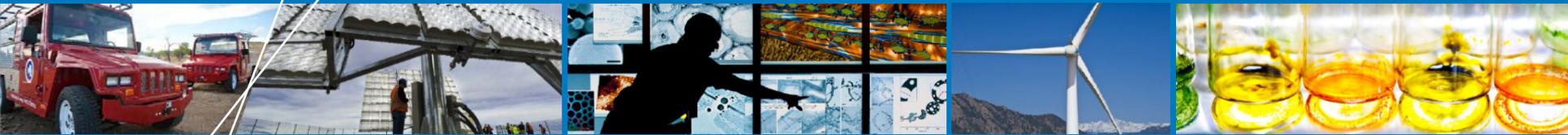


U.S. Zero Emission Bus Evaluation Results & Status



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National Renewable Energy Laboratory
Feb 8, 2016

ZEB Evaluation Objectives

- Validate zero-emission bus¹ (ZEB) performance and cost compared to DOE/FTA targets and conventional technologies
- Document progress and “lessons learned” on implementing fuel cell systems in transit operations to address barriers to market acceptance

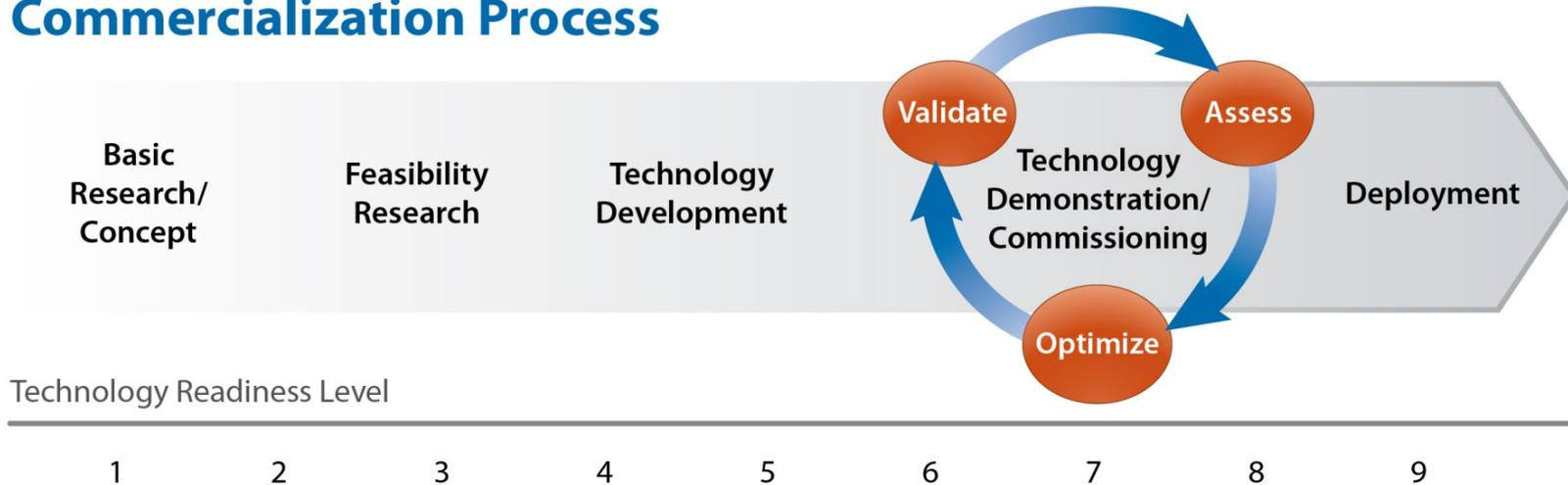
Current FCEB Targets ²	Units	2016 Target	Ultimate Target
Bus lifetime	Years / miles	12/500,000	12/500,000
Powerplant lifetime	Hours	18,000	25,000
Bus availability	%	85	90
Roadcall frequency (Bus/fuel cell system)	Miles between road call	3,500/15,000	4,000/20,000
Operation time	Hours per day/ days per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

¹ ZEB technologies include fuel cell electric buses (FCEB) and battery electric buses (BEB)

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

Technology Readiness Levels

Commercialization Process



Manufacturer teams for ZEBs currently operating in the United States

Bus OEM	Length (ft)	Fuel Cell System	Hybrid System	Design Strategy	Energy Storage	TRL Level*
Van Hool	40	US Hybrid	Siemens ELFA integrated by Van Hool	Fuel cell dominant	Lithium-based batteries	7 ✓
EIDorado	40	Ballard	BAE Systems	Fuel cell dominant	Lithium-based batteries	7 ✓
Proterra	35	Hydrogenics	Proterra	Battery dominant FCEB	Lithium-titanate batteries	6
EVAmerica	32	Ballard	Embedded Power	Battery dominant FCEB	Lithium-titanate batteries	6
Proterra	35	N/A	Proterra	Battery electric	Lithium-titanate batteries	7 ✓
BYD	40	N/A	BYD	Battery Electric	Iron-phosphate	6 - 7

* TRL assessment based on data collected and other factors – limited data on BEBs to date

