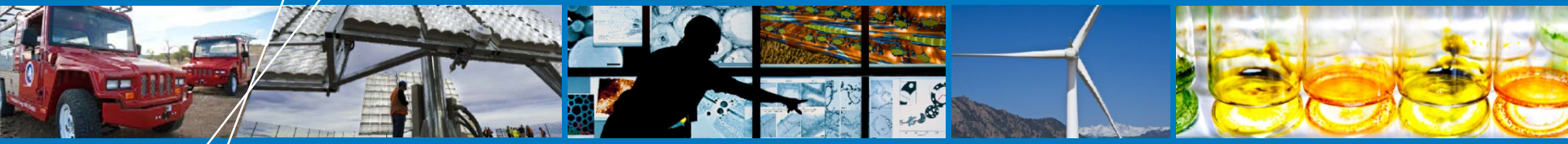
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Technology Validation: Fuel Cell Bus Evaluations



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June 10, 2015

Project ID# TV008

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline and Budget

- Project Start: FY03
- End: Project continuation and direction determined annually by DOE.
- Total DOE Funds Received to Date: $3.525 M (13 years)
- FY14 DOE funding: $300K
- FY15 planned DOE funding: $265

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

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

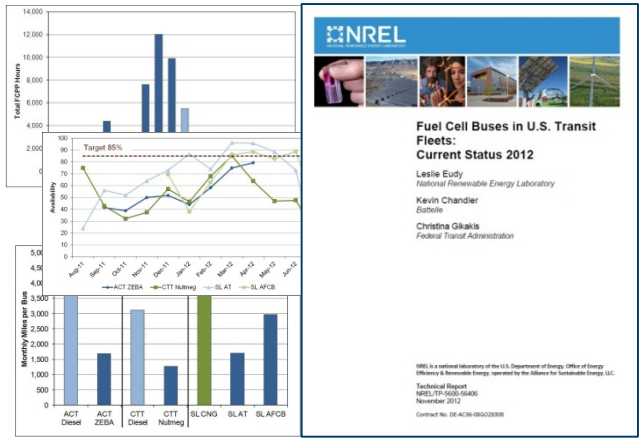
Approach

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)

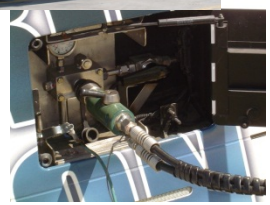
Individual Site Reports

- Documents performance results and experience for each transit agency
- Builds database of results
- Reports published and posted on NREL web site



Annual FCEB status report (milestone)

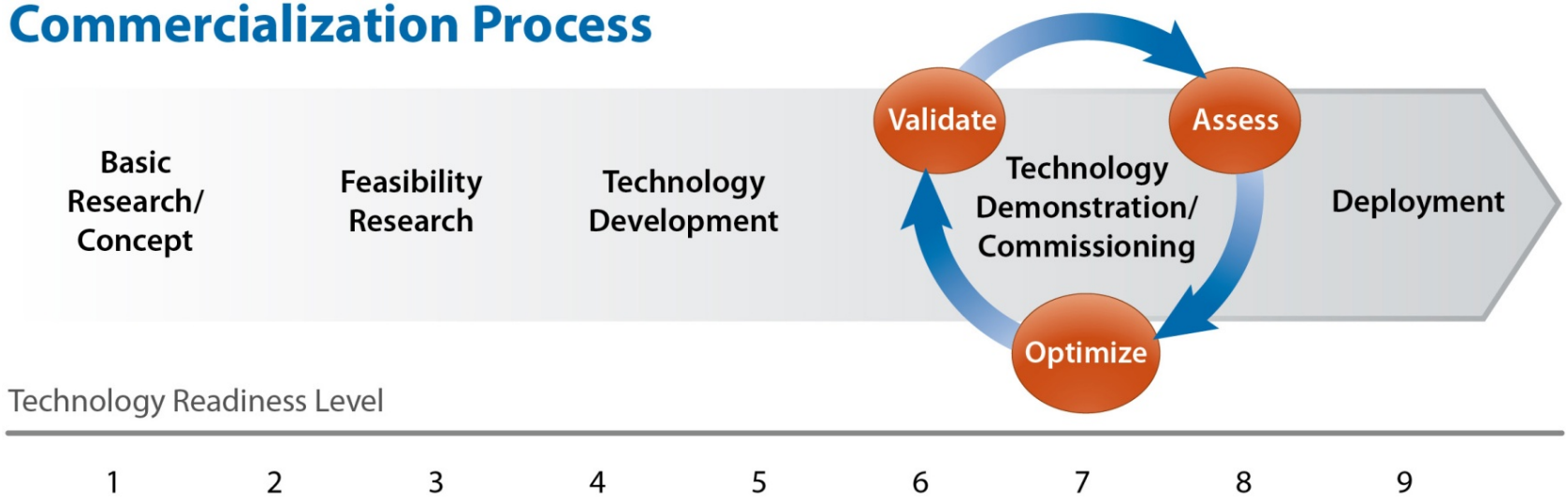
- Crosscutting analysis comparing results from all sites
- Assesses progress and needs for continued success
- Provides input on annual status for DOE/DOT Targets



