NREL
NATIONAL RENEWABLE ENERGY LABORATORY





Battery Electric Bus Evaluation Results

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2017 APTA Bus and Paratransit Conference, Reno, NV

May 8, 2017

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL Snapshot

Dedicated Solely to Advancing Energy Efficiency and Renewable Energy

- Leading clean-energy innovation for more than 37 years
- ~1,760 employees with world-class facilities
- Campus is a living model of sustainable energy
- Economic impact at $872M nationwide
- Owned by the Department of Energy and Operated by the Alliance for Sustainable Energy

NREL Role in ZEB Evaluation

- 3rd Party evaluation of advanced technology in real-world service
- Established evaluation protocol provides consistent data collection and analysis for comparison
- Provide feedback to government (federal, state, local) to understand status and continue funding necessary R&D
- Share information with the transit industry that will aid in purchase decisions on the technology
  - Unbiased data in common format
  - Comparison to baseline technology

Evaluation Objectives and DOE/FTA Targets

- Validate zero emission buses[1] (ZEB) performance and cost compared to DOE/DOT targets and conventional technologies
- Document progress and "lessons learned" on implementing ZEBs in transit operations to address barriers to market acceptance

Current Targets[2]	Units	2016 Target	Ultimate Target
Bus lifetime	Years/miles	12/500,000	12/500,000
Powerplant lifetime	Hours	18,000	25,000
Bus availability	%	85	90
Roadcall frequency (bus/fuel cell system)	Miles between roadcall	3,500/15,000	4,000/20,000
Operation time	Hours per day/ days per week	20/7	20/7
Maintenance cost	$/mile	0.75	0.40
Fuel economy	Miles per diesel gallon equivalent	8	8

[1] ZEBs can be battery electric buses (BEB) or fuel cell electric buses (FCEB)

[2] Fuel Cell Technologies Program Record # 12012, Sep 2012, www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf

Current Status of BEBs

	Fleet Minimum	Fleet Maximum	Fleet Average
Bus lifetime (years)	0.8	2.9	2.3
Bus lifetime (miles)	17,960	85,274	64,045
Bus availability (%)	74	97	88
Charges (number per day)	1	31	8
Roadcall frequency – bus (MBRC)			5,656
Roadcall frequency – propulsion system			15,023
Roadcall frequency – energy storage system			320,496
Operation time per day (hours)	<1	22.4	9
Scheduled and unscheduled maintenance cost ($/mile)[1]	0.13	0.29	0.19
Fuel economy (miles per DGE)	16.09	18.72	17.29

Data from 2 fleets – 15 total buses

[1] Buses are currently under warranty – all advanced technology maintenance is handled by OEM

Foothill Transit, West Covina, California

BEBs service Start: April 2014

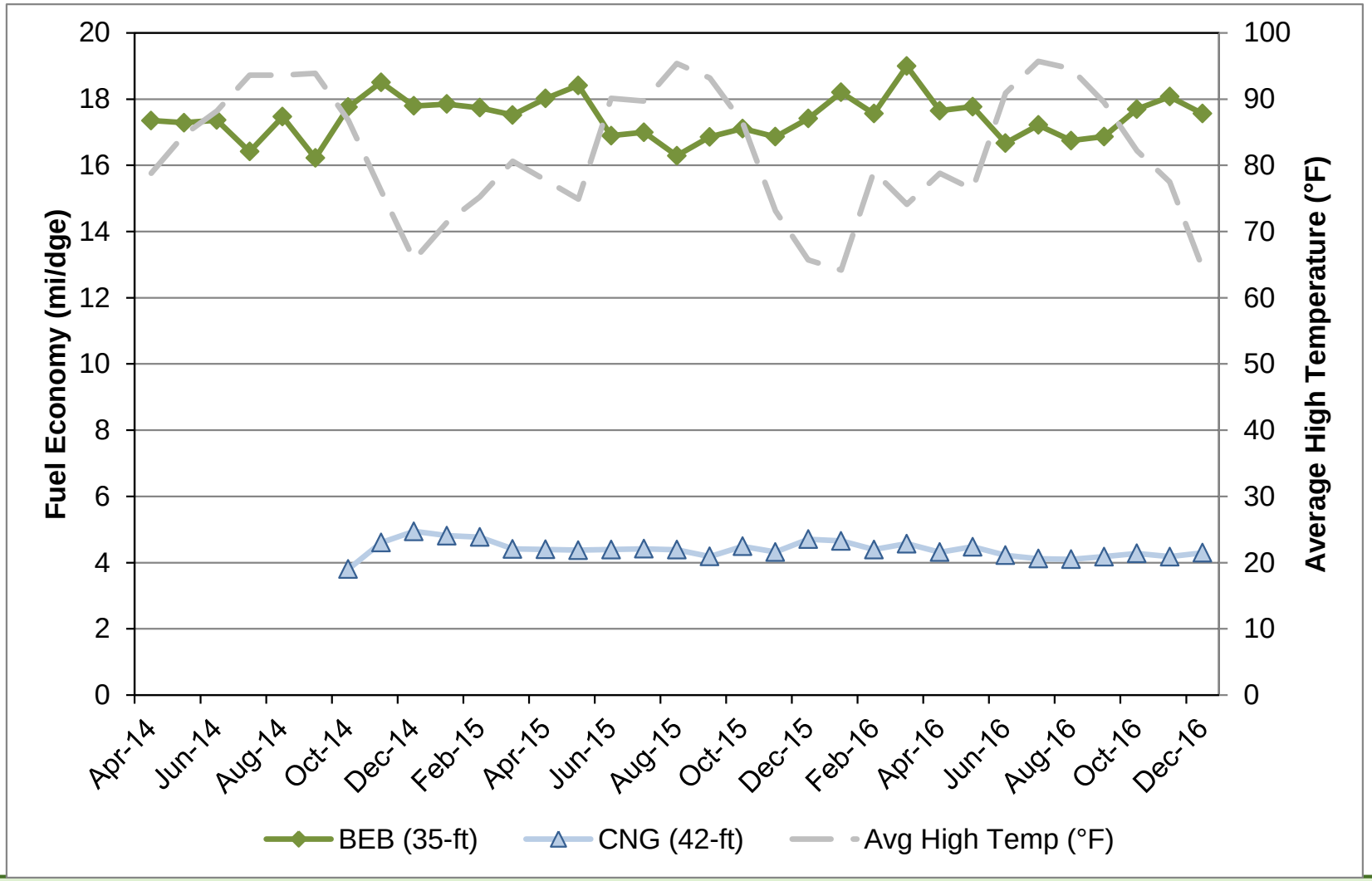
Baseline comparison:

