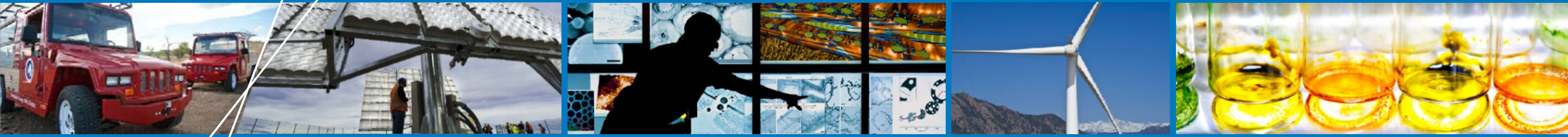
Technology Validation: Fuel Cell Bus Evaluations



Leslie Eudy
National Renewable Energy Laboratory
June 7, 2016

Project ID# TV008

Overview

Timeline and Budget

- Project start: FY03
- End: Project continuation and direction determined annually by DOE
- FY15 DOE funding: $265K
- FY16 planned DOE funding: $200K
- Total DOE funds received to date: $3.725 M (14 years)

Additional funding: U.S. Department of Transportation (DOT)/Federal Transit Administration (FTA)

Barriers

- A. Lack of current fuel cell vehicle (bus) performance and durability data
- C. Lack of current H_2 fueling infrastructure performance and availability data

Partners

- Transit fleets: Operational data, fleet experience
- Manufacturers: Vehicle specs, data, and review
- Fuel providers: Fueling data and review

Relevance

- 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

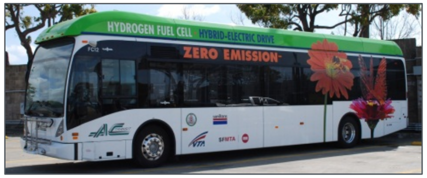
Current Targets*	Units	2016 Target	Ultimate Target
Bus lifetime	Years/miles	12/500,000	12/500,000
Powerplant lifetime	Hours	18,000	25,000
Bus availability	%	85	90
Roadcall frequency (bus/fuel cell system)	Miles between roadcall	3,500/15,000	4,000/20,000
Operation time	Hours per day/ days per week	20/7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

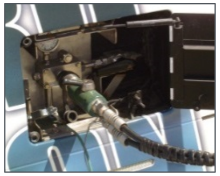
* Fuel Cell Technologies Program Record # 12012, Sep 2012, www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf

Approach

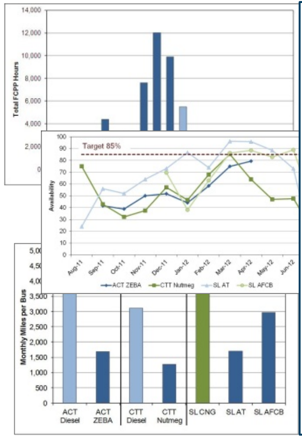
Data Collection/Analysis
- NREL third-party analysis uses standard protocol for collecting existing data from transit partners
- Includes comparisons to conventional technology buses in similar service (diesel, CNG, diesel hybrid)

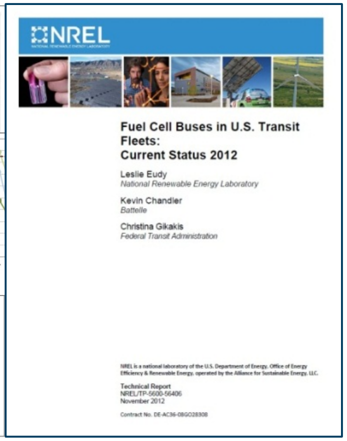
CNG = compressed natural gas





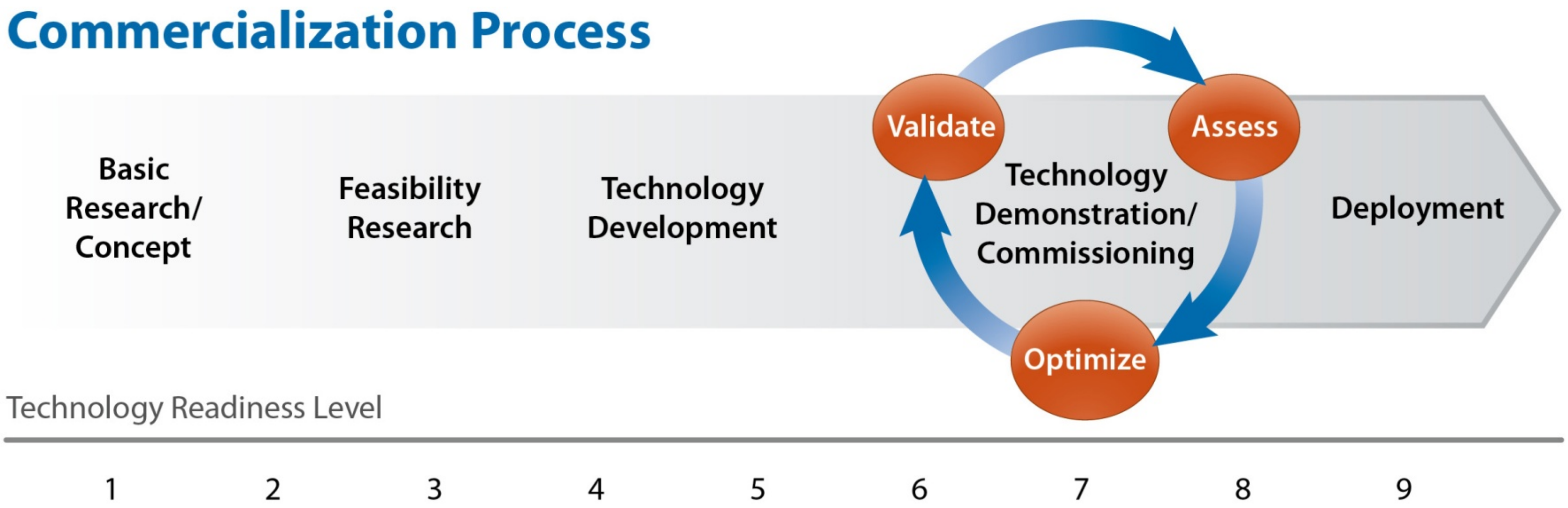
Individual Site Reports
- Documents performance results and experience for each transit agency
- Builds database of results
- Reports published and posted on NREL website





Annual FCEB Status Report (milestone)
- Crosscutting analysis comparing results from all sites
- Assesses progress and needs for continued success
- Provides input on annual status for DOE/DOT Targets

Approach:
NREL Assesses Technology Readiness Levels



Manufacturer teams for FCEBs 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 ✓
New Flyer	40	Ballard	Siemens ELFA integrated by Bluways	Fuel cell dominant	Lithium-based batteries	7
ElDorado	40	Ballard	BAE Systems	Fuel cell dominant	Lithium-based batteries	7 ✓
Proterra	35	Hydrogenics	Proterra integration	Battery dominant	Lithium-titanate batteries	6
EVAmerica	35	Ballard	Embedded Power	Battery dominant	Lithium-titanate batteries	6

OEM = original equipment manufacturer

✓ Data included in presentation

Approach: Data Summary for 2016

Specifications for FCEBs included in data summary

FCEB Identifier	ACT ZEBA	SL AFCB
Transit agency	AC Transit	SunLine
Location	Oakland, CA	Thousand Palms, CA
Number of buses	13	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
Number of cylinders	8	8
Capacity (kg)/pressure (bar)	40 / 350	50 / 350