Accomplishments: Progress Toward Targets

NREL Assesses Technology Readiness Levels

Commercialization Process



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

✓ Data included in Presentation

Data Summary for 2015

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	12	3
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

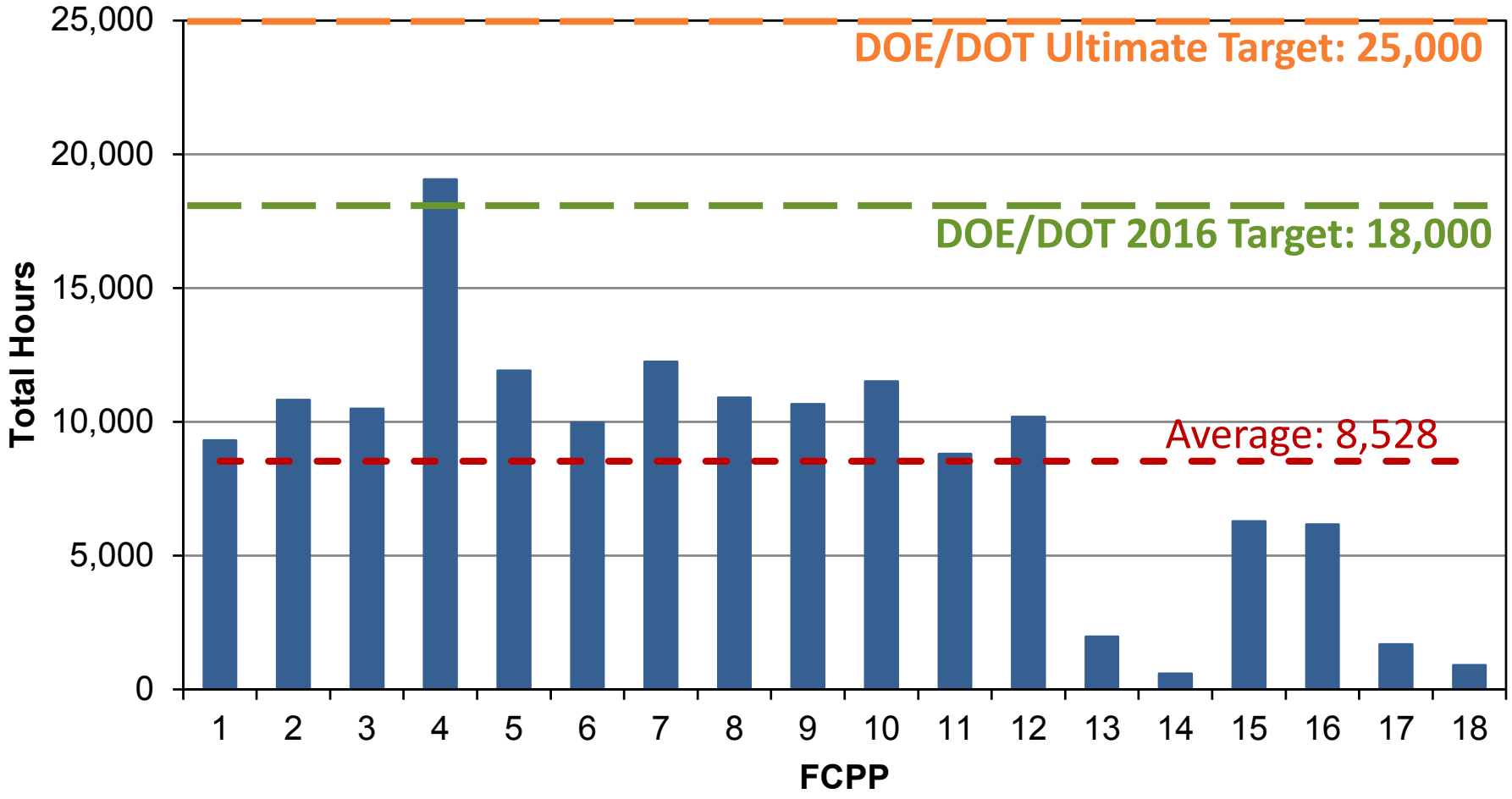
SL AFCB

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

Accomplishments : Progress Toward Targets

Top Fuel Cell Powerplant exceeds 19,000 Hours

Top FCPP > 19,000 hours, surpassing DOE/DOT target; 67% of FCPPs over 8,000 hours