NABI CNG, 42-ft

Foothill Transit BEB Specifications

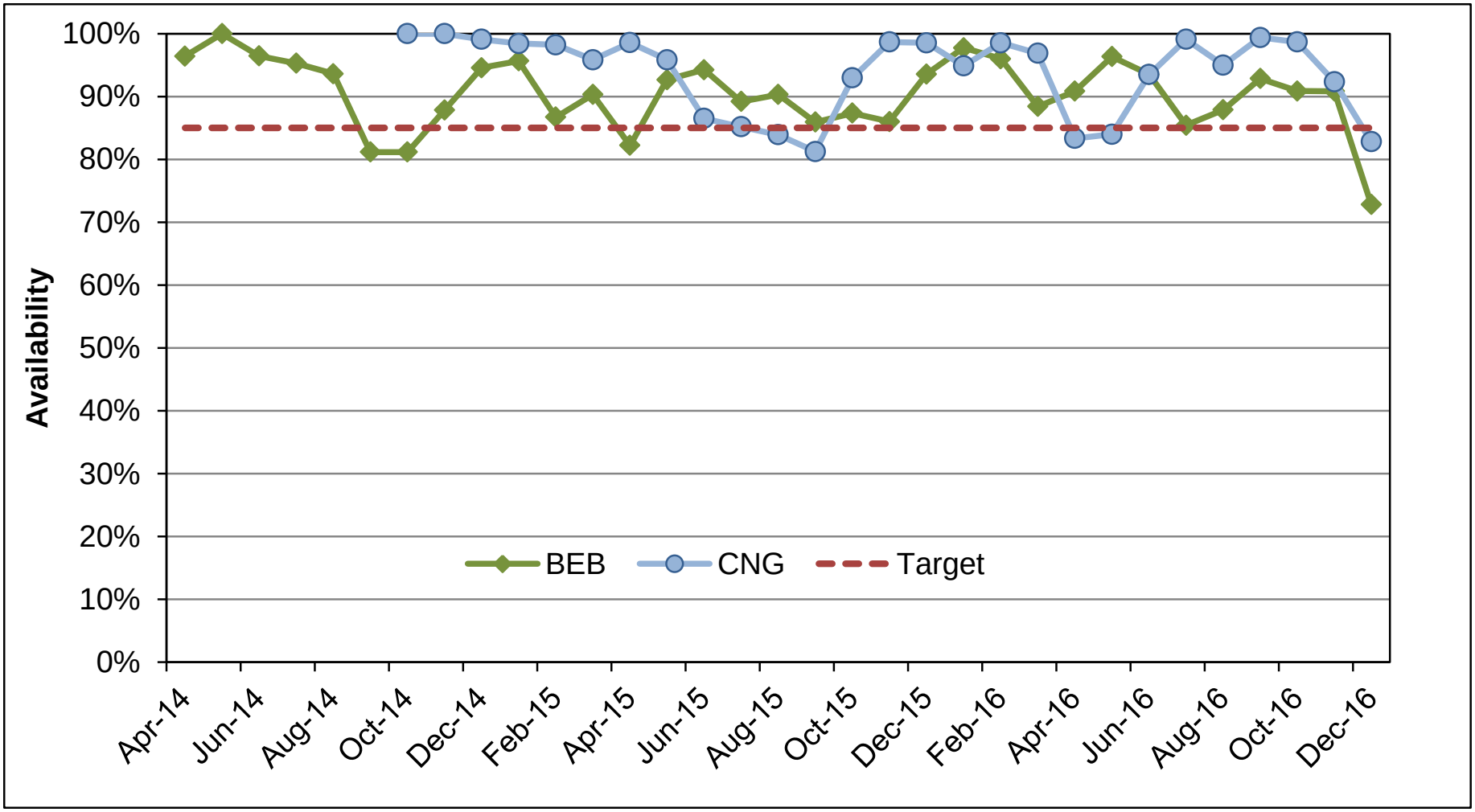
FCEB Identifier	BEB
Number of Buses	12
Bus OEM	Proterra
Bus length/height	35 ft / 126 in
Charging strategy	Fast-charge, on-route
Motor	Permanent magnet, UQM, PP220
Rated Power (kW)	220 (peak)
Energy Storage - OEM	Lithium-titanate
Capacity	368 volts, 88 kWh

Foothill Transit BEB Efficiency



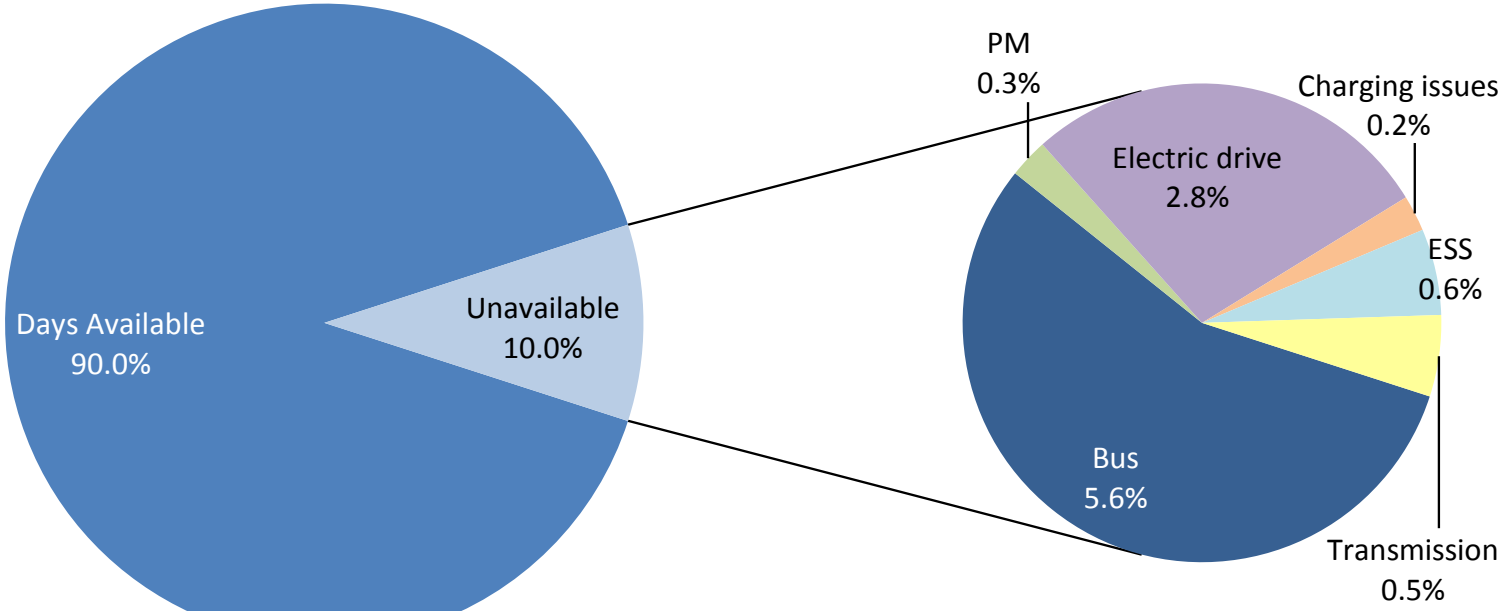
BEB equivalent fuel economy 4x higher than CNG buses. High cost of electricity results in higher cost per mile.