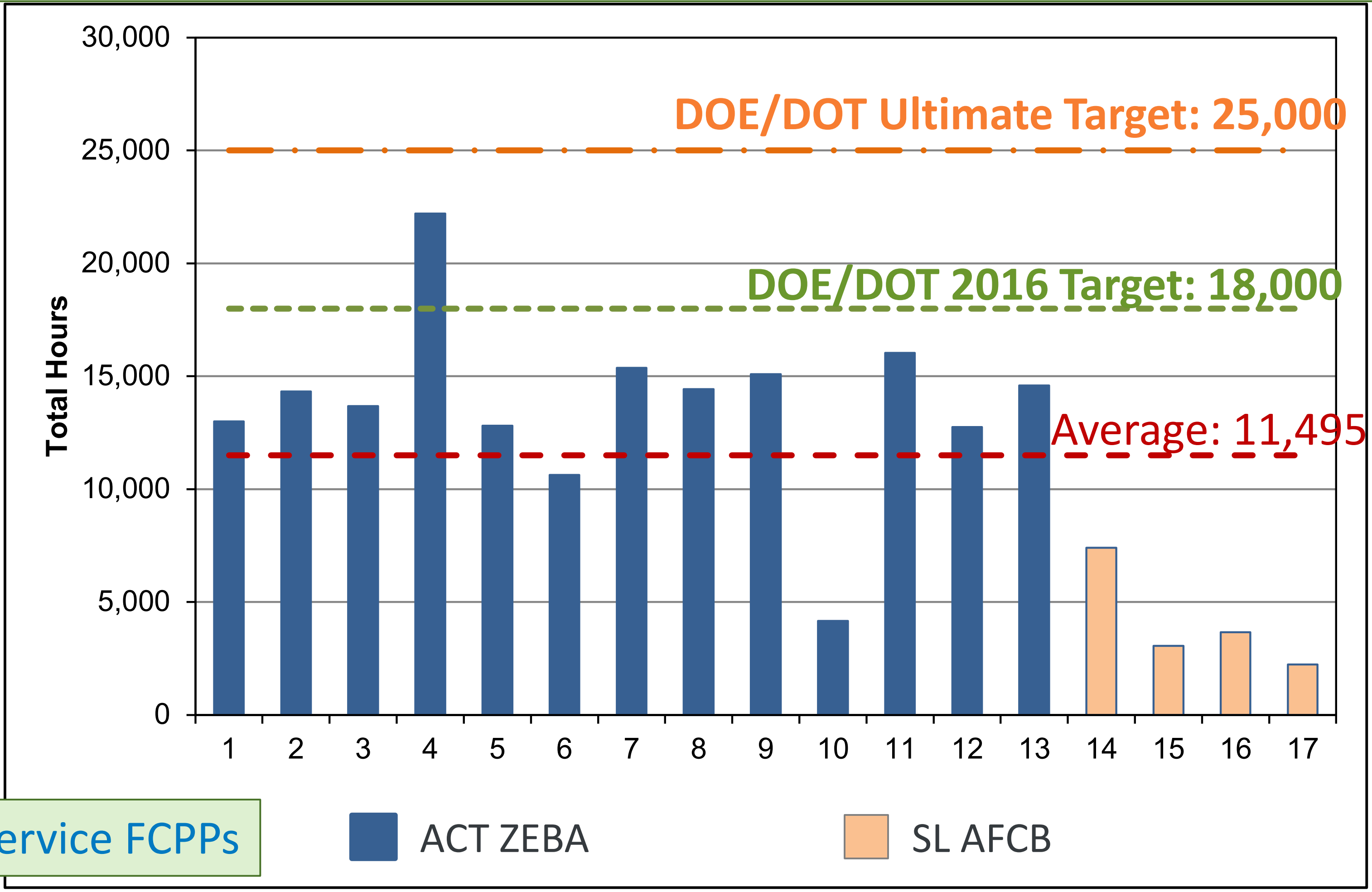
OEM = original equipment manufacturer
ACT ZEBA = AC Transit Zero Emission Bay Area
SL AFCB = SunLine American Fuel Cell Bus
FC = fuel cell

ACT ZEBA

SL AFCB

Accomplishments: Progress Toward Targets
Top Fuel Cell Powerplant Exceeds 22,000 Hours

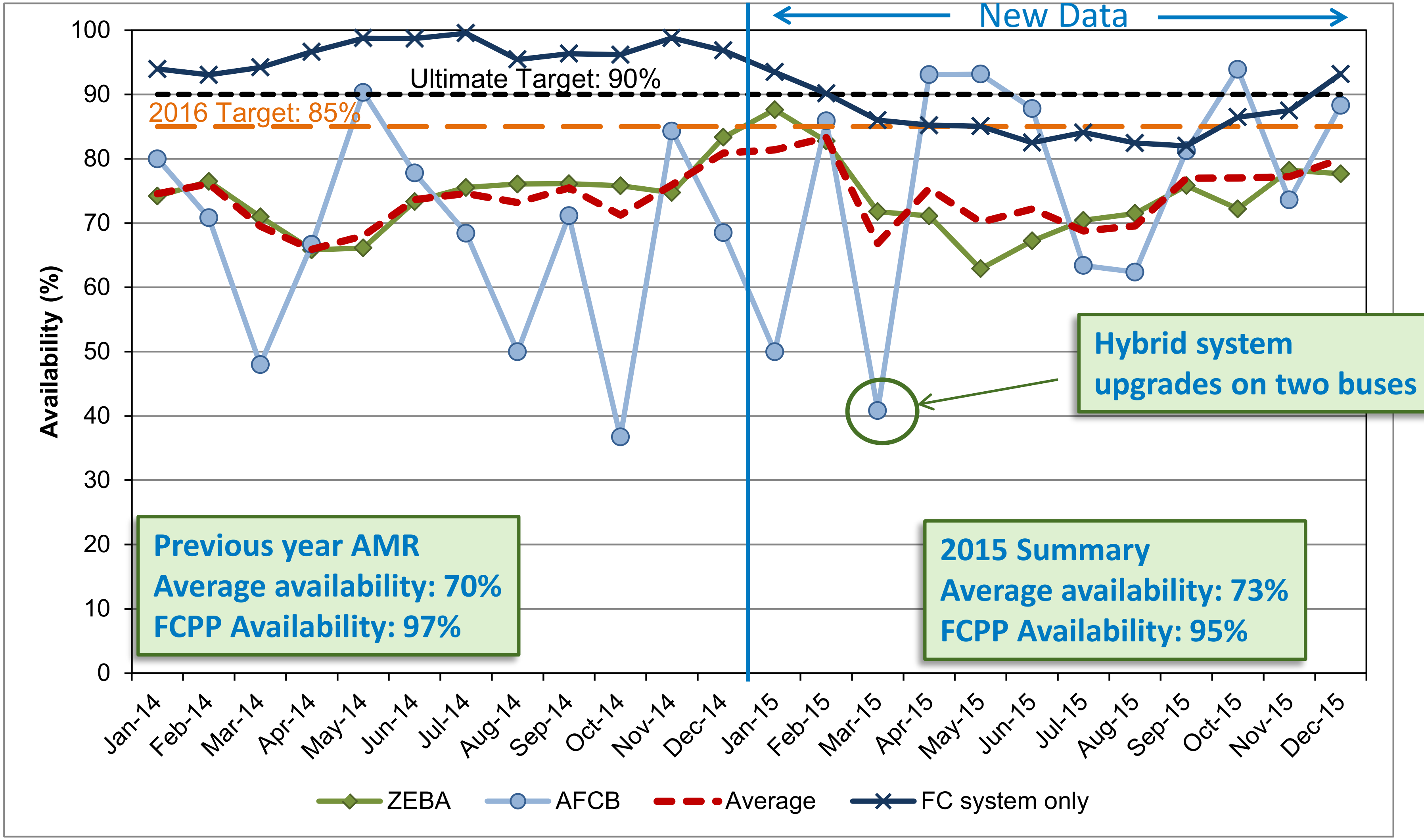
Top fuel cell powerplant (FCPP) >22,000 hours, surpassing DOE/DOT 2016 target; 71% of FCPPs (12) over 10,000 hours



Total hours accumulated on each FCPP as of 2/29/16

Accomplishments: Progress Toward Targets
Average Bus Availability Improves to 73%

