,512.50	9,500.00	9,600.00
Total cost (for system)	6,525.59	6,401.02	37,891.86	16,728.61
Total cost (for system) per bus	106.98	104.93	1,222.32	539.63
Total cost (for system) per mile	0.013	0.024	0.028	0.021
Transmission Repairs (ATA VMRS 27)				
Parts cost	0.00	0.00	3,937.66	4,468.32
Labor hours	0.0	0.0	70.5	15.5
Average labor cost	0.00	0.00	3,525.00	775.00
Total cost (for system)	0.00	0.00	7,462.66	5,243.32
Total cost (for system) per bus	0.00	0.00	240.73	169.14
Total cost (for system) per mile	0.000	0.000	0.005	0.006
Inspections Only - No Parts Replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	904.8	600.8	1733.8	905.3
Average labor cost	45,237.50	30,037.50	86,687.50	45,262.50
Total cost (for system)	45,237.50	30,037.50	86,687.50	45,262.50
Total cost (for system) per bus	741.60	492.42	2,796.37	1,460.08
Total cost (for system) per mile	0.094	0.112	0.063	0.056

Maintenance Cost by Vehicle System

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	6,204.13	4,939.06	50,237.40	8,552.74
Labor hours	563.6	374.8	1,601.3	645.6
Average labor cost	28,177.50	18,740.00	80,062.50	32,279.00
Total cost (for system)	34,381.63	23,679.06	130,299.90	40,831.74
Total cost (for system) per bus	563.63	388.18	4,203.22	1,317.15
Total cost (for system) per mile	0.071	0.088	0.095	0.050
HVAC System Repairs (ATA VMRS 01)				
Parts cost	106.19	106.19	41,440.58	496.40
Labor hours	115.3	85.5	513.3	30.0
Average labor cost	5,762.50	4,275.00	25,662.50	1,500.00
Total cost (for system)	5,868.69	4,381.19	67,103.08	1,996.40
Total cost (for system) per bus	96.21	71.82	2,164.62	64.40
Total cost (for system) per mile	0.012	0.016	0.049	0.002
Lighting System Repairs (ATA VMRS 34)				
Parts cost	1,371.09	862.58	3,445.12	163.42
Labor hours	19.0	9.8	174.5	8.5
Average labor cost	950.00	487.50	8,725.00	425.00
Total cost (for system)	2,321.09	1,350.08	12,170.12	588.42
Total cost (for system) per bus	38.05	22.13	392.58	18.98
Total cost (for system) per mile	0.005	0.005	0.009	0.001

Maintenance Cost by Vehicle System

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	5,190.78	4,038.02	9,277.95	6,178.41
Labor hours	148.3	72.3	158.3	111.3
Average labor cost	7,412.50	3,612.50	7,912.50	5,562.50
Total cost (for system)	12,603.28	7,650.52	17,190.45	11,740.91
Total cost (for system) per bus	206.61	125.42	554.53	378.74
Total cost (for system) per mile	0.026	0.028	0.013	0.014
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	12.13	12.13	7,052.54	12.10
Labor hours	1.0	1.0	70.0	2.5
Average labor cost	50.00	50.00	3,500.00	125.00
Total cost (for system)	62.13	62.13	10,552.54	137.10
Total cost (for system) per bus	1.02	1.02	340.40	4.42
Total cost (for system) per mile	0.000	0.000	0.008	0.000
Tire Repairs (ATA VMRS 17)				
Parts cost	15.44	15.44	27.95	0.00
Labor hours	59.0	34.5	226.8	92.8
Average labor cost	2,950.00	1,725.00	11,337.50	4,637.50
Total cost (for system)	2,965.44	1,740.44	11,365.45	4,637.50
Total cost (for system) per bus	48.61	28.53	366.63	149.60
Total cost (for system) per mile	0.006	0.006	0.008	0.006

Fleet Summary Statistics: SI Units

	FCEB Total	FCEB Data Period	MY 2008 CNG Total	MY 2016 CNG Data Period
Number of vehicles	8	8	5	5
Period used for fuel and oil analysis	7/14–7/19	1/17–7/19	3/12–12/16	1/17–7/19
Total number of months in period	61	31	58	31
Fuel and oil analysis base fleet mileage	744,493	410,674	2,192,298	1,298,021
Period used for maintenance analysis	7/14–7/19	1/17–7/19	3/12–12/16	1/17–7/19
Total number of months in period	61	31	58	31
Maintenance analysis base fleet kilometers	778,468	432,544	2,204,455	1,309,286
Average monthly kilometers per vehicle	3,713	2,882	8,425	8,447
Availability	77	73	87	87
Fleet fuel usage in H2 kg/CNG liter equiv.	84,780.1	46,364.0	1,792,959.9	887,095.7
Roadcalls	110	72	152	53
Total KMBRC	7,077	6,008	14,503	24,704
Propulsion roadcalls	65	41	59	24
Propulsion KMBRC	11,976	10,550	37,364	54,554
Fleet kg hydrogen/100 km (1.13 kg H2/gal diesel fuel)	11.39	11.29		
Rep. fleet fuel consumption (L/100 km)	38.14	37.82	73.20	61.17
Hydrogen cost per kg/ GGE cost per liter	7.49	7.25	0.25	0.25
Fuel cost per kilometer	0.85	0.82	0.21	0.17
Total scheduled repair cost per kilometer	0.06	0.07	0.06	0.06
Total unscheduled repair cost per kilometer	0.23	0.28	0.26	0.09
Total maintenance cost per kilometer	0.28	0.35	0.32	0.14
Total operating cost per kilometer	1.14	1.17	0.52	0.32

Maintenance Cost Summary: SI Units

Maintenance Cost Summary

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Fleet mileage	778,468	432,544	2,204,455	1,309,286
Total parts cost	31,334.24	24,600.57	321,061.44	61,561.10
Total labor hours	3,793.1	2,515.6	7,668.5	2,539.3
Average labor cost (@ \$50.00 per hour)	189,652.50	125,777.50	383,422.50	126,966.50
Total maintenance cost	220,986.74	150,378.07	704,483.94	188,527.60
Total maintenance cost per bus	27,623.34	18,797.26	88,060.49	37,705.52
Total maintenance cost per kilometer	0.28	0.35	0.32	0.14

Propulsion System Maintenance Cost Summary

	FCEB Total	FCEB Data Period	MY2008 CNG Total	MY2016 CNG Data Period
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	15,054.53	11,516.18	177,532.51	38,980.11
Labor hours	1,851.75	1,256.75	2,726.70	548.75
Average labor cost	92,587.50	62,837.50	136,335.00	27,437.50
Total cost (for system)	107,642.03	74,353.68	313,867.51	66,417.61
Total cost (for system) per bus	13,455.25	9,294.21	62,773.50	13,283.52
Total cost (for system) per kilometer	0.138	0.172	0.142	0.051

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