Foothill Transit BEB Availability by Month



Availability generally over the target. Overall availability for data period is 90%

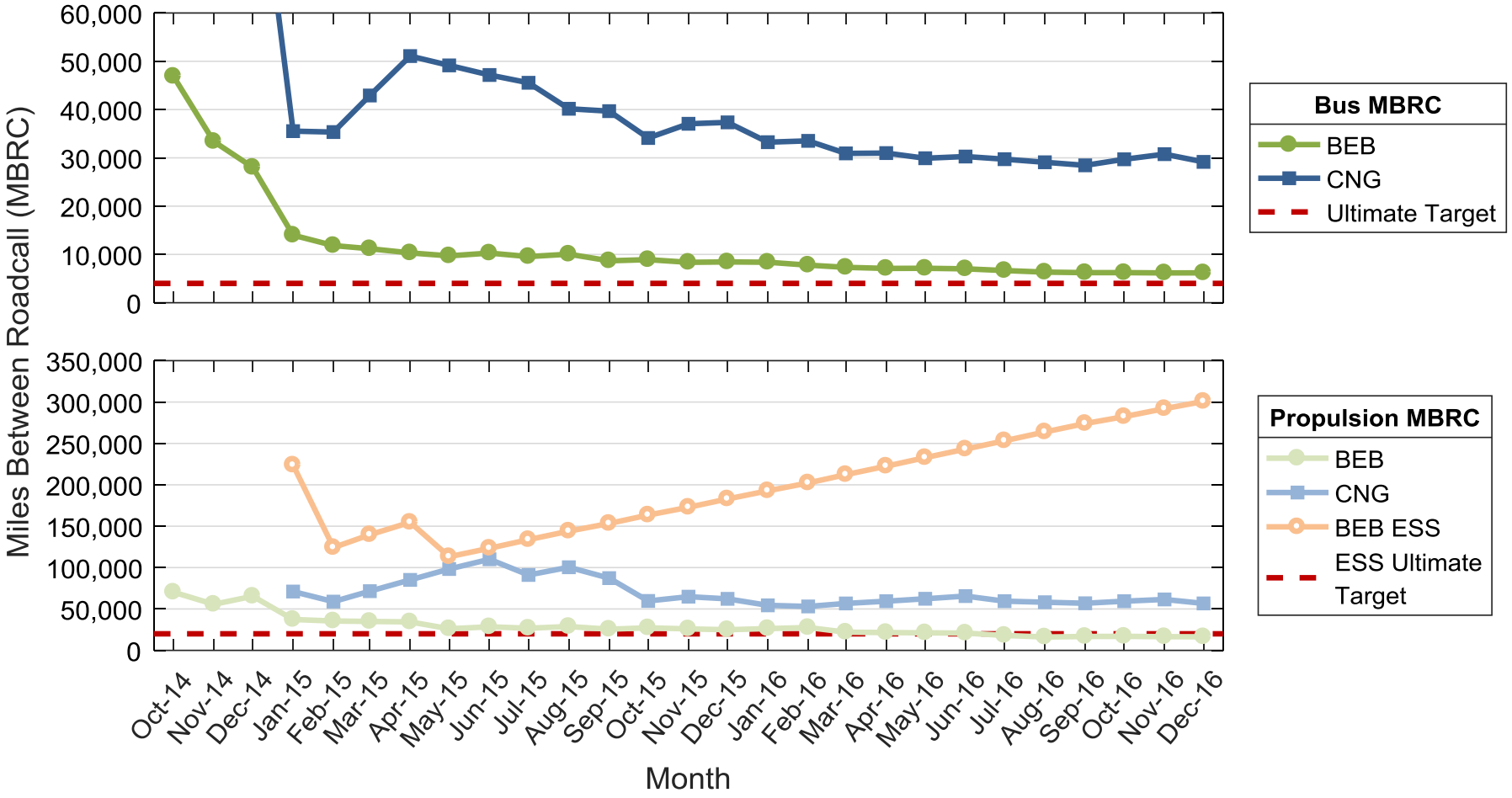
Foothill Transit BEB Availability - Overall



BEB Fleet	Number	%
Available	8,550	90
Bus	527	5.6
PM	25	0.3
Electric Drive	263	2.8
Charging issues	23	0.2
ESS	55	0.6
Transmission	52	0.5
Total days	9,495	100

Bus issues are the primary reasons for unavailability, followed by electric drive

Foothill Transit BEB Reliability



Early results show the BEB performance exceeds the ultimate targets.

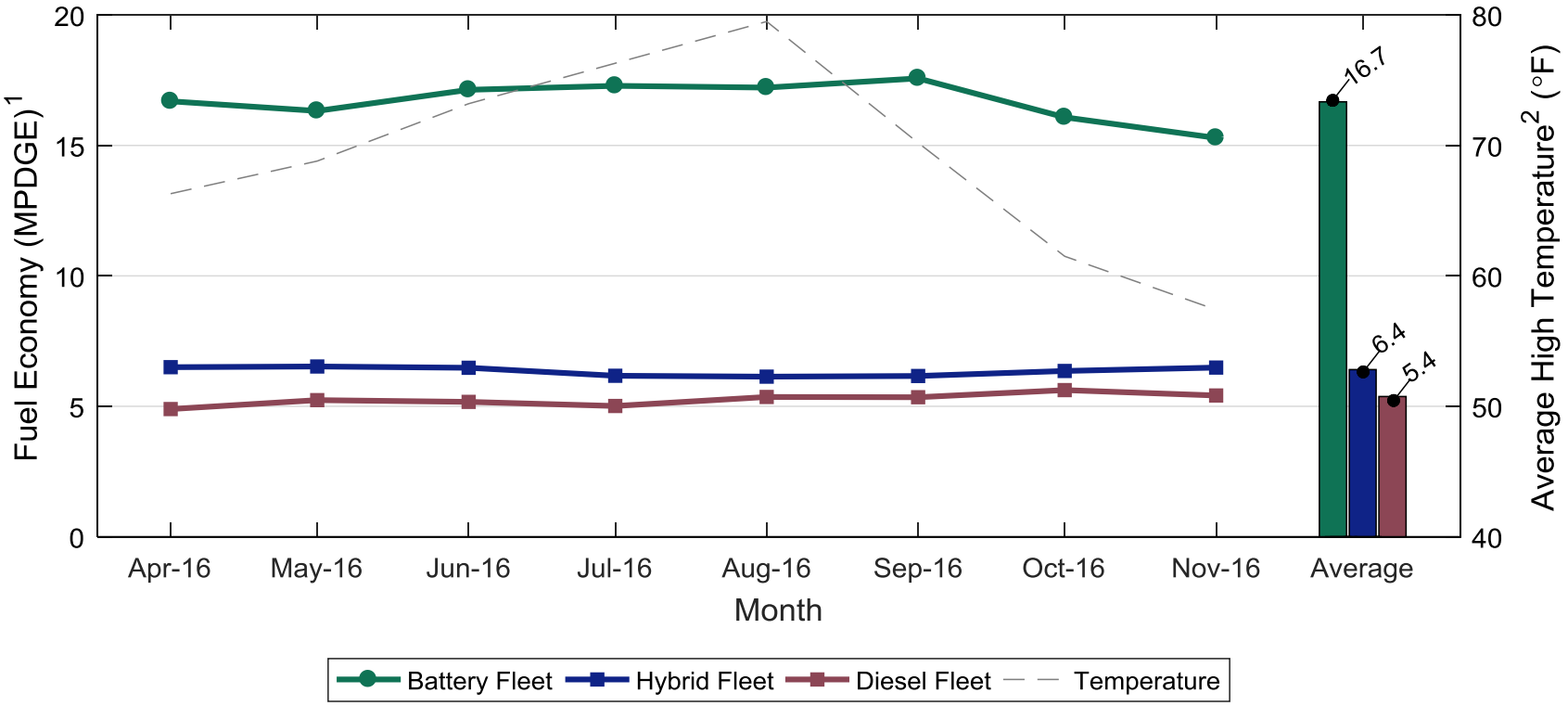
King County Metro, Seattle, WA (TIGGER)