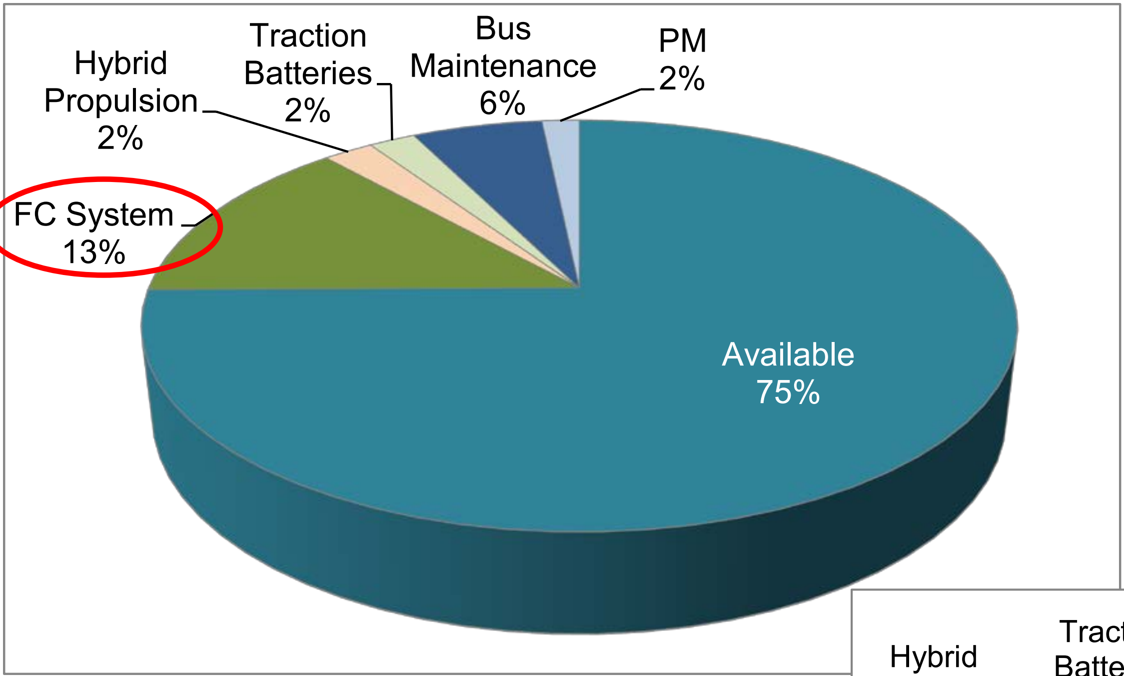
Monthly bus availability



Availability = planned operation days compared to actual operation days

Accomplishments: Progress Toward Targets

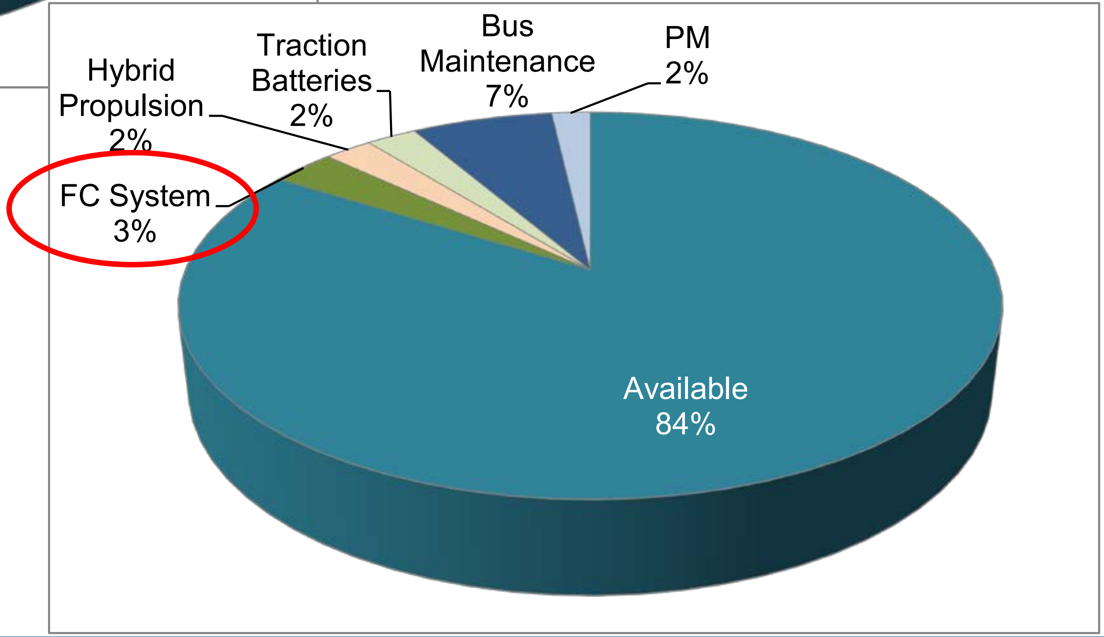
Availability Summary: 2015 Data



FCEB Fleet	Number	%
Available	4,129	84
FC system	148	3
Hybrid propulsion	111	2
Traction batteries	116	2
Bus maintenance	325	7
PM	89	2
Total days	4,918	100

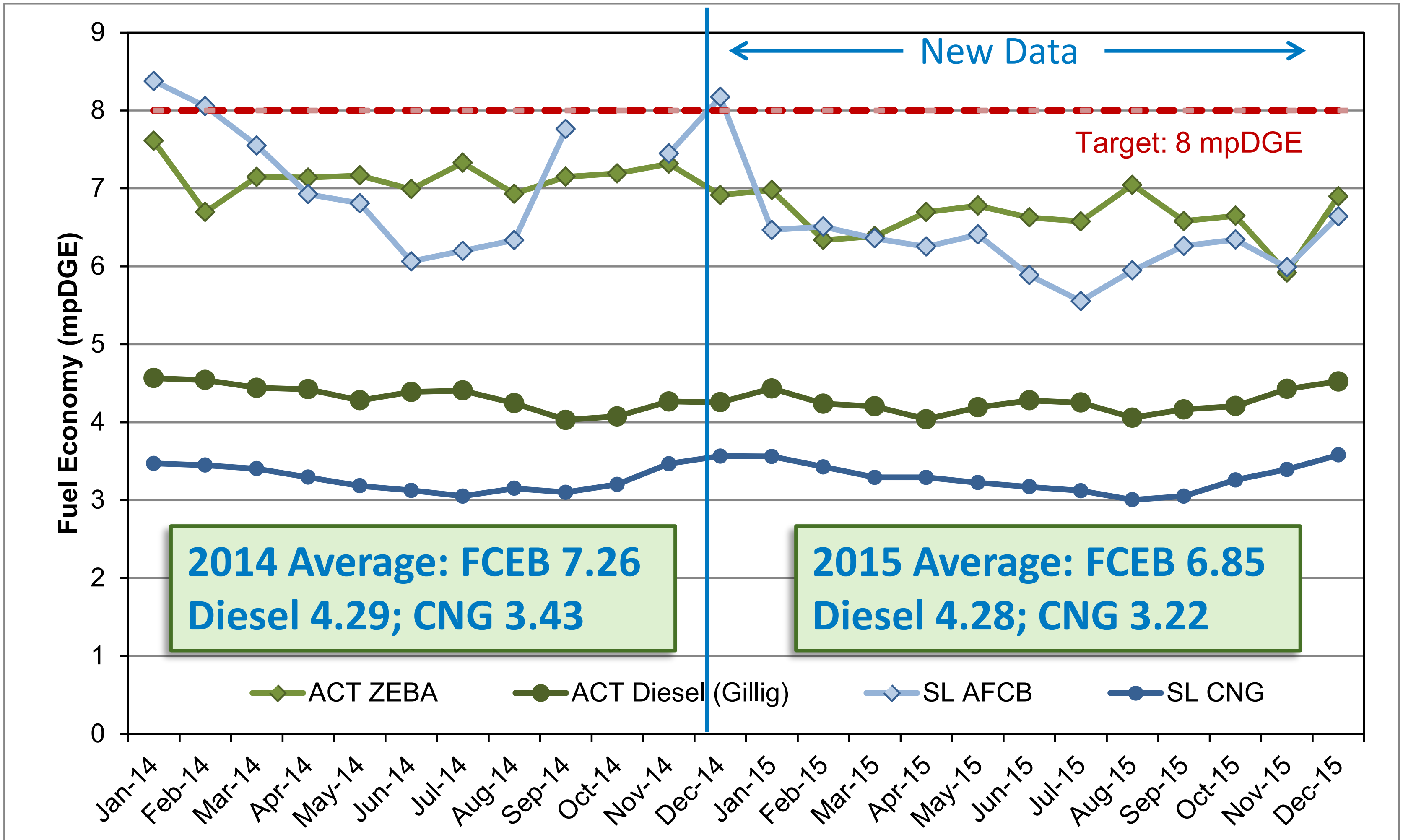
PM = preventive maintenance

Two ZEBA buses were down most of 2015 for FC system issues that were difficult to diagnose; removal of those two buses from data brings availability to 84%