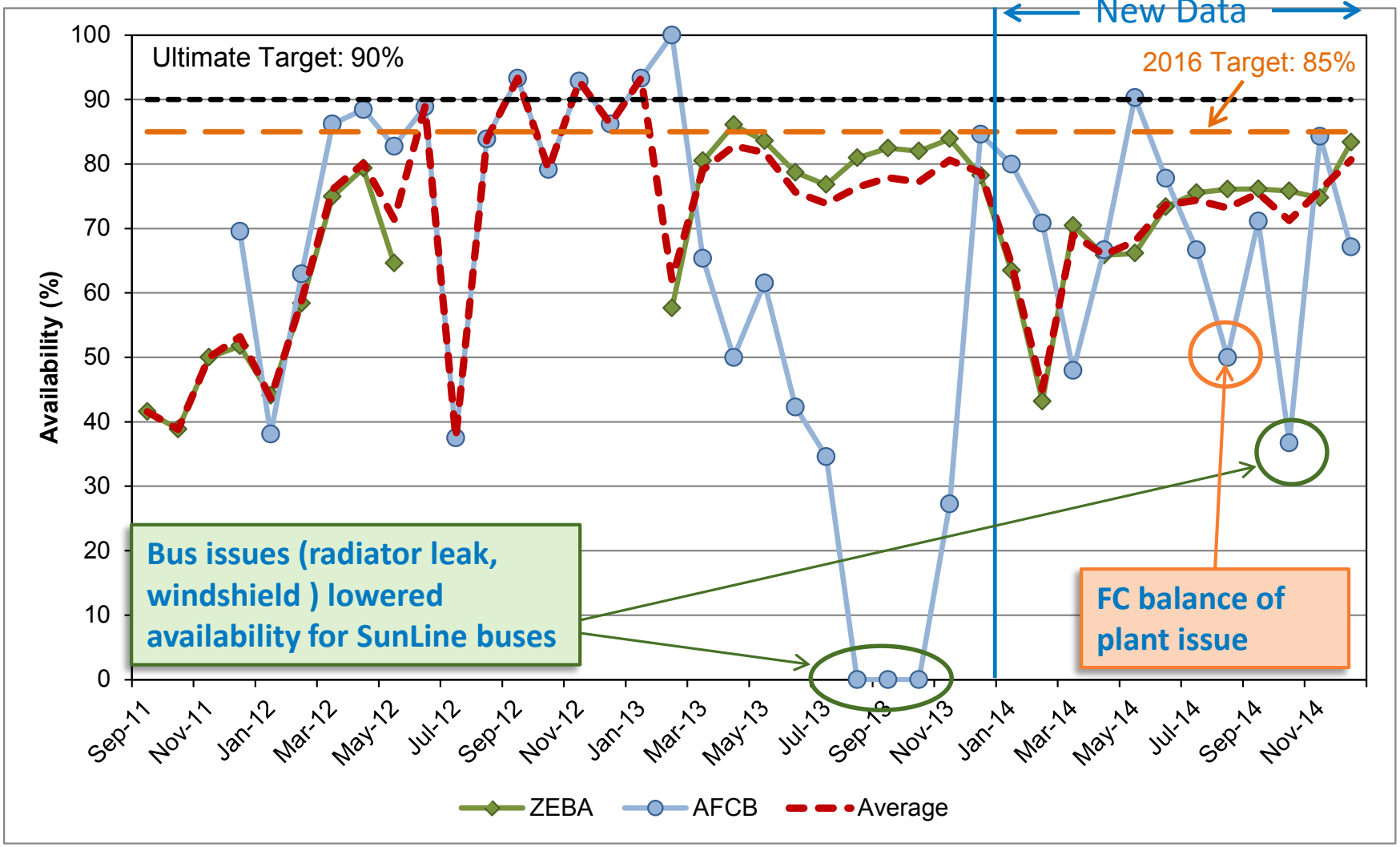


Total hours accumulated on each FC powerplant (FCPP) as of 3/31/15

Accomplishments : Progress Toward Targets

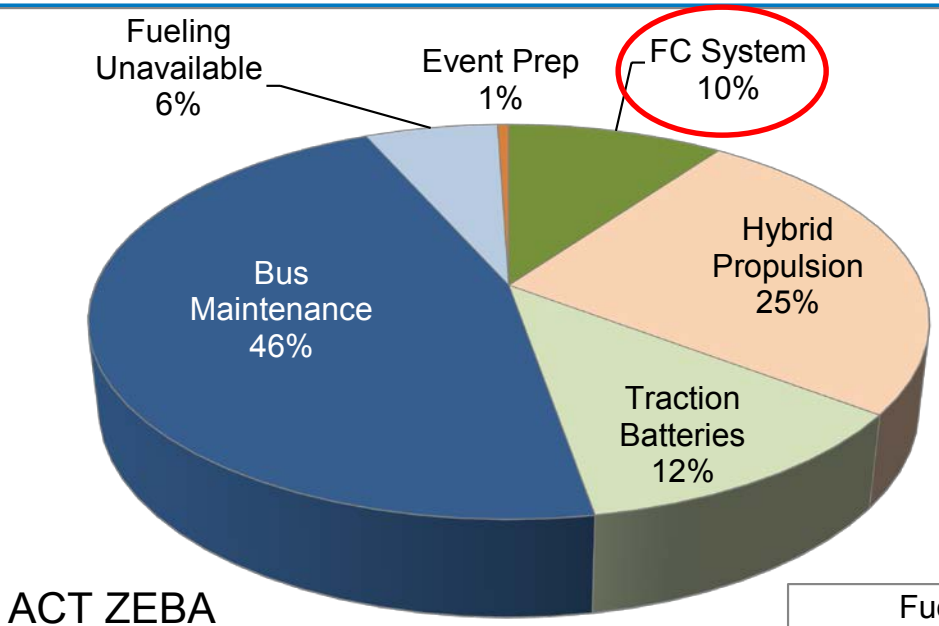