- BEB in service date: April 2016
- 3 Proterra, 40-ft Catalyst buses and fast charging station (8 more on order)
- Baseline buses: diesel, diesel hybrid, and electric trolley buses

KC Metro BEB Specifications

FCEB Identifier	BEB
Number of Buses	3
Bus OEM	Proterra
Bus length/height	40 ft / 126 in
Charging strategy	Fast-charge, on-route
Motor	Permanent magnet, UQM, PP220
Rated Power (kW)	220 (peak)
Energy Storage	Lithium-titanate
Capacity	331 volts, 106 kWh

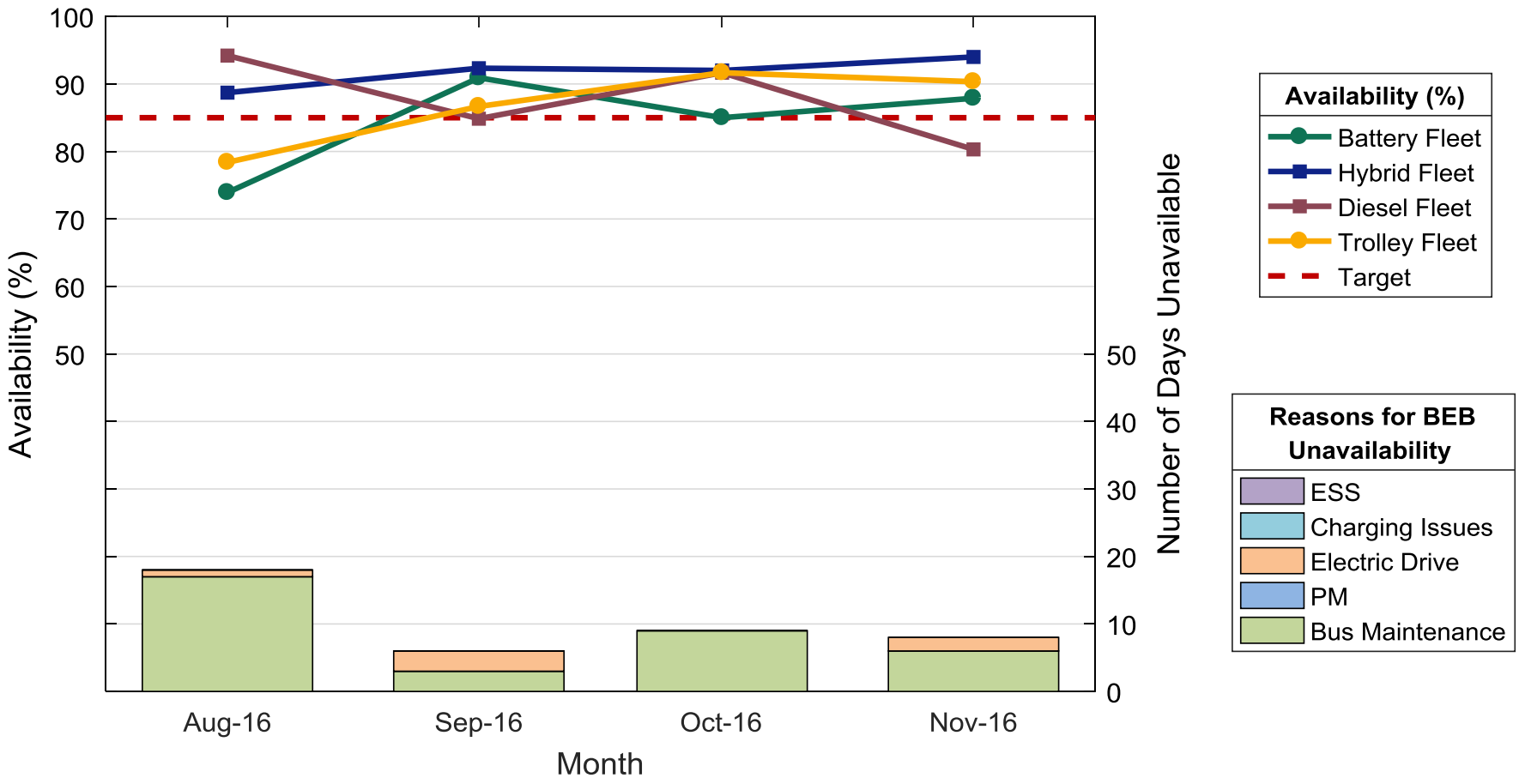
KC Metro BEB Efficiency



1. BEB electrical energy converted to diesel gallon equivalent (DGE); conversion factor = 37.7 kWh/diesel gallon, based on the energy content of electricity (3,412 Btu) and diesel fuel LHV (128,488 Btu).
2. Renton Municipal Airport average daily high temperatures; data acquired from: *https://www.ncdc.noaa.gov/*

BEB equivalent fuel economy 3x higher than diesel buses and 2.6x higher than diesel hybrid buses. High cost of electricity results in higher cost per mile.

KC Metro Availability by Month

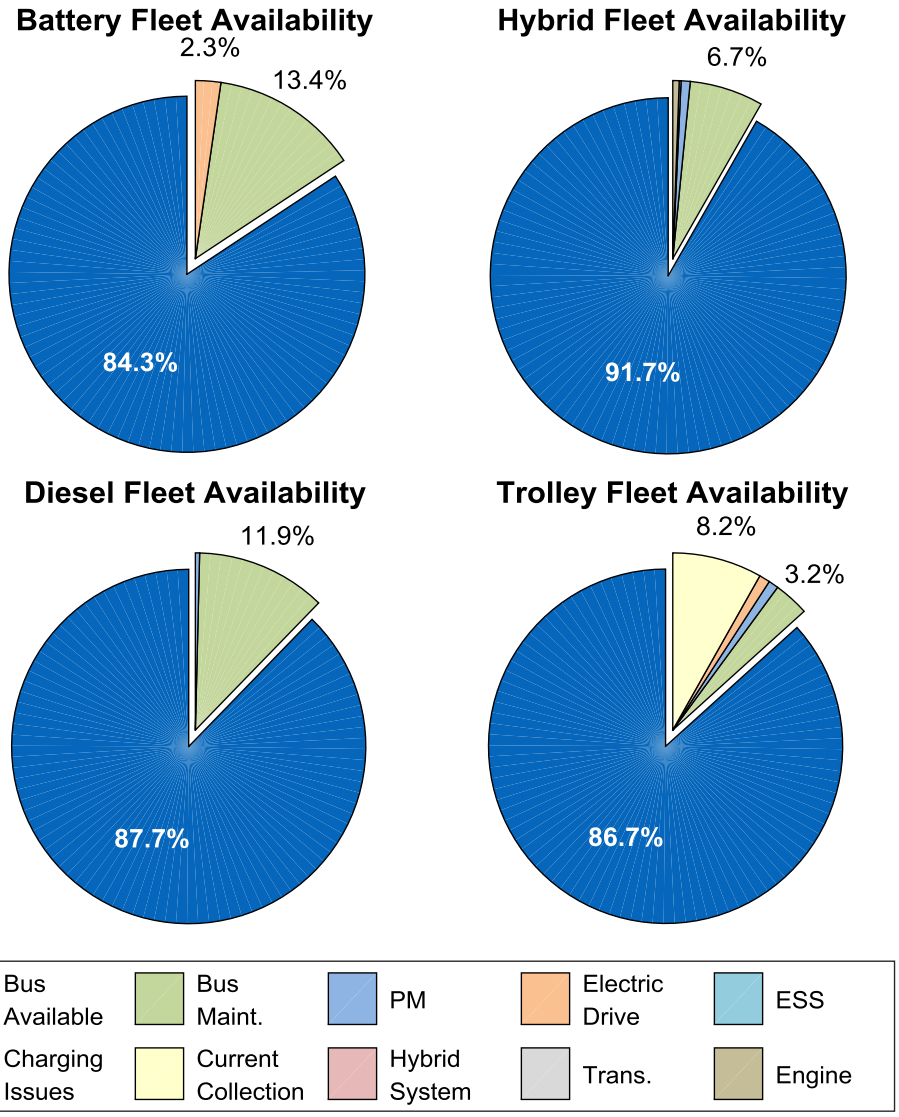


Overall availability for data period:

BEB 84% Diesel hybrids 92%

Diesel 88% Trolley 87%

KC Metro Availability - Overall



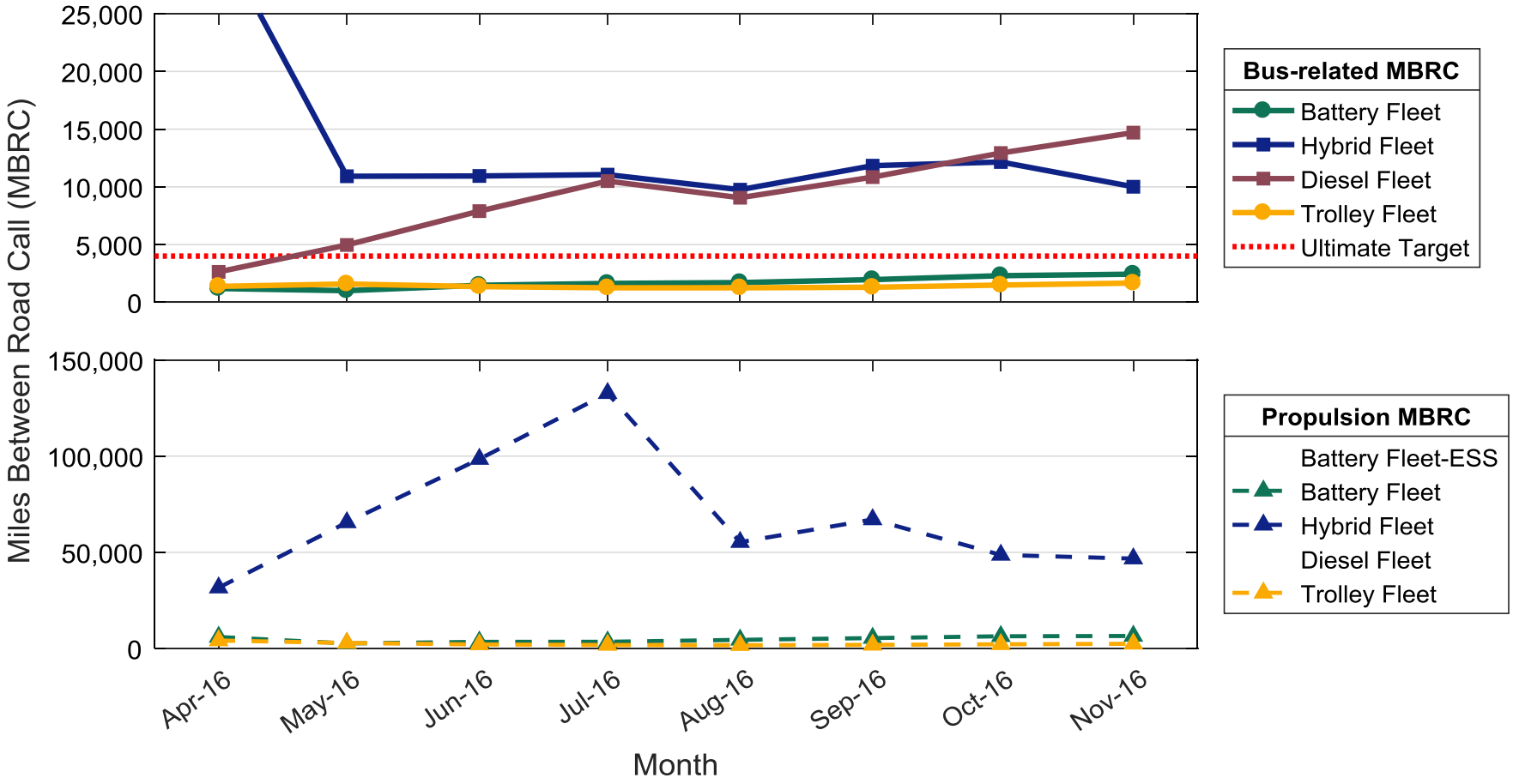
Primary reasons for unavailability

BEB: Bus related issues, followed by electric drive

Hybrid and diesel buses: Bus related issues

Trolley buses: current collection, followed by bus related issues

KC Metro Reliability



BEB bus-related MBRC increasing. To date, no ESS related roadcalls have occurred.

Remaining Challenges and Barriers for ZEBs

Specific to BEBs

- Plan/build of opportunity charging stations & garage chargers
- Select appropriate routes for technology – fast-charge, in-depot charging
- Address challenge of electric rates and demand charges
- Scale up for larger fleets – how best to accommodate plug in charging/ parking
- Training transition for maintenance staff
- Develop supply chain for parts

Web site:

http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html

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Fuel Cell Buses in Public Transit

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Evaluation Objectives and DOE/FTA Targets

- Validate fuel cell electric bus (FCEB) performance and cost compared to DOE/DOT targets and conventional technologies
- Document progress and "lessons learned" on implementing fuel cell systems in transit operations to address barriers to market acceptance

Current Targets*	Units	2016 Target	Ultimate Target
Bus lifetime	Years/miles	12/500,000	12/500,000
Powerplant lifetime	Hours	18,000	25,000
Bus availability	%	85	90
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* Fuel Cell Technologies Program Record # 12012, Sep 2012, www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf

Specifications for FCEBs included in data summary

FCEB Identifier	ACT ZEBA	SL AFCB	UCI AFCB
Transit agency	AC Transit	SunLine	UCI
Location	Oakland, CA	Thousand Palms, CA	Irvine, CA
Number of buses	13	4	1
Bus OEM	Van Hool	ElDorado National	
Bus length/height	40 ft / 136 in.	40 ft / 140 in.	
Fuel cell OEM	UTC Power	Ballard	
Model	PureMotion 120	Fcvelocity–HD6	
Power (kW)	120	150	
Hybrid system	Siemens ELFA, Van Hool integration	BAE Systems HybriDrive	
Design strategy	Fuel cell dominant	Fuel cell dominant	
Energy storage – OEM	EnerDel	A123	
Type	Li-ion	Nanophosphate Li-ion	
Capacity	17.4 kWh	11 kWh	
Number of cylinders	8	8	
Capacity (kg)/pressure (bar)	40 / 350	50 / 350	
Technology readiness level	7	7	

OEM = original equipment manufacturer
ACT ZEBA = AC Transit Zero Emission Bay Area
SL AFCB = SunLine American Fuel Cell Bus
UCI = University of California at Irvine