Monthly Fuel Economy Compared to Baseline

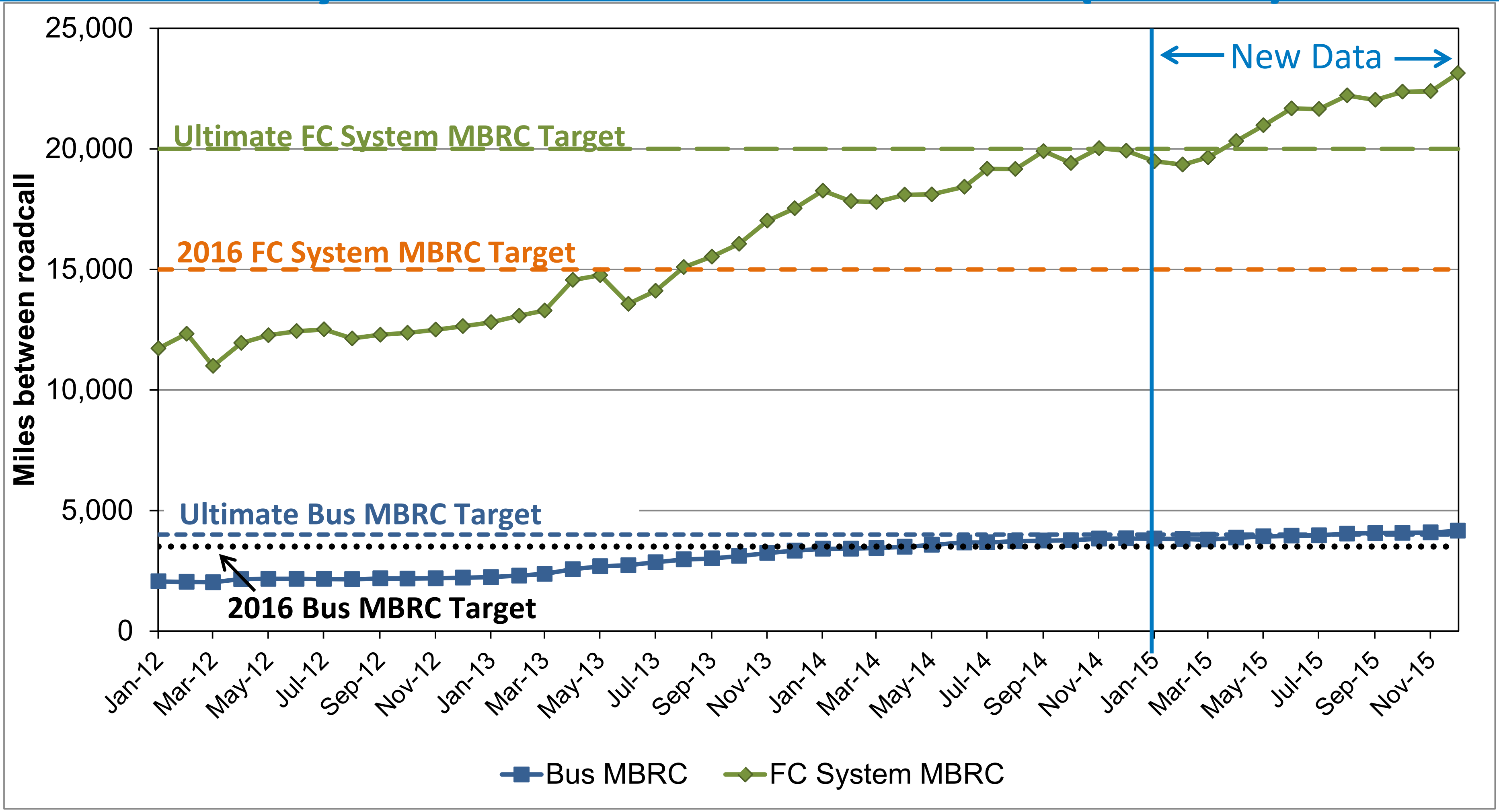
mpDGE = miles per diesel gallon equivalent



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

Accomplishments: Progress Toward Targets

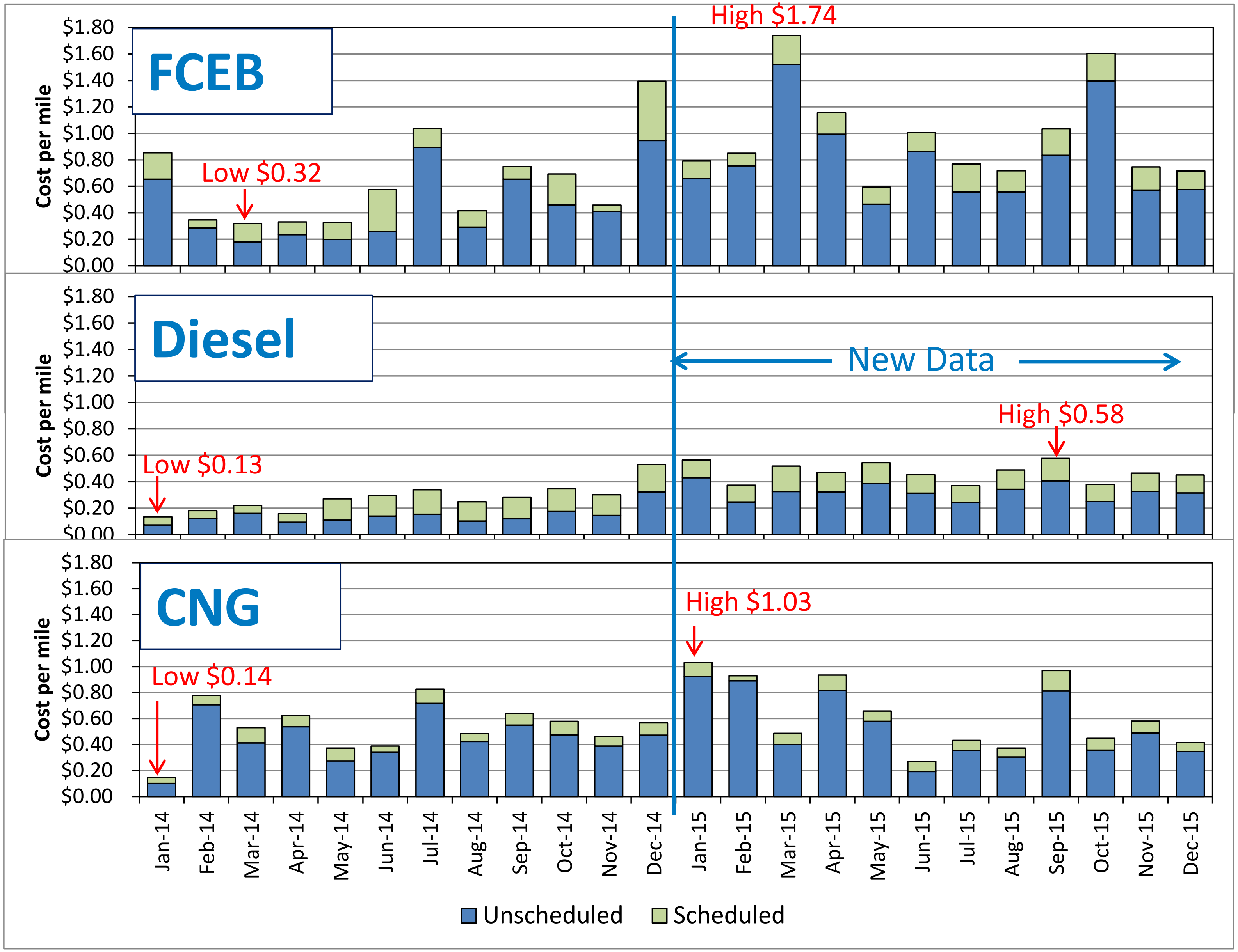
Reliability: Miles Between Roadcall (MBRC)