Average Bus Availability improves to 70%

Monthly bus availability



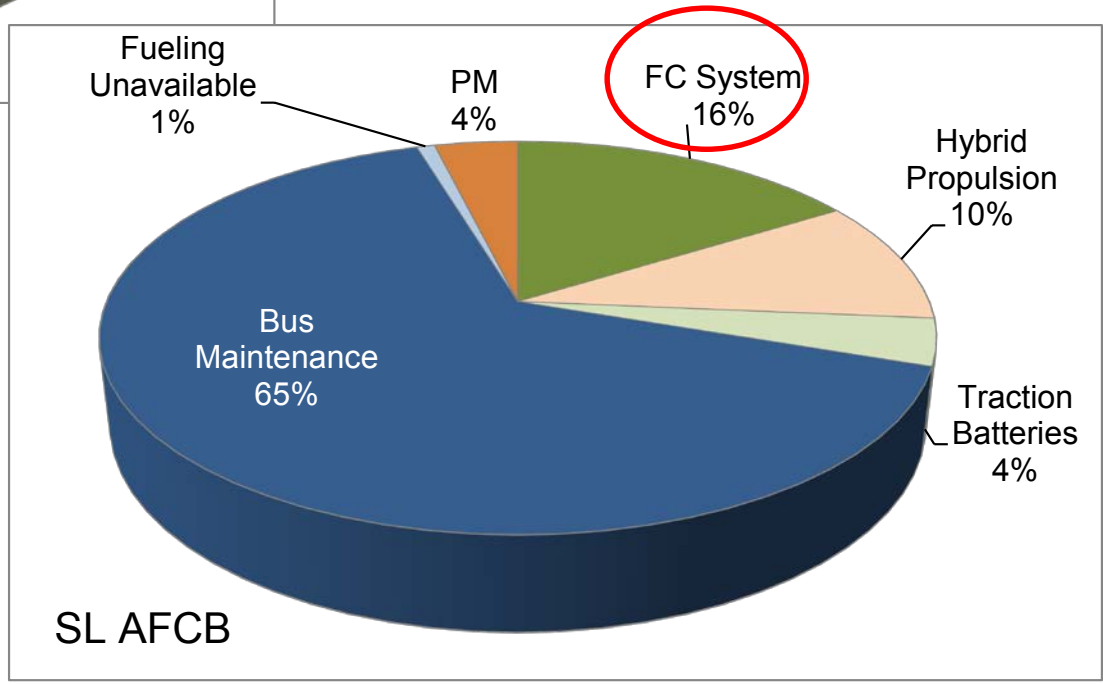
Availability = planned operation days compared to actual operation days