ACT ZEBA

SL AFCB

UCI AFCB

Current Status of FCEBs

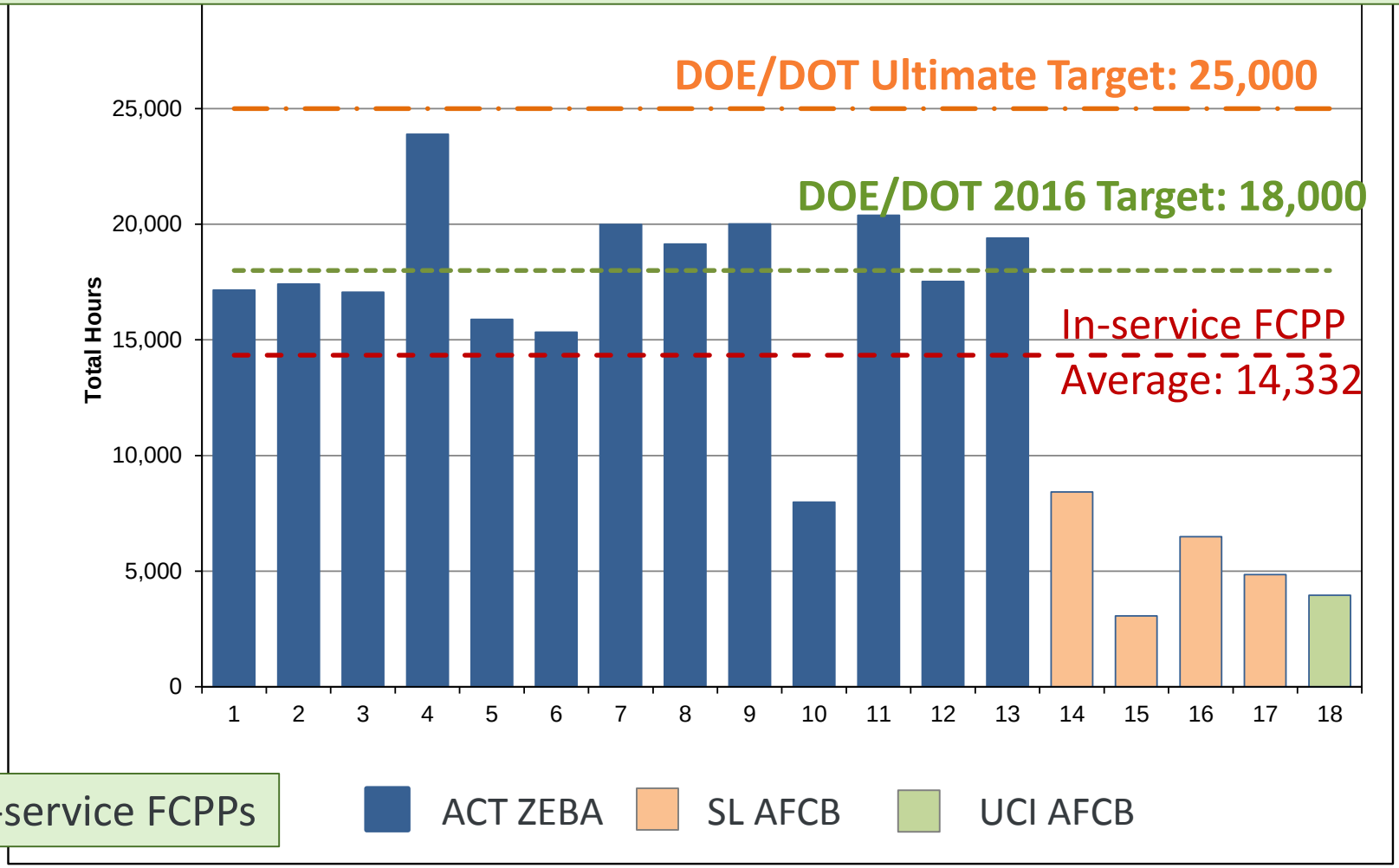
	Fleet Minimum	Fleet Maximum	Fleet Average
Bus lifetime (years)	1.3	6.4	4.7
Bus lifetime (miles)	32,485	167,352	118,989
Power plant lifetime (hours)	3,589	23,423	13,801
Bus availability (%)	44	93	76
Fuel fills (number per day)	1	1	1
Roadcall frequency – bus (MBRC)			4,710
Roadcall frequency – propulsion			8,146
Roadcall frequency – fuel cell system			20,705
Operation time (average hours per day)	7.4	13.7	11.8
Scheduled and unscheduled maintenance cost ($/mile)[1]	0.46	1.61	1.03
Range (miles)	215	274	247
Fuel economy (miles per DGE)	5.66	7.22	6.51

Data Summary from 3 fleets – 18 total buses.

[1] Buses from two fleets are still under warranty, although most of the maintenance is handled by transit staff

FC Powerplant Life

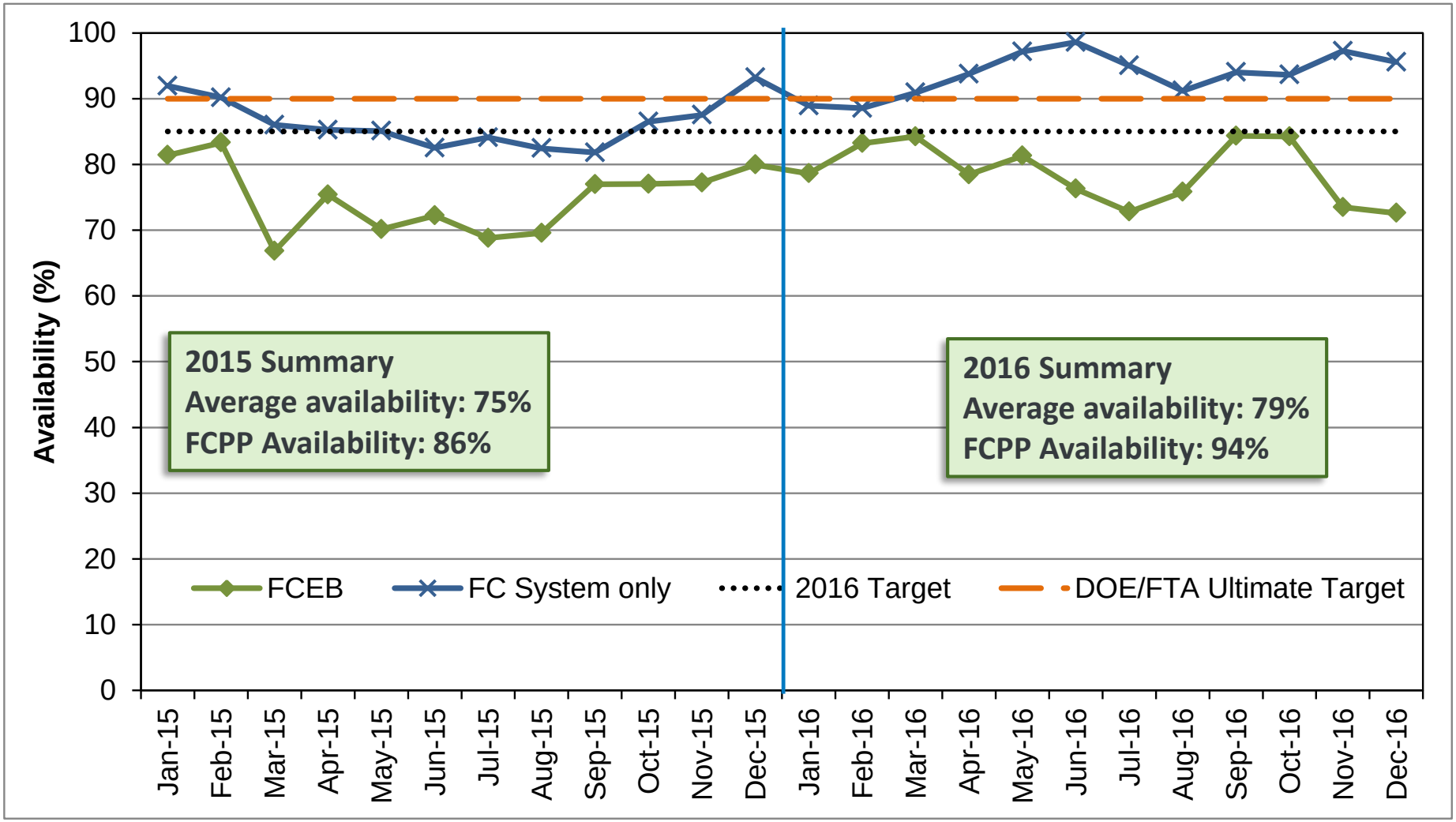
Top fuel cell powerplant (FCPP) >23,800 hours, surpassing DOE/DOT 2016 target; 67% of FCPPs (12) more than 15,000 hours