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

Accomplishments: Progress Toward Targets

Maintenance Costs per Mile by Month



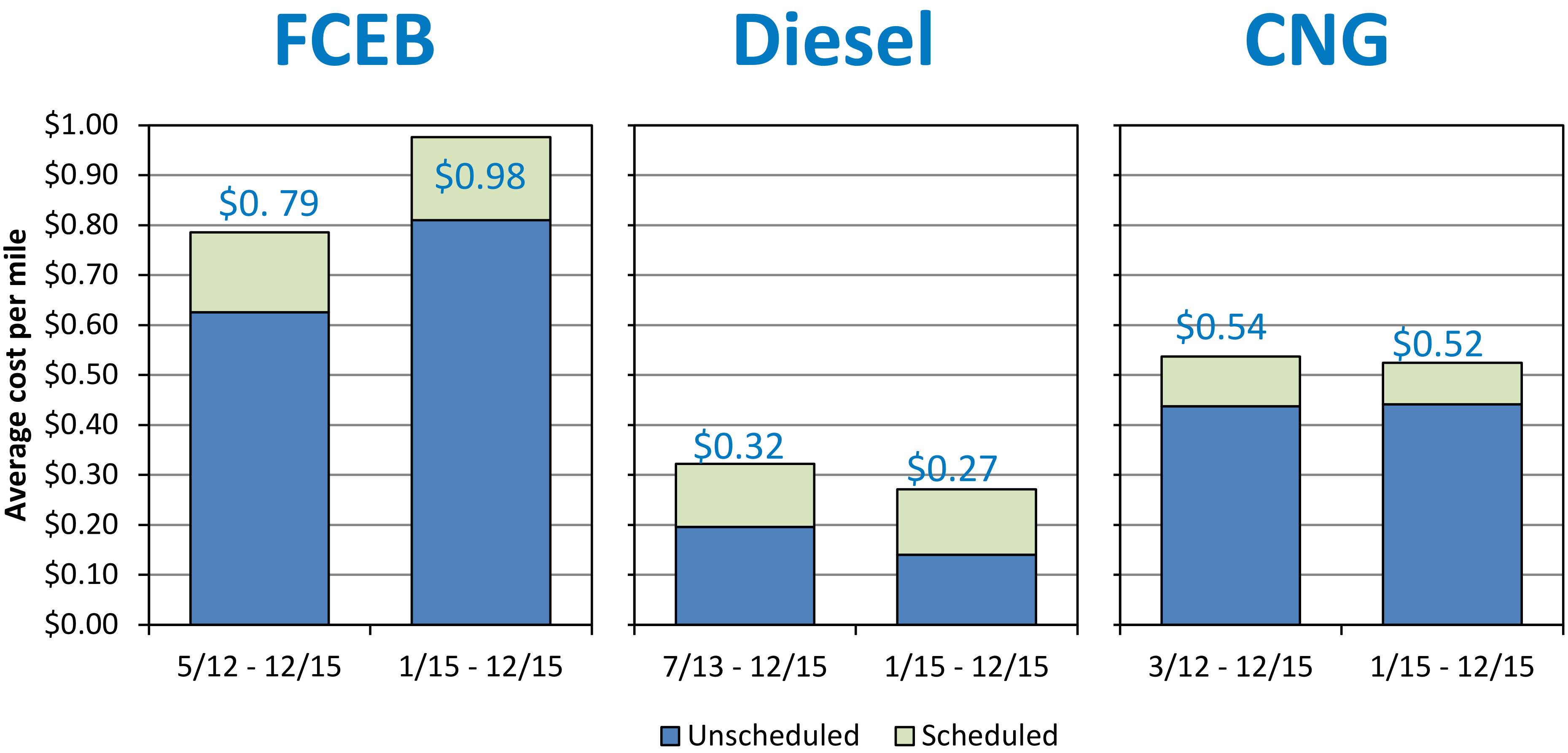
2015 Average FCEB $0.98

Diesel $0.27

CNG $0.52

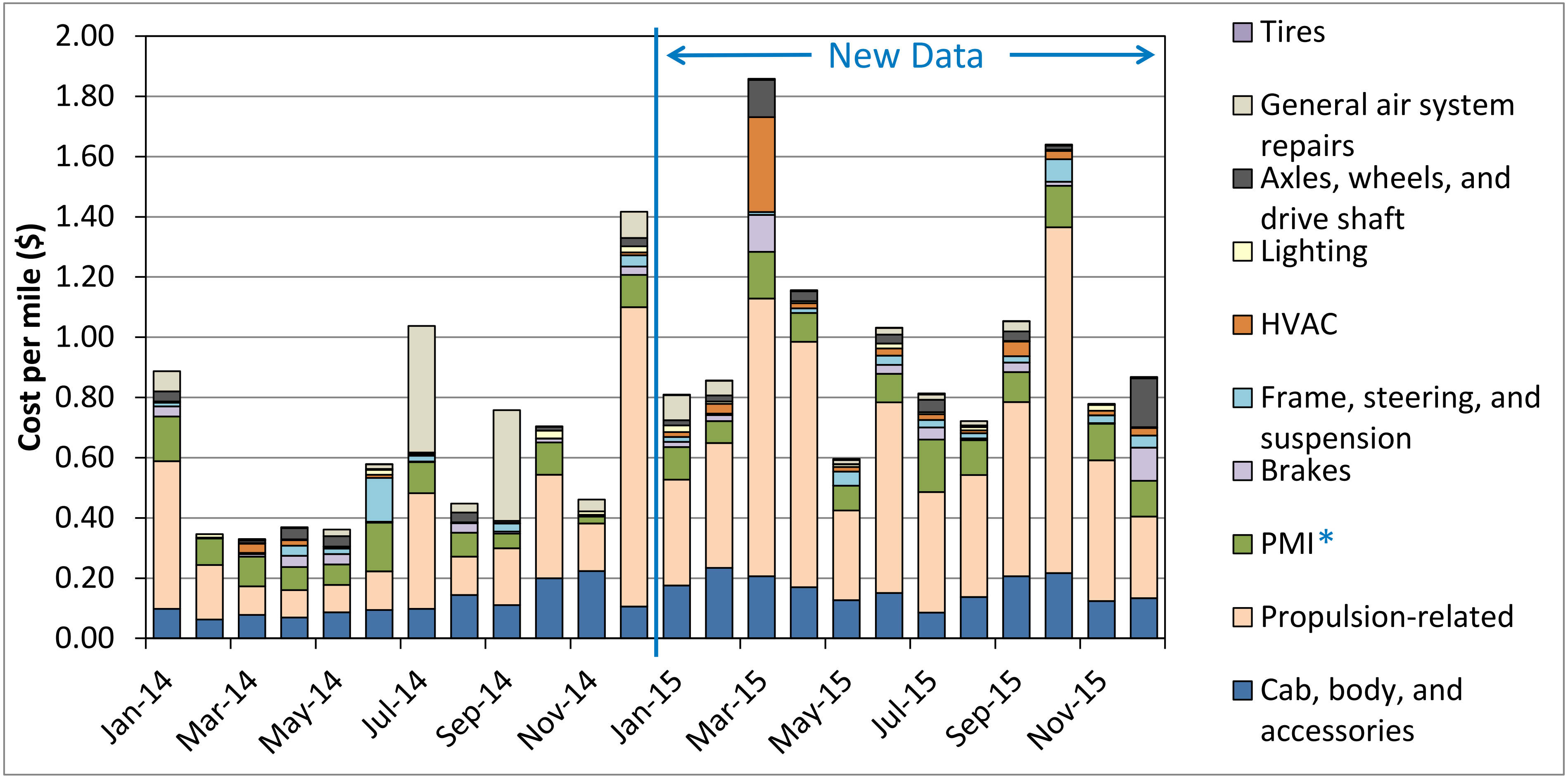
Accomplishments: Progress Toward Targets

Maintenance Costs per Mile – Average for Data Periods



– Average cost per mile shown for overall data period and for the past year
– Costs tend to rise as buses age and pass warranty period
– Average miles for each bus type – FCEB: 91,400; Diesel: 144,500; CNG: 399,000