✓ Data included in Presentation

FCEB Data Summary for 2015

Specifications for TRL 7 FCEBs included in data summary

FCEB Identifier	ACT ZEBA	SL AFCB
Transit Agency	AC Transit	SunLine
Number of Buses	12	4
Bus OEM	Van Hool	ElDorado National
Bus length/height	40 ft / 136 in	40 ft / 140 in
Fuel Cell OEM	US Hybrid	Ballard
Model	PureMotion 120	FCvelocity, HD6
Power (kW)	120	150
Hybrid System	Siemens ELFA, integrated by Van Hool	BAE Systems HybriDrive
Design strategy	FC dominant	FC dominant
Energy Storage - OEM	EnerDel	A123
Type	Li-ion	Nanophosphate Li-ion
Capacity	17.4 kWh	11 kWh
# cylinders	8	8
Capacity (kg) / Pressure (Bar)	40 / 350	50 / 350

ACT ZEBA

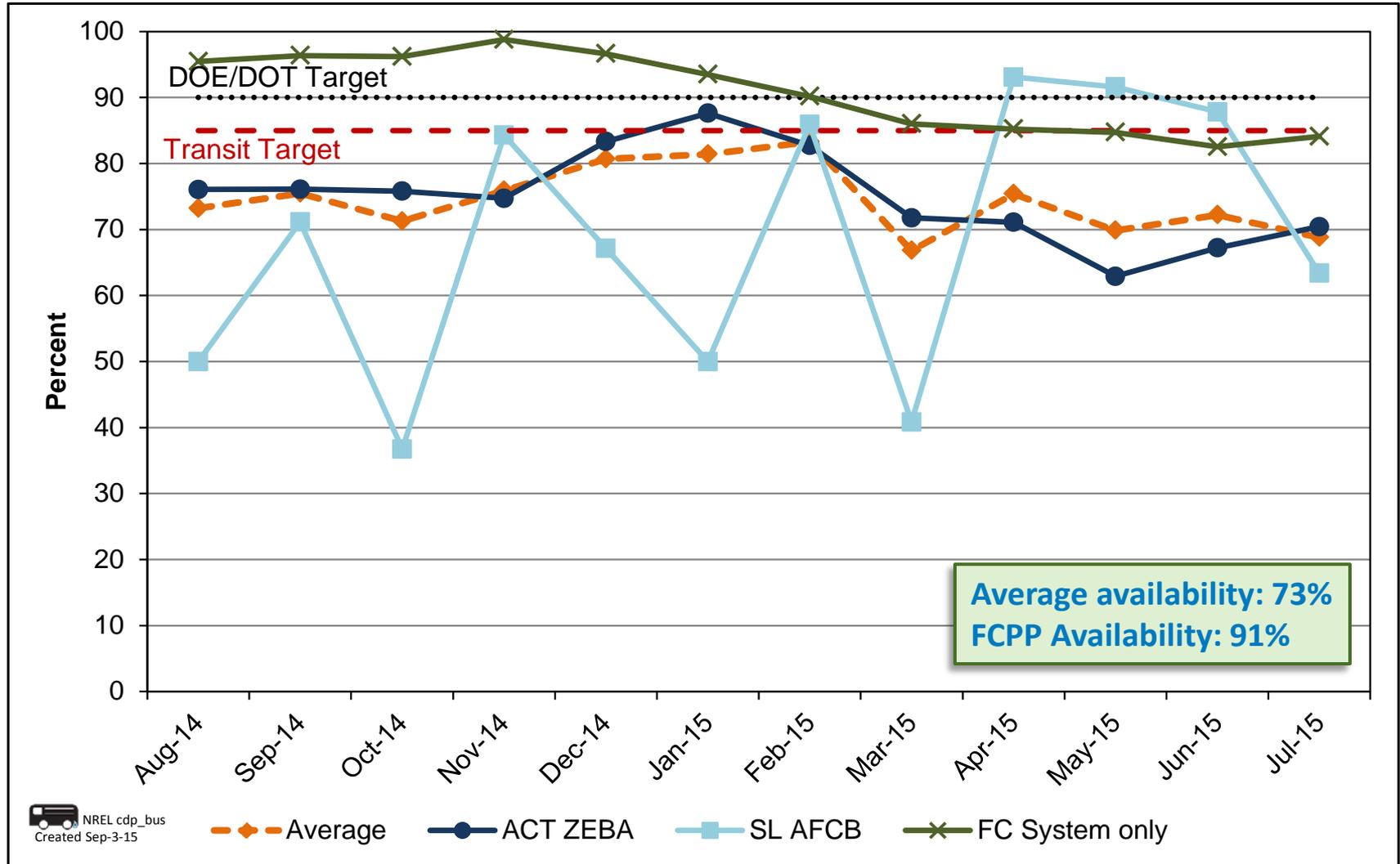


SL AFCB



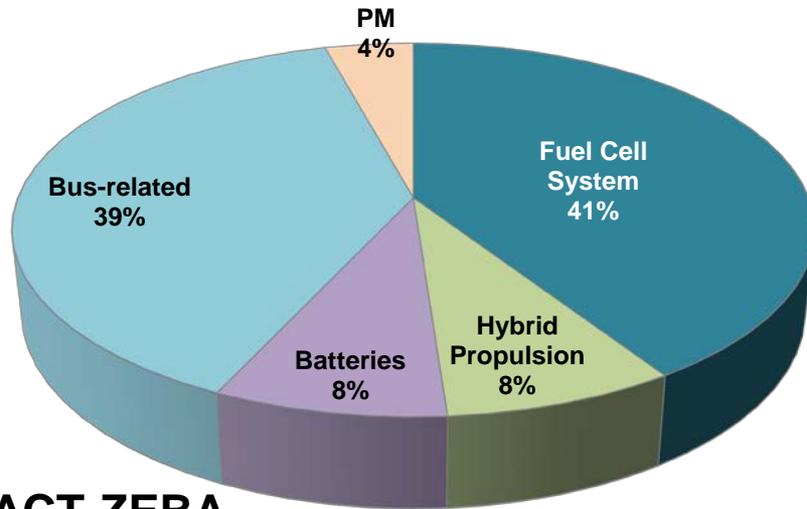
Average Bus Availability

Monthly bus availability

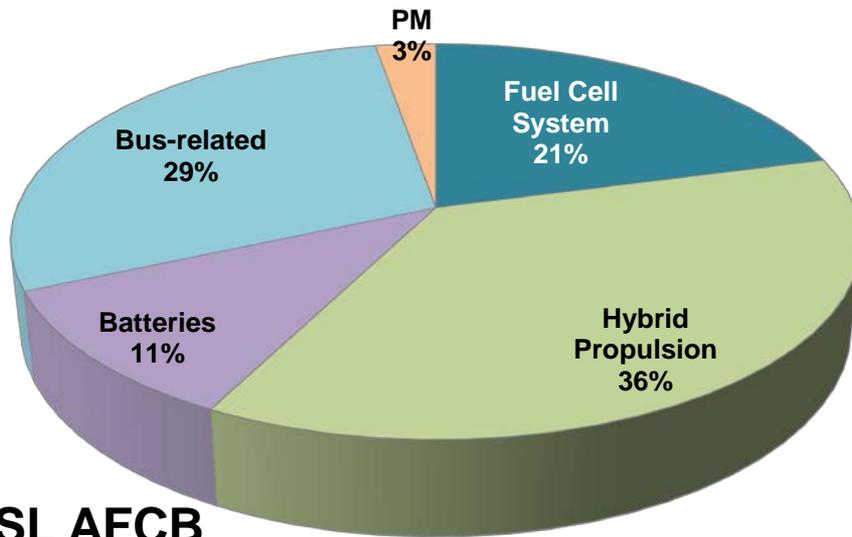


Availability = planned operation days compared to actual operation days

Reasons for Unavailability by Site



ACT ZEBA



SL AFCB

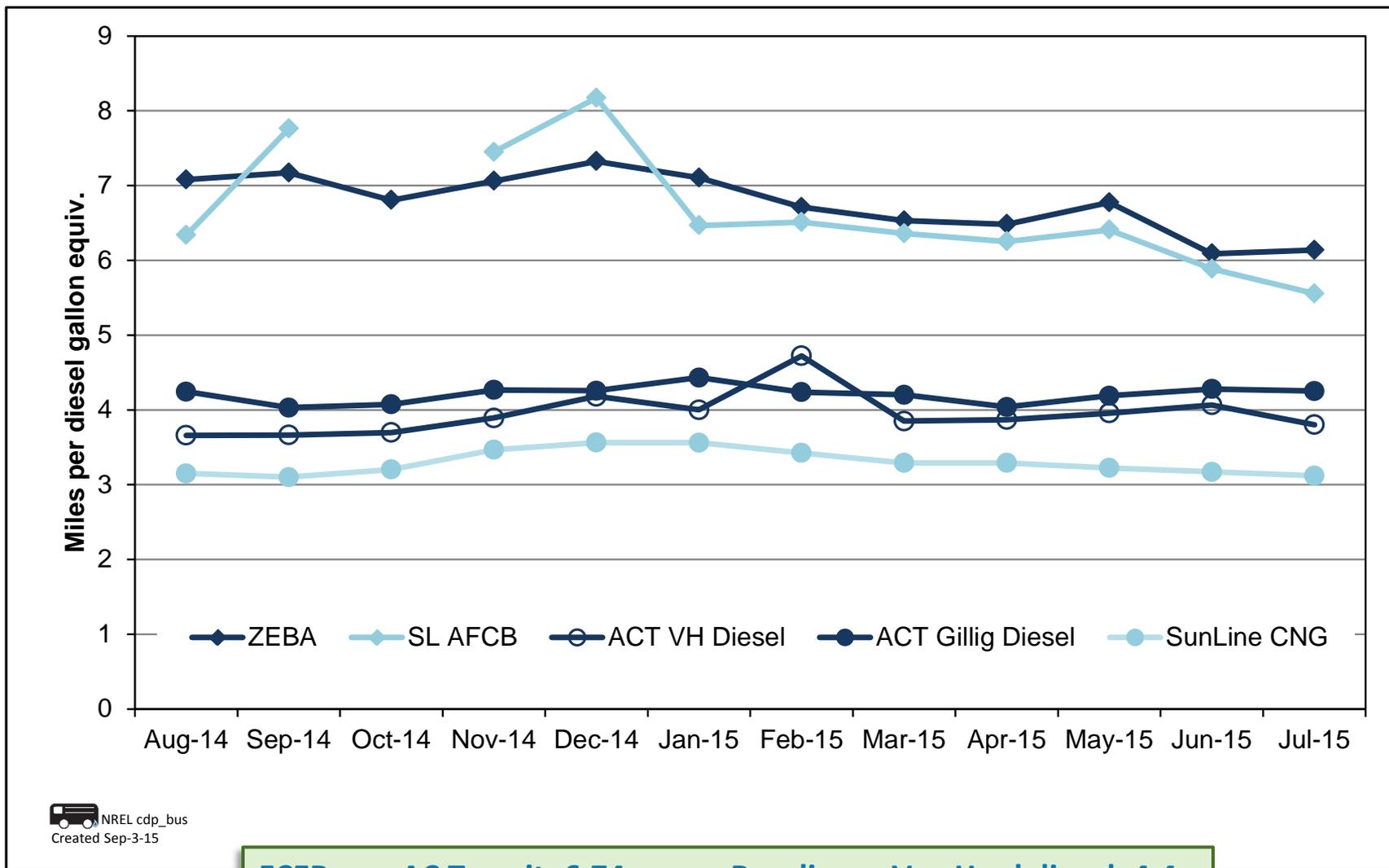
 NREL cdp_bus
Created Sep-3-15

ACT ZEBA	Number	%
FC System	448	41
Hybrid propulsion	88	8
Traction batteries	88	8
Bus maintenance	427	39
Preventive maint.	46	4
Total unavailable days	1097	100
Total planned days	4380	