Total hours accumulated on each FCPP as of 2/28/17

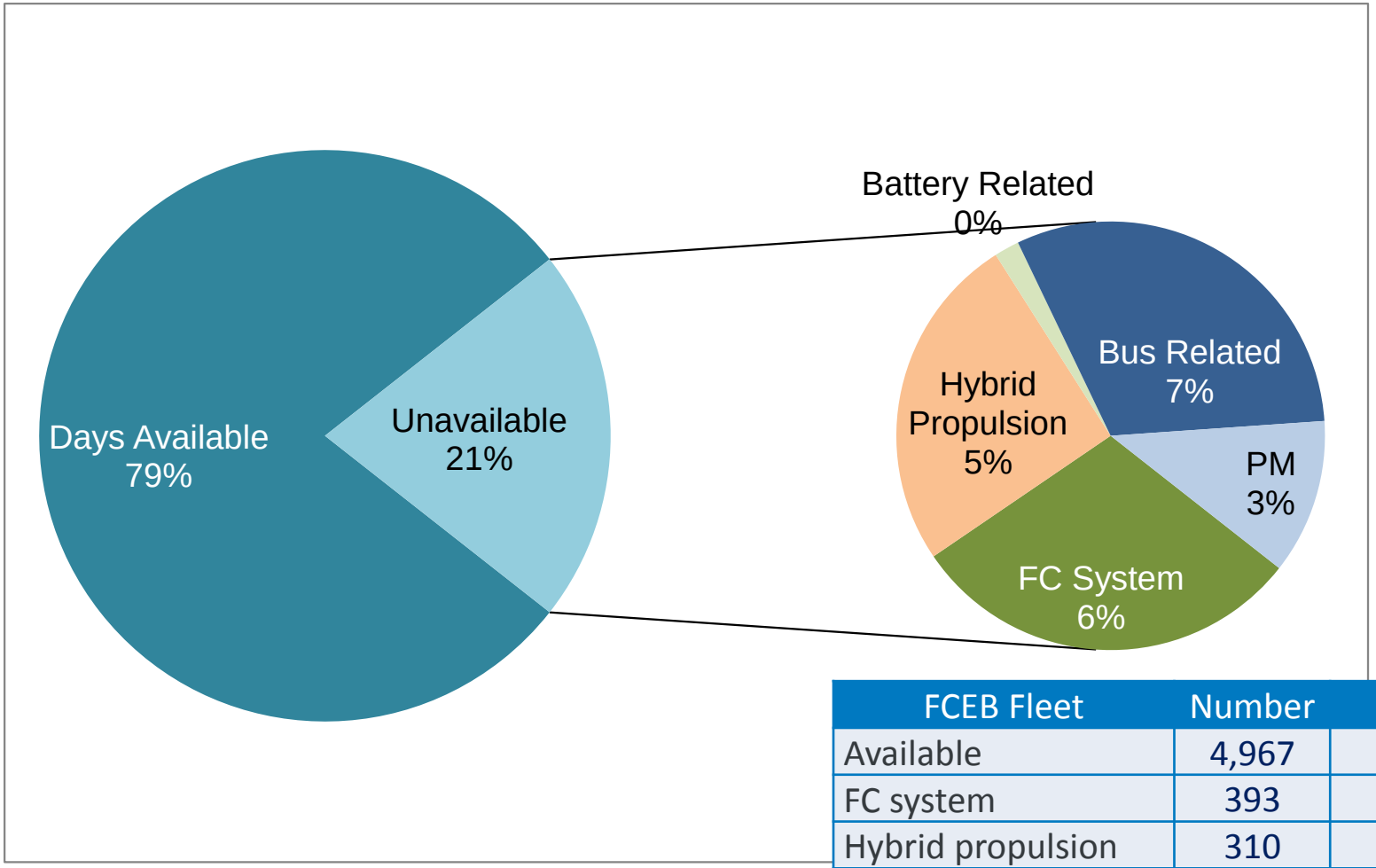
Availability

Monthly bus availability



Availability = planned operation days compared to actual operation days

Availability Summary: 2016 Data

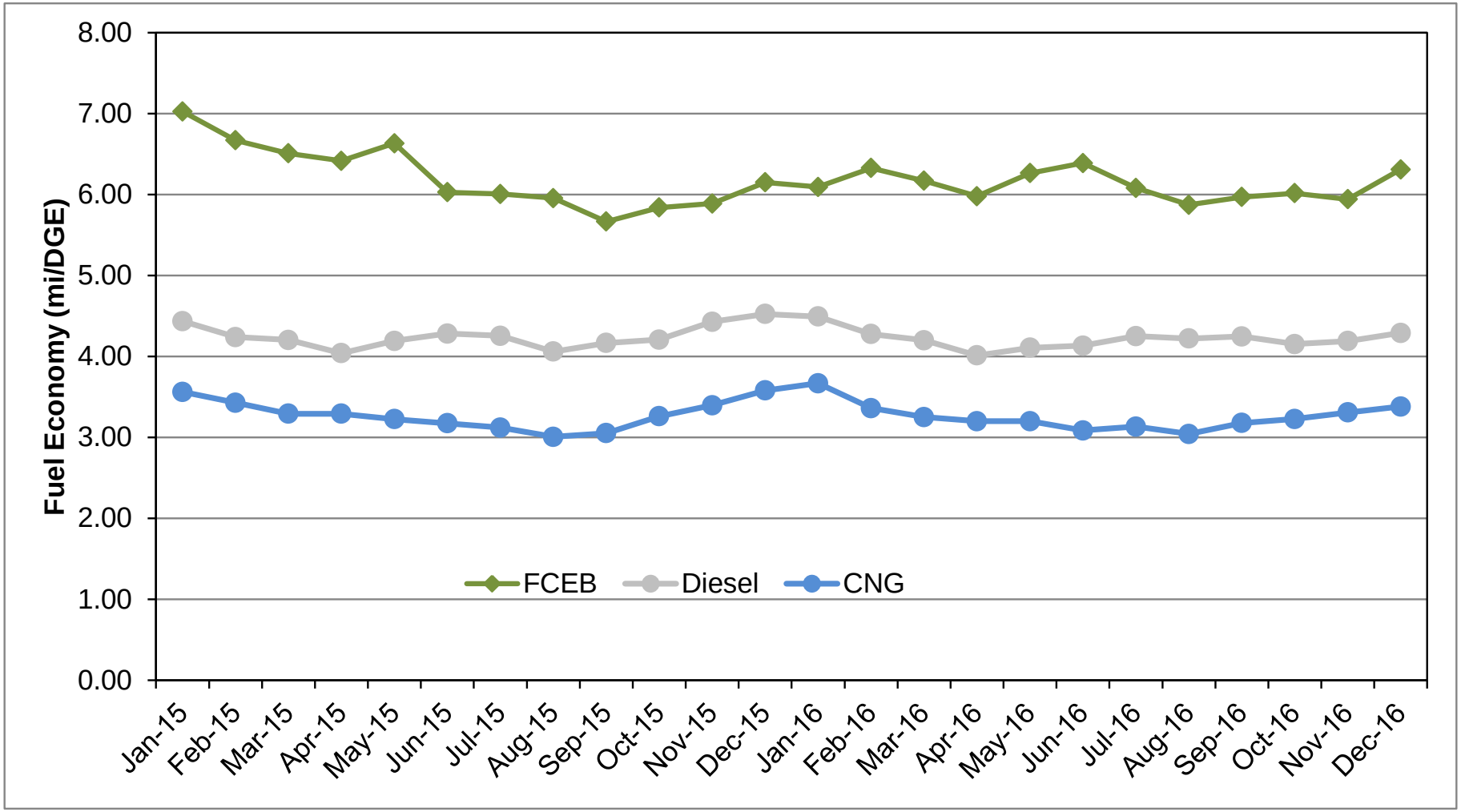


FCEB Fleet	Number	%
Available	4,967	79
FC system	393	6
Hybrid propulsion	310	5
Traction batteries	25	<1
Bus maintenance	411	7
PM	157	3
Total days	6,263	100

FC = fuel cell
PM = preventive maintenance

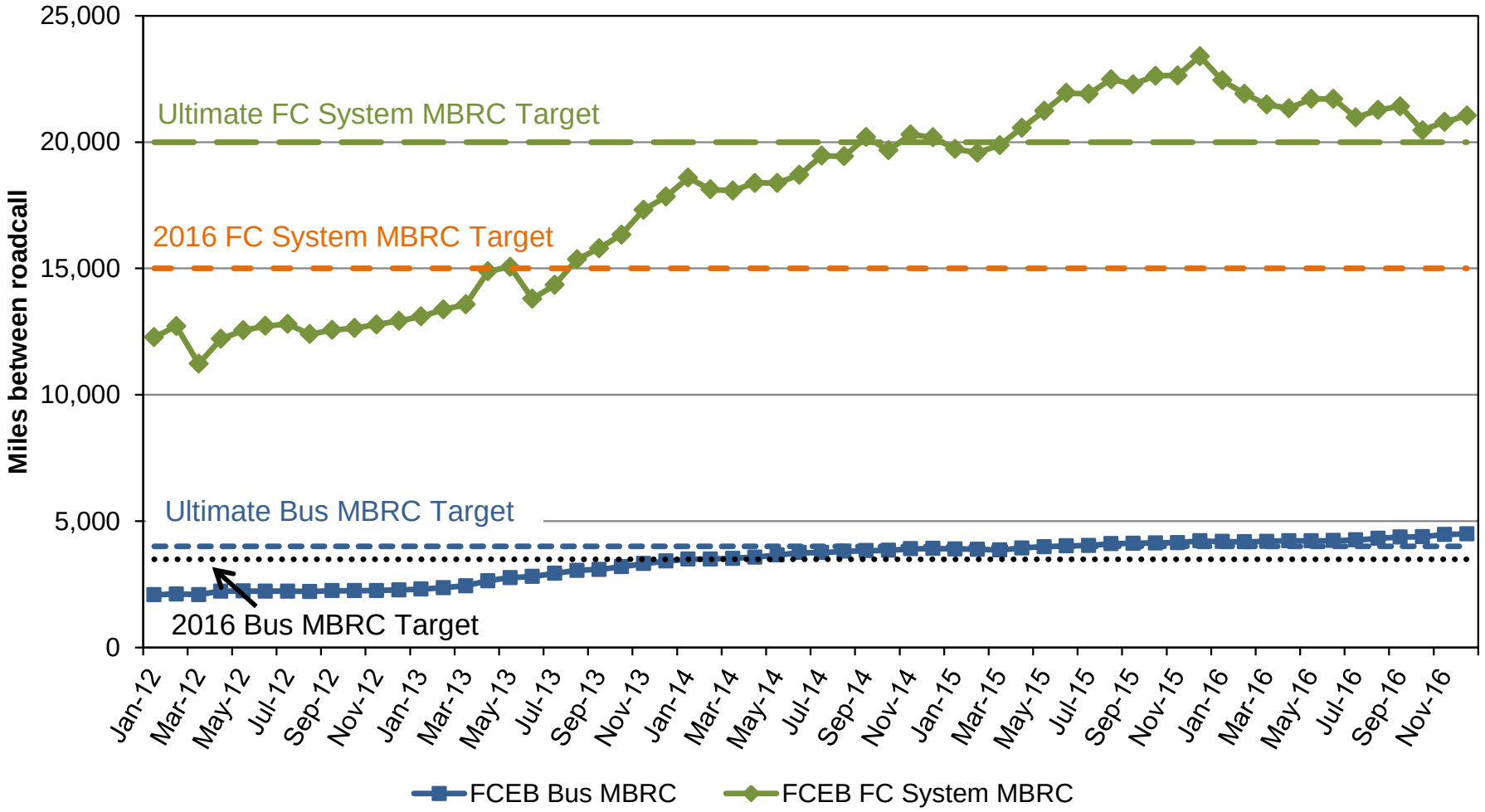
Monthly Fuel Economy Compared to Baseline

mpDGE = miles per diesel gallon equivalent



Drop in fuel economy over time could be due to several factors: degradation of fuel cells, changes in routes used, changes in hybrid system calibration

FCEB Reliability



- FCEB reliability **surpassed ultimate targets in 2015**
- Maintenance staff becoming more familiar with system, applying new tools to anticipate and fix issues before they fail in service

FCEB Fueling

Fueling Experience

- Dispenser can be located in the fueling aisle with other services
- Average fueling time: 18 minutes
- Average fill amount: 20 kilograms

Remaining Challenges and Barriers for FCEBs

Specific to FCEBs

- Increase durability and reliability of components
- Continue transition of build process to OEM
- Addition of fueling infrastructure
- Develop robust supply chain for components and parts to lower cost and downtime
  - Multiple component suppliers to stabilize supply
  - Standardized with conventional bus components to lower cost
- Establish support centers for advanced technology components
- Increase learning curve for maintenance staff
  - Develop training specific to FCEBs and incorporate in traditional classes
  - Provide tools to agencies for monitoring and troubleshooting issues
- Reduce cost, both capital and operating

Web site:

http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html

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