Maintenance Cost per Mile by System

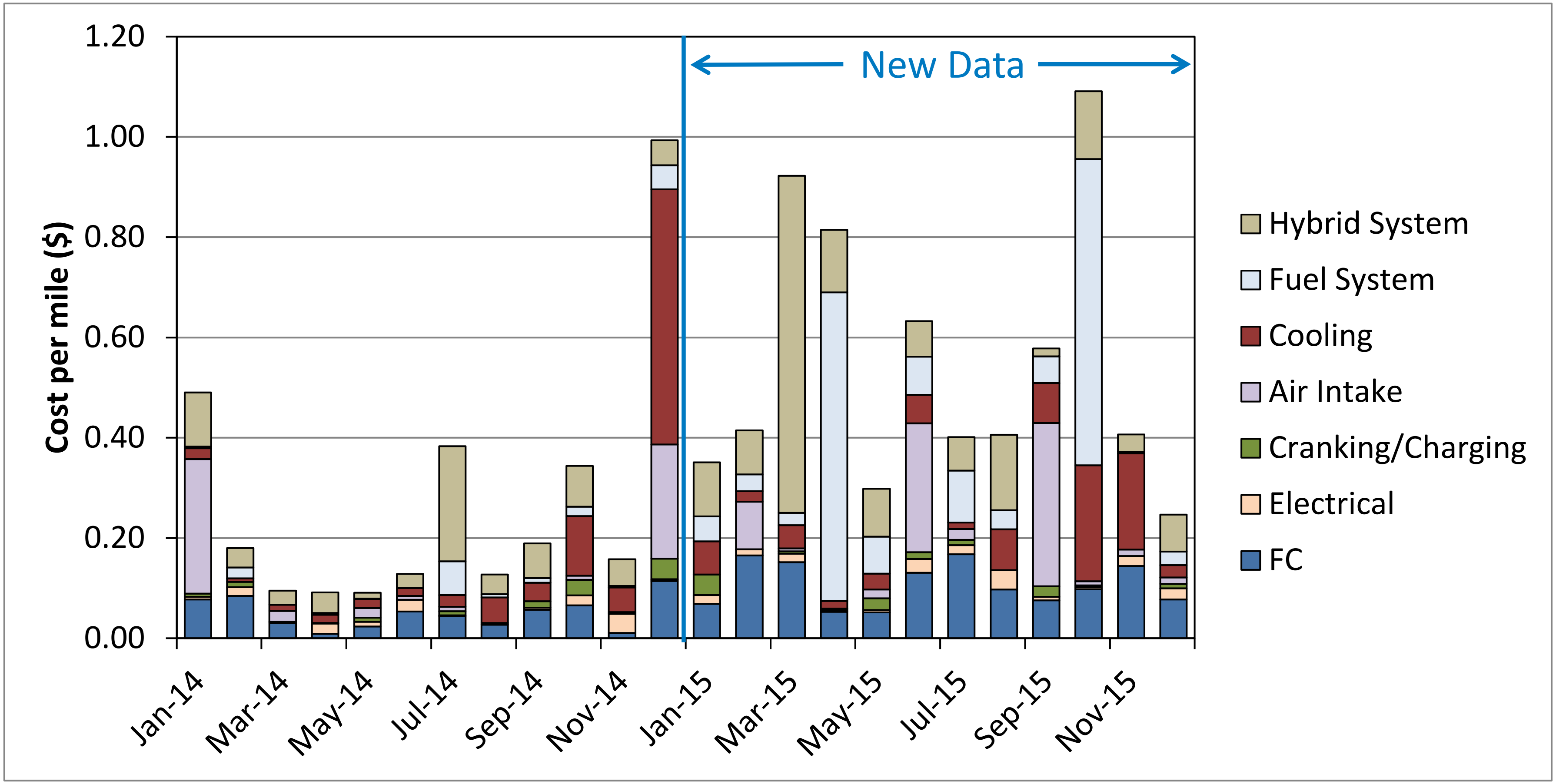


Propulsion system costs make up 50.6% of total maintenance costs (46.9% in 2014) followed by cab, body, and accessories at 16.5%

*PMI = preventive maintenance inspection

Accomplishments: Progress Toward Targets

Maintenance Cost per Mile by Propulsion Sub-System



- FC system costs are 18.9% of total maintenance costs (8.3% in 2014)
- High cost components results in increased cost per mile
- Components with highest cost for 2015 include inverter (Mar), H2 solenoids (Apr, Oct), air compressor (June, Sep), inductor (Oct)

Accomplishments and Progress:
Responses to Previous Year Reviewers' Comments

- **Reporting spare FCPPs with in-service FCPPs makes it challenging to interpret real stack life.**
  - Spare FCPP hours have been removed from chart. (Slide 7)
- **The team should potentially include hybrid diesel technology for comparison.**
  - NREL evaluates what baseline buses are available for each demo. The buses need to be used in similar service for the best comparison – this is not always possible.
  - NREL plans to collect hybrid bus data for baseline comparisons where available.
- **NREL should add battery electric buses to the data collection for comparison.**
  - NREL is now collecting electric bus data under funding from the California Air Resources Board (CARB) and FTA, using the same data collection protocol. This will allow future comparisons; however, the buses are not being operated by the same agencies as the FCEBs are.
- **NREL should consider applying a Technology Readiness Level concept to maintenance staff level of experience.**
  - NREL will explore this idea for inclusion in its Annual Status Report for FCEBs.

Collaborations

- **Transit agencies (1) provide data on buses, fleet experience, and training and (2) review reports**
  - California: AC Transit, Golden Gate Transit, Santa Clara VTA, SamTrans, SunLine, UC Irvine, Orange County Transportation Authority
  - Massachusetts: Massachusetts Bay Transportation Authority
- **Manufacturers provide some data on buses and review reports**
  - Bus OEMs: Van Hool, New Flyer, ElDorado National
  - Fuel cell OEMs: Ballard, Hydrogenics, US Hybrid
  - Hybrid system OEMs: BAE Systems, Van Hool, US Hybrid
- **Other organizations share information and analysis results**
  - National: California Air Resources Board, Northeast Advanced Vehicle Consortium, Center for Transportation and the Environment, CALSTART
  - International: Various organizations from Germany, Brazil, Canada, Japan, England, Norway, Italy, Sweden

Remaining Challenges and Barriers

For technology validation and data collection project:

- **Establish good relationships with additional transit agencies to allow data collection for new FCEB designs**
- **Continue data collection to track progress as buses age and to understand operational costs after buses are out of warranty**

For industry to meet technical targets and commercialize FCEBs:

- **Increase durability and reliability of the fuel cell, battery system, and other components**
- **Develop robust supply chain for components and parts**
- **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**

Proposed Future Work

Jun 2016

<table>
<tr><th colspan="14">Fuel Cell Electric Bus Evaluations for DOE and FTA</th></tr>
<tr><th rowspan="2">Demonstration</th><th rowspan="2">State</th><th rowspan="2">City</th><th rowspan="2"># Buses</th><th colspan="2">2015</th><th colspan="4">2016</th><th colspan="4">2017</th></tr>
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<tr><td rowspan="2">AFCB (LoNo)</td><td>CA</td><td>Thousand Palms</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">SunLine</td></tr>
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<tr><td>Advanced Generation FCEB (60-ft)*</td><td>CA</td><td>Oakland</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">AC Transit</td></tr>
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* National Fuel Cell Bus Program project

National Fuel Cell Bus Program

Color coded by Design Strategy:
- Fuel cell dominant hybrid electric
- Battery dominant hybrid electric

Data collection includes a total of 21 FCEBs at 6 transit sites.

Proposed Future Work

- **Remainder of FY 2016**
  - Complete following data analyses/reports:
    - AC Transit, ZEBA Demo Report, May 2016
    - SunLine AFCB Report, Aug 2016
    - Analysis summary of UC Irvine bus performance, Sep 2016
    - 2016 Annual Status Report, Sep 2016
  - Begin data collection on FCEBs in Boston, OCTA
- **FY 2017**
  - Kick off new FCEB evaluations as buses go into service
  - Complete individual site reports as scheduled
  - Complete annual crosscutting analysis across sites

Technology Transfer Activities

Project provides non-biased evaluation of technology developed by industry

- **Project documents performance results and lessons learned to aid market in understanding needs for full commercialization**
  - Manufacturers
  - Transit agencies
  - Policymaking organizations
  - Funding organizations
- **No technology (hardware/software) is developed through this project**

Summary

Documented progress toward targets:

	Fleet Min	Fleet Max	Fleet Average	2016 Target	Ultimate Target	Target Met
Bus lifetime (years)	0.7	5.4	3.9	12	12	
Bus lifetime (miles)	8,351	131,203	91,381	500,000	500,000	
Powerplant lifetime[1] (hours)	2,013	22,203	11,462	18,000	25,000	2016
Bus availability (%)	40	92	73	85	90	
Roadcall frequency[2] (bus)	4,374	4,513	4,492	3,500	4,000	Ultimate
Roadcall frequency (fuel cell system)	19,085	23,261	22,532	15,000	20,000	Ultimate
Maintenance cost ($/mi)	0.53	2.06	1.61	0.75	0.40	
Fuel economy (mpDGE)	5.81	7.48	6.85	8	8	
Range (miles)[3]	221	345	271	300	300	

[1] Fuel cell hours accumulated to date from newest FCPP to oldest FCPP. Does not indicate end of life.

[2] MBRC: average for current designs.

[3] Estimated range based on fuel economy and 95% tank capacity. Transit agencies report lower real-world range.