SL AFCB	Number	%
FC System	54	21
Hybrid propulsion	95	37
Traction batteries	28	11
Bus maintenance	75	29
Preventive maint.	7	3
Total unavailable days	259	100
Total planned days	920	

Unavailability categorized based on current reported diagnosis and could change as new information is received.

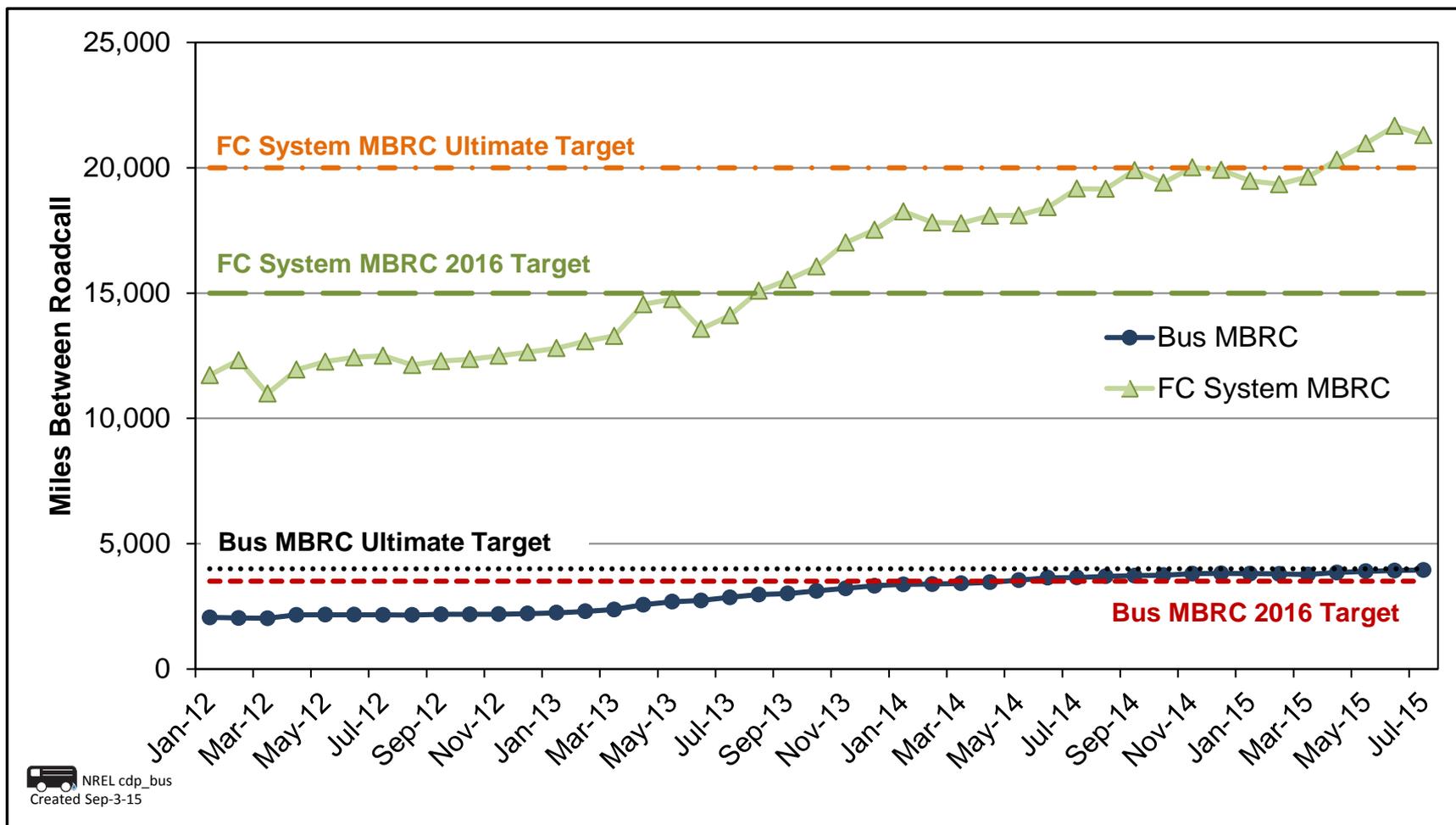
Monthly Fuel Economy compared to Baseline



FCEBs: AC Transit: 6.74
SunLine: 6.43

Baselines: Van Hool diesel: 4.4
Gillig diesel: 3.9
CNG: 4.51

Reliability: Miles Between Roadcall (MBRC)



Overall bus and FC System MBRC shows an upward trend, surpassing both the 2016 and ultimate targets.

Current Status of FCEBs

	Fleet Minimum	Fleet Maximum	Fleet Average
Bus lifetime (years)	0.25	4.9	3.6
Bus lifetime (miles)	7,978	117,217	81,108
Power plant lifetime (hours)	667	20,024	10,102
Bus availability (%)	40	92	73
Fuel fills (number per day)	1	1	1
Roadcall frequency – bus (MBRC)	1,809	6,849	4,280
Roadcall frequency – fuel cell system (MBRC)	9,045	104,886	20,531
Operation time (average hours per day)	7.4	13.7	11.8
Scheduled and unscheduled maintenance cost (\$/mile) ¹	0.54	1.33	1.16
Range (miles)	242	345	275
Fuel economy (miles per DGE)	5.56	7.71	6.8

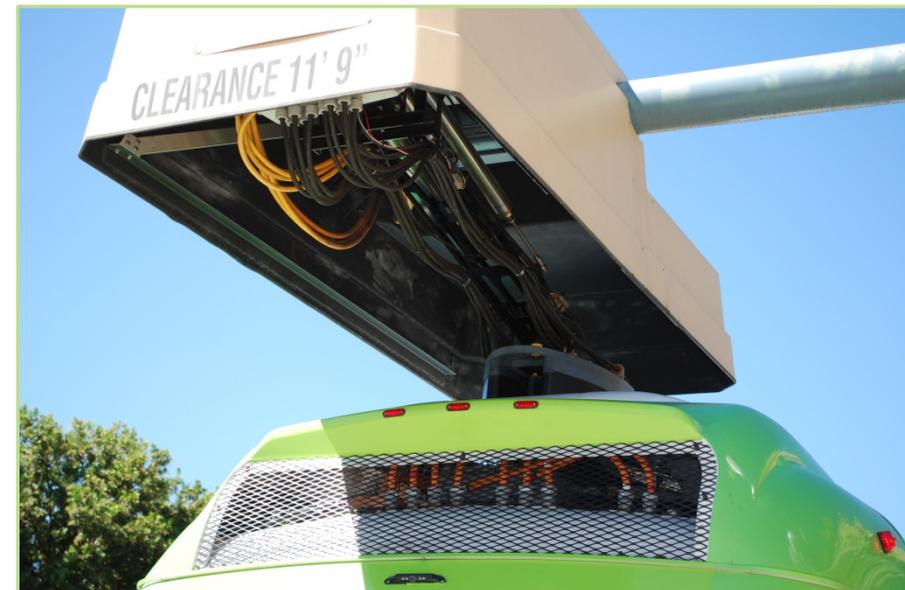
Data Summary from 2 fleets – 16 total buses.

¹ Buses from one fleet are still under warranty, although most of the maintenance is handled by transit staff