Technical Back-Up Slides

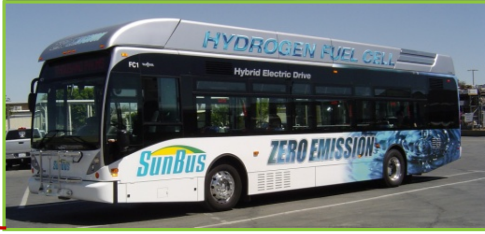
Accomplishments: Progress Toward Targets

Comparison to Previous-Generation FCEBs

Specifications for 1st-Generation FCEBs

FCEB Identifier	VH1 (Van Hool 1st Gen)	VTA
Transit agency	AC Transit, CTTRANSIT, SunLine	Santa Clara Valley Transportation Authority (VTA)
Number of buses	5	3
Bus OEM	Van Hool	Gillig
Bus length/height	40 ft / 139 in.	40 ft / 144 in.
Fuel cell OEM	UTC Power	Ballard
Model	PureMotion 120	P5-2
Power (kW)	120	300
Hybrid system	Siemens ELFA, integrated by ISE Corp	Not a hybrid system
Design strategy	FC dominant	N/A
Energy storage—OEM	MES-DEA	N/A
Type	Sodium/Nickel Chloride	N/A
Capacity	53 kWh	N/A
Number of cylinders	8	11
Capacity (kg)/pressure (bar)	50 / 350	55 / 350

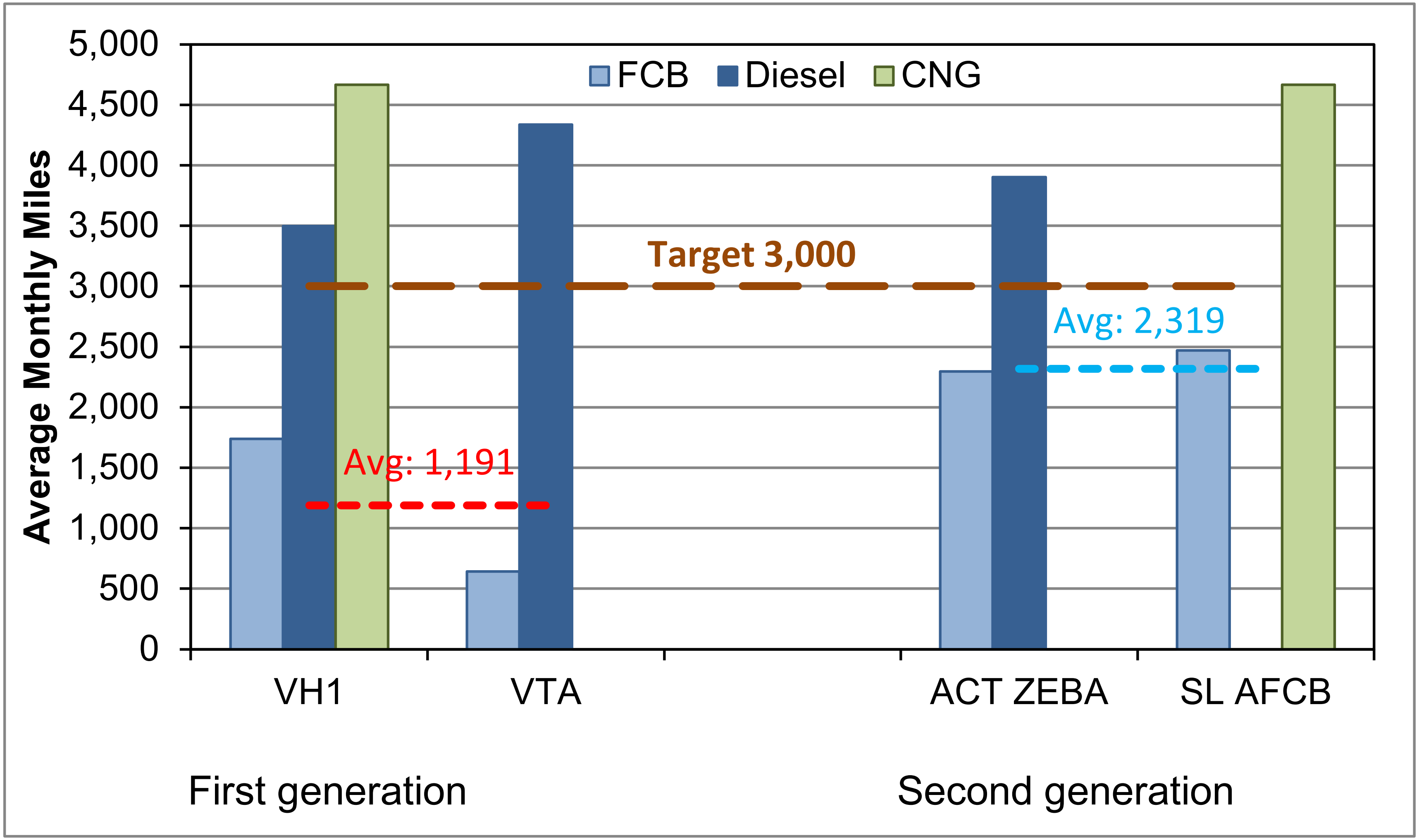
VH1



VTA

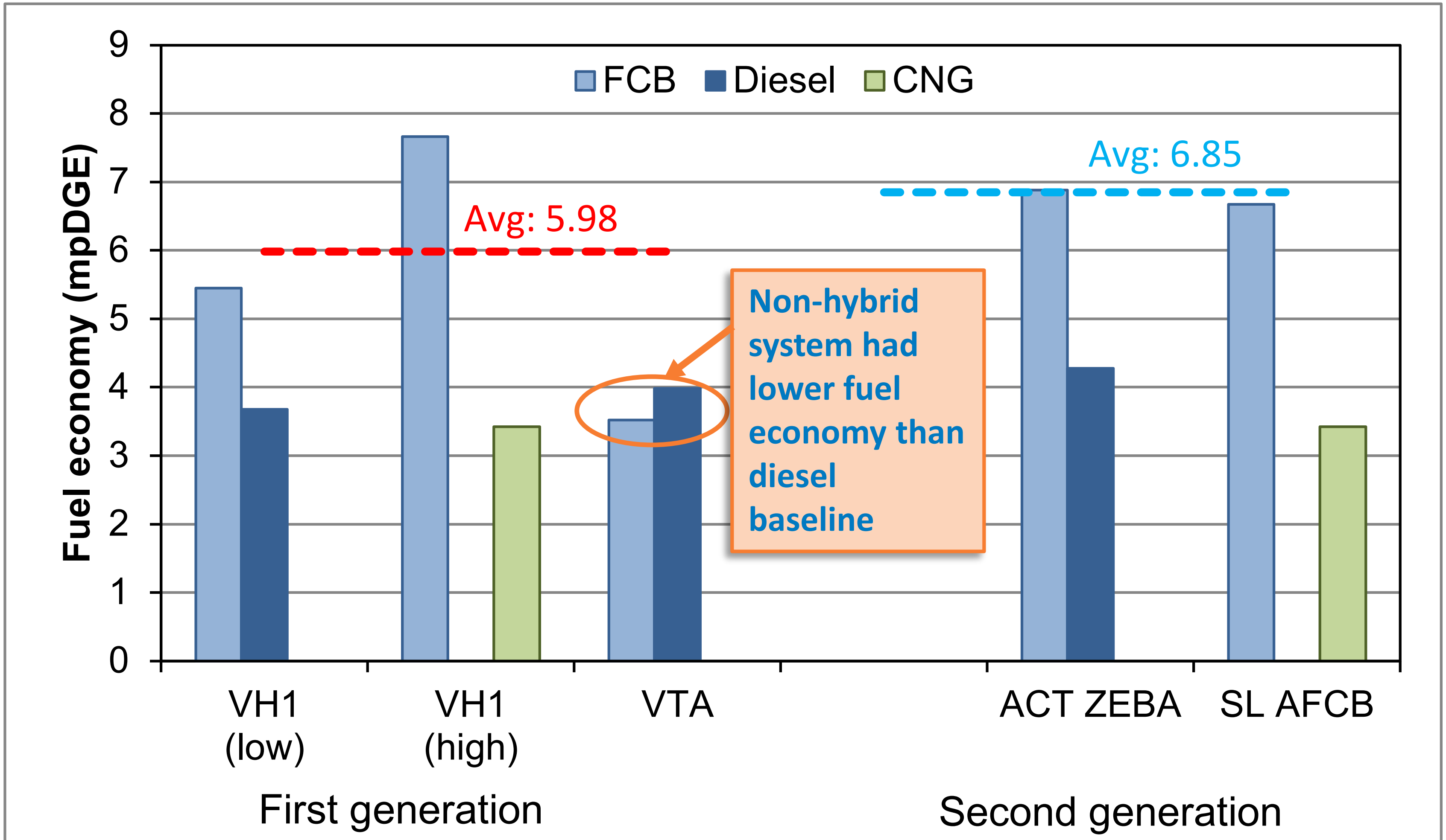
Accomplishments: Progress Toward Targets