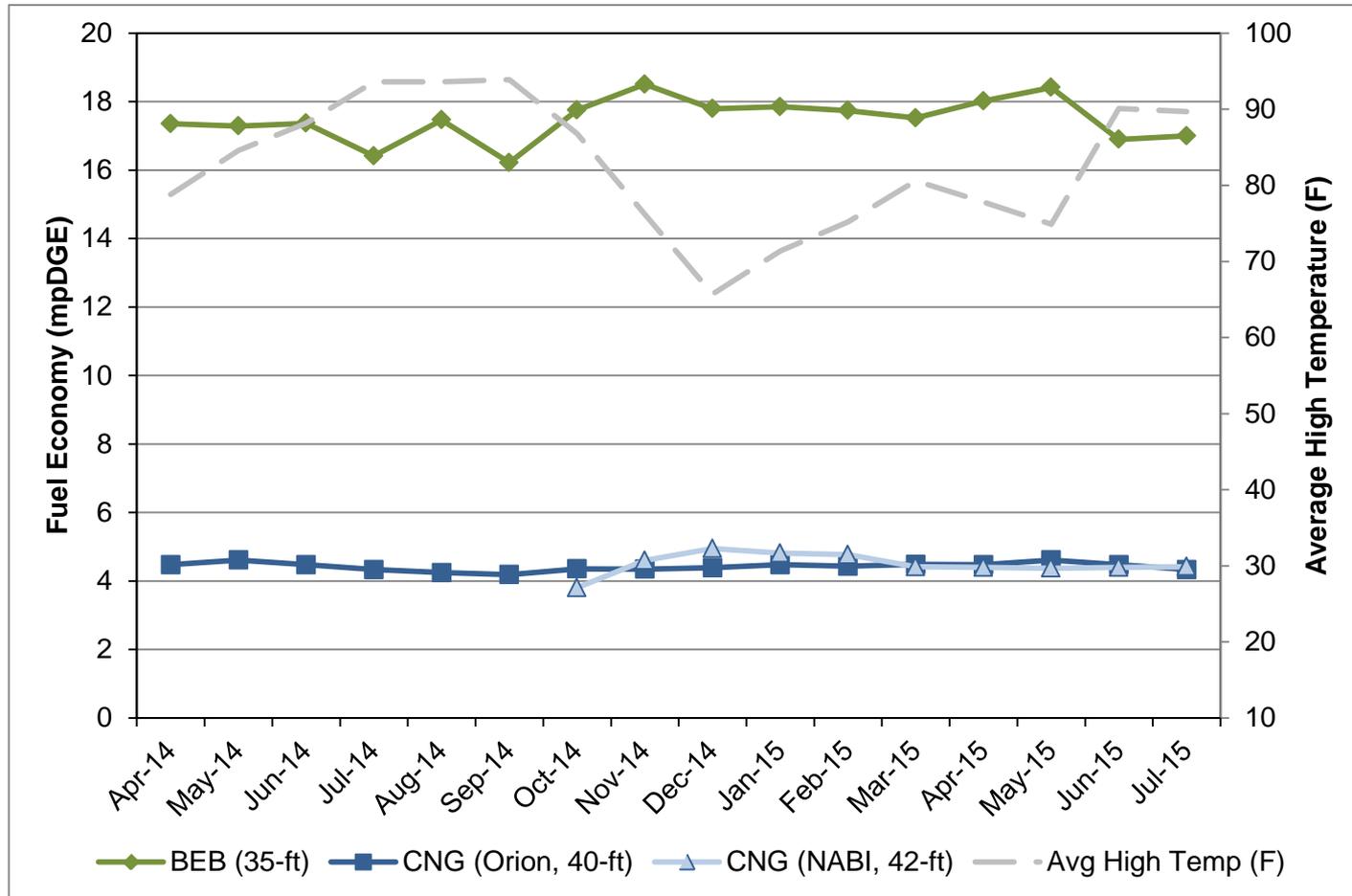
Foothill Transit BEBs

Specifications Foothill BEBs

FCEB Identifier	BEB
Transit Agency	Foothill Transit
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	Altairnano
Type	Lithium-titanate
Capacity	368 volts, 88 kWh

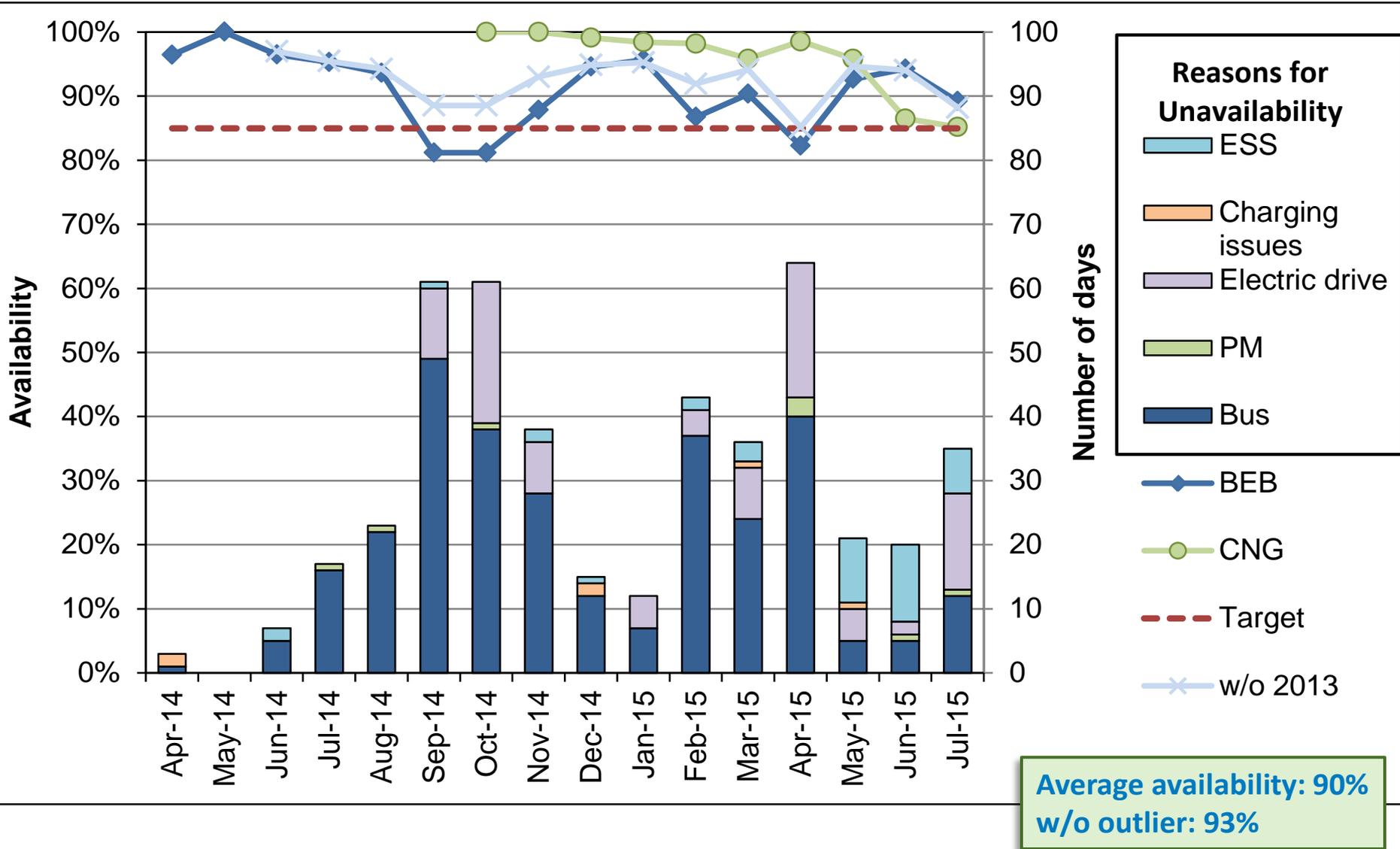


Monthly Fuel Economy compared to Baseline

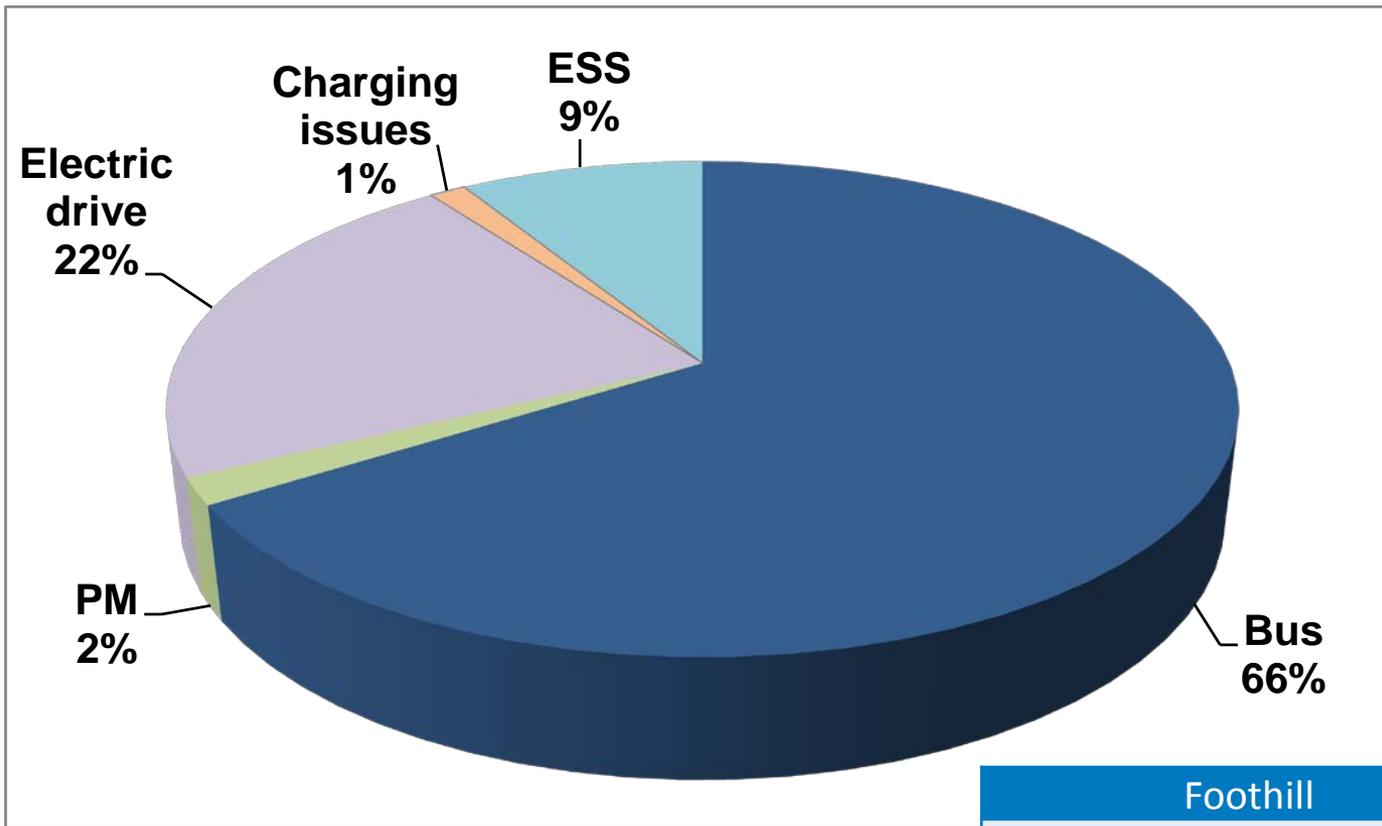


BEB average: 2.15 kWh/mi, 17.48 mi/DGE
CNG baselines: Orion 40-ft: 4.4 mi/DGE
NABI 42-ft: 4.51 mi/DGE