Monthly Miles 2 Times Higher Than 1st Gen



Transit agencies are increasing service; approaching target, but still lower than conventional buses

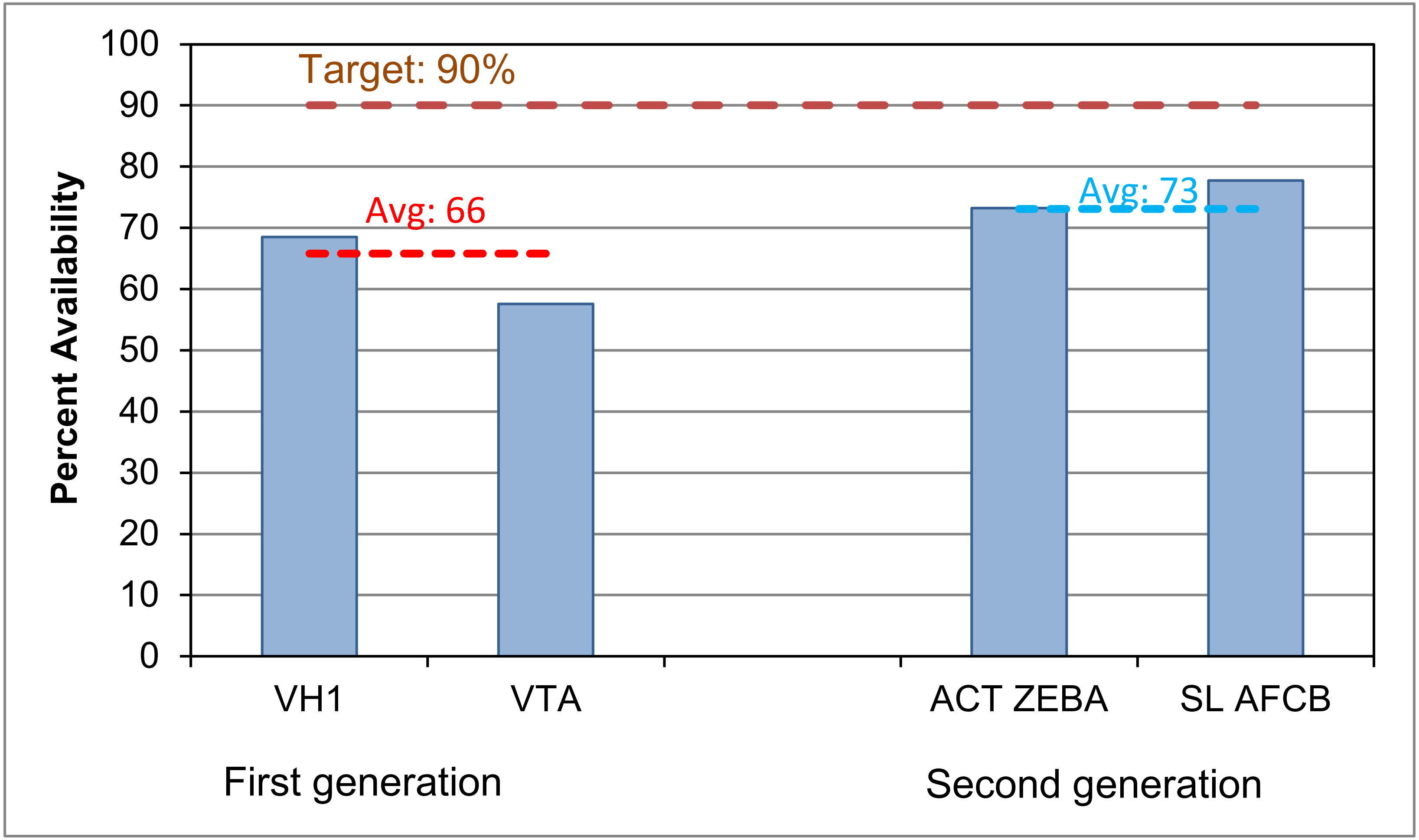
Fuel Economy up to 2 Times Better Than Baseline



– Lowest fuel economy was for 1st-gen system that was not a hybrid (VTA)
– Highly variable depending on duty cycle, but generally higher than baseline buses

Accomplishments: Progress Toward Targets

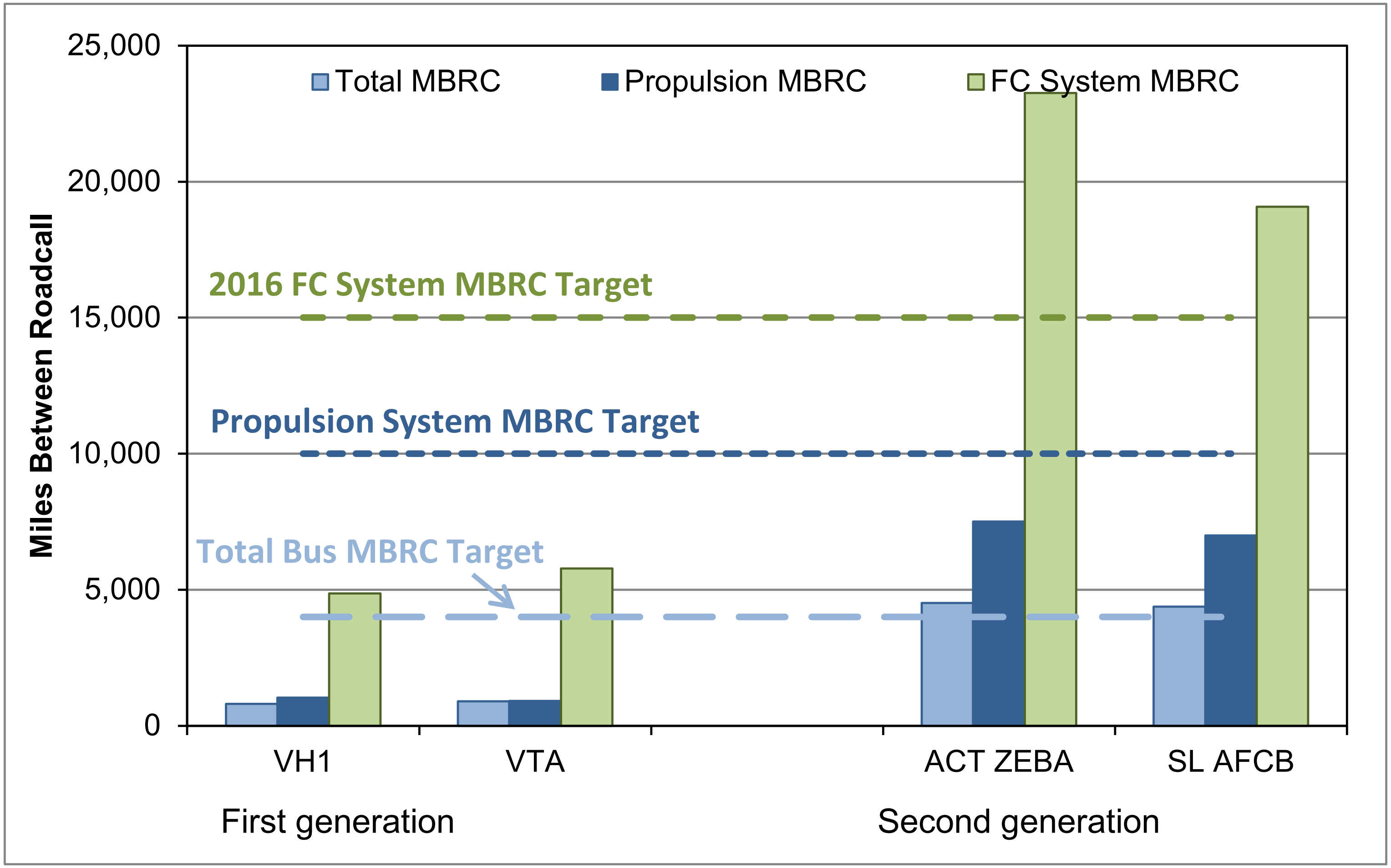
Availability Increased to 73%



- Recent FCPP issues with FCEBs at AC Transit lowered availability for 2nd generation
- Removing these two buses brings the AC Transit overall availability to 77%

Accomplishments: Progress Toward Targets

Reliability: MBRC Significantly Higher Than 1st Gen



	Total MBRC	Propulsion MBRC	FC System MBRC
1st gen average	1,263	1,555	7,710
2nd gen average	4,492	7,432	22,532
Percent improvement	256%	378%	192%

*MBRC = miles between roadcall