Average Bus Availability

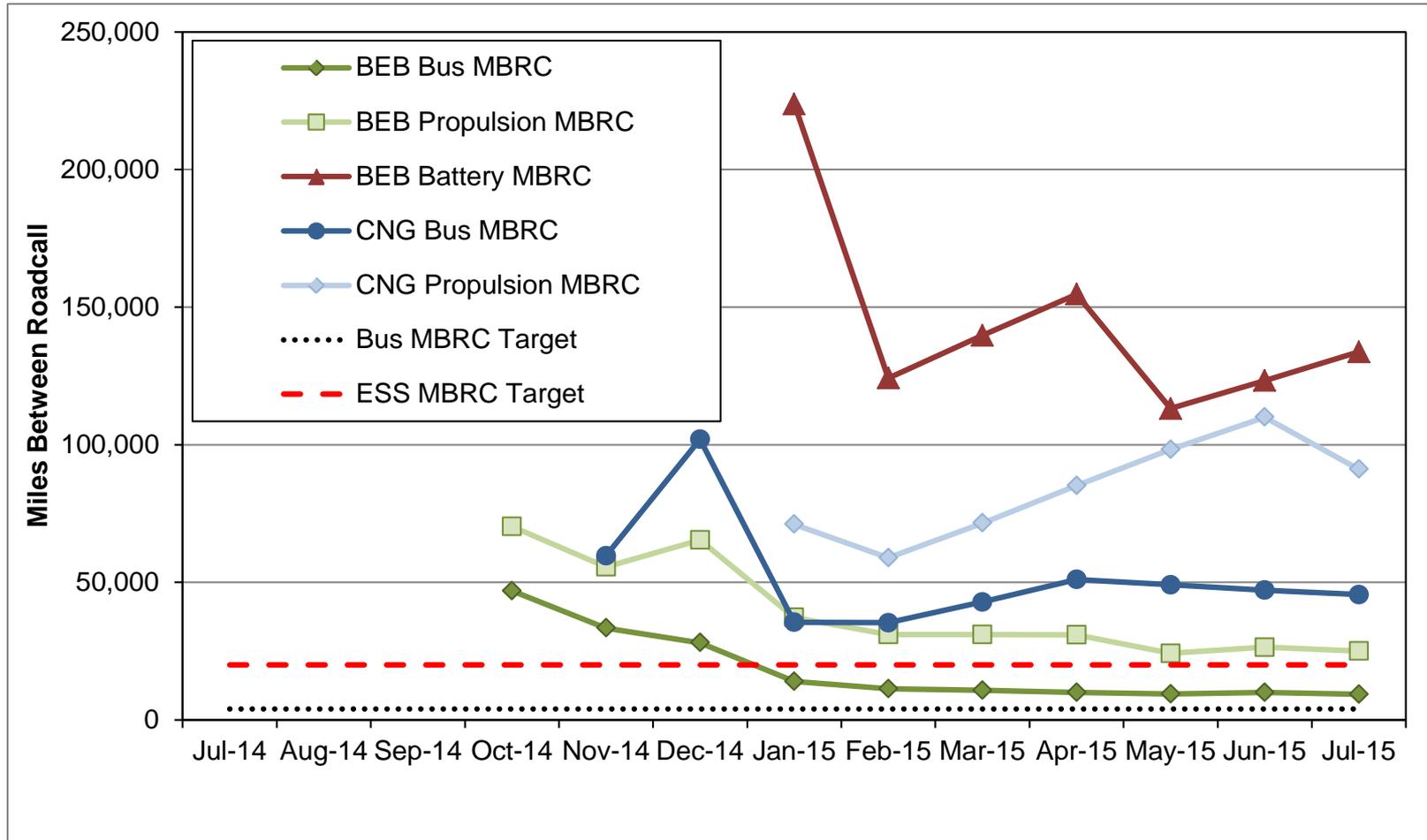


Reasons for Unavailability



Foothill	Number	%
Energy Storage System (ESS)	40	9
Electric drive	101	22
Charging issues	6	1
Bus maintenance	301	66
Preventive maintenance	8	2
Total unavailable days	456	100
Total planned days	4,600	

Reliability: Miles Between Roadcall (MBRC)



Early results show the BEB performance meets the ultimate targets.

Current Status of BEBs

	Fleet Minimum	Fleet Maximum	Fleet Average
Bus lifetime (years)	1	1.3	1.19
Bus lifetime (miles)	17,243	40,532	33,437
Bus availability (%)	62	98	90
Charges (number per day)	1	29	10
Roadcall frequency – bus (MBRC)	5,748	31,944	9,331
Roadcall frequency – propulsion system (MBRC)	1,724	32,743	25,078
Roadcall frequency – energy storage system (MBRC)			133,748
Operation time (average hours per day)	7.2	12.0	10.7
Scheduled and unscheduled maintenance cost (\$/mile) ¹	0.08	0.27	0.16
Fuel economy (miles per DGE)	16.23	18.19	17.48

Data from only 1 fleets – 12 total buses

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

Technology Cost Over Time

FCEB Capital Costs (multiple manufacturers)

Number of Buses	Bus Description	Purchase Year	Cost per Bus
3	Non-hybrid fuel cell buses	2003	\$3,100,000
5	40-ft fuel cell electric buses	2005	\$3,200,000
16	40-ft fuel cell electric buses	2009	\$2,500,000
20	40-ft fuel cell electric buses	2009	\$2,100,000
1	40-ft prototype FCEB	2011	\$2,400,000
10	40-ft fuel cell electric buses	2015	~\$1,900,000

BEB Capital Costs (one manufacturer)

Number of Buses	Bus Description	Purchase Year	Cost per Bus
3	35-ft fast charge buses	2009	\$1,000,000
12	35-ft fast charge buses	2013	\$904,490
2	40-ft fast charge buses	2014	\$825,000
13	40-ft extended range buses	2015	\$789,000

Remaining Challenges and Barriers for ZEBs

Specific to FCEBs

- Increase durability and reliability of components
- Continue transition of build process to OEM
- Addition of fueling infrastructure

Specific to BEBs

- Plan/build of opportunity charging stations & garage chargers
- Select appropriate routes for technology
- Address challenge of electric rates and demand charges

Common to all ZEBs

- Develop robust supply chain for components and parts
- Increase learning curve for maintenance staff—training and tools
- Reduce cost, both capital and operating

For more information

NREL Hydrogen Technology Validation web page:

www.nrel.gov/hydrogen/proj_tech_validation.html

The screenshot shows the NREL website's "Hydrogen & Fuel Cells Research" section. The page features a navigation menu with categories like "ABOUT NREL", "SCIENCE & TECHNOLOGY", and "TECHNOLOGY TRANSFER". The main content area is titled "Hydrogen Technology Validation" and includes a definition of technology validation, a list of projects (Hydrogen Production & Delivery, Hydrogen Storage, Fuel Cells, Technology Validation, Fuel Cell Vehicle Learning Demonstration, Fuel Cell Bus Evaluations, Early Fuel Cell Market Demonstrations, Safety, Codes & Standards, Analysis, Education, Manufacturing), and a list of three major validation efforts: Hydrogen Fuel Cell Vehicle and Infrastructure Learning Demonstration, Hydrogen Fuel Cell Bus Evaluations, and Early Fuel Cell Market Demonstrations. The page also includes a sidebar with various research and staff links, a search bar, and a footer with NREL's affiliation with the U.S. Department of Energy and the Alliance for Sustainable Energy, LLC.

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