Reasons for Unavailability by Site



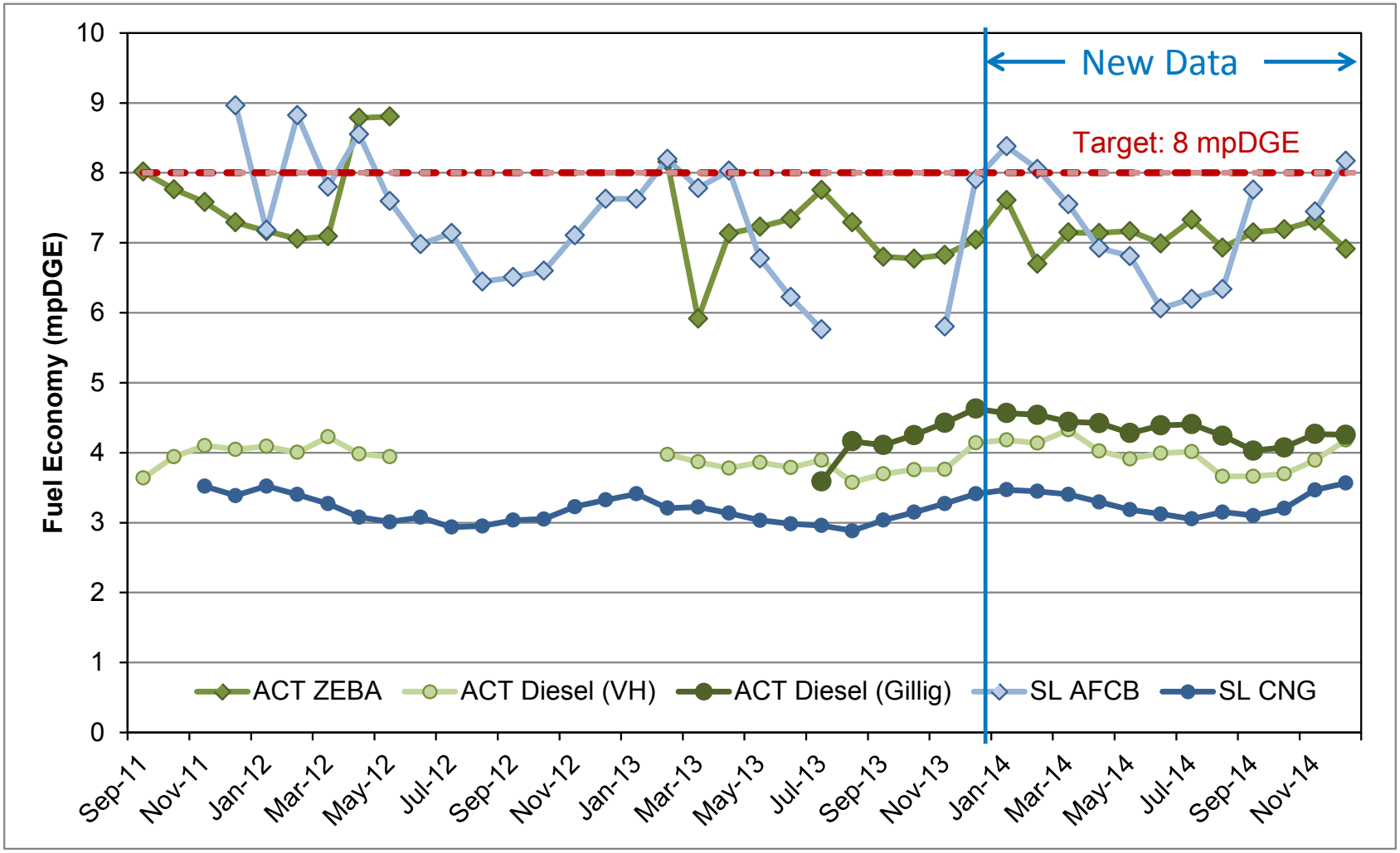
ACT ZEBA	Number	%
FC System	286	10
Hybrid Propulsion	733	25
Traction Batteries	344	12
Bus Maintenance	1,329	46
Fueling Unavailable	176	6
Event Prep	15	1
Total days	2,883	100

SL AFCB	Number	%
Fuel Cell System	59	16
Hybrid Propulsion	37	10
Traction Batteries	14	4
Bus Maintenance	237	65
Fueling Unavailable	3	1
Preventative Maint.	14	4
Total days	364	100



Accomplishments : Progress Toward Targets

Monthly Fuel Economy Compared to Baseline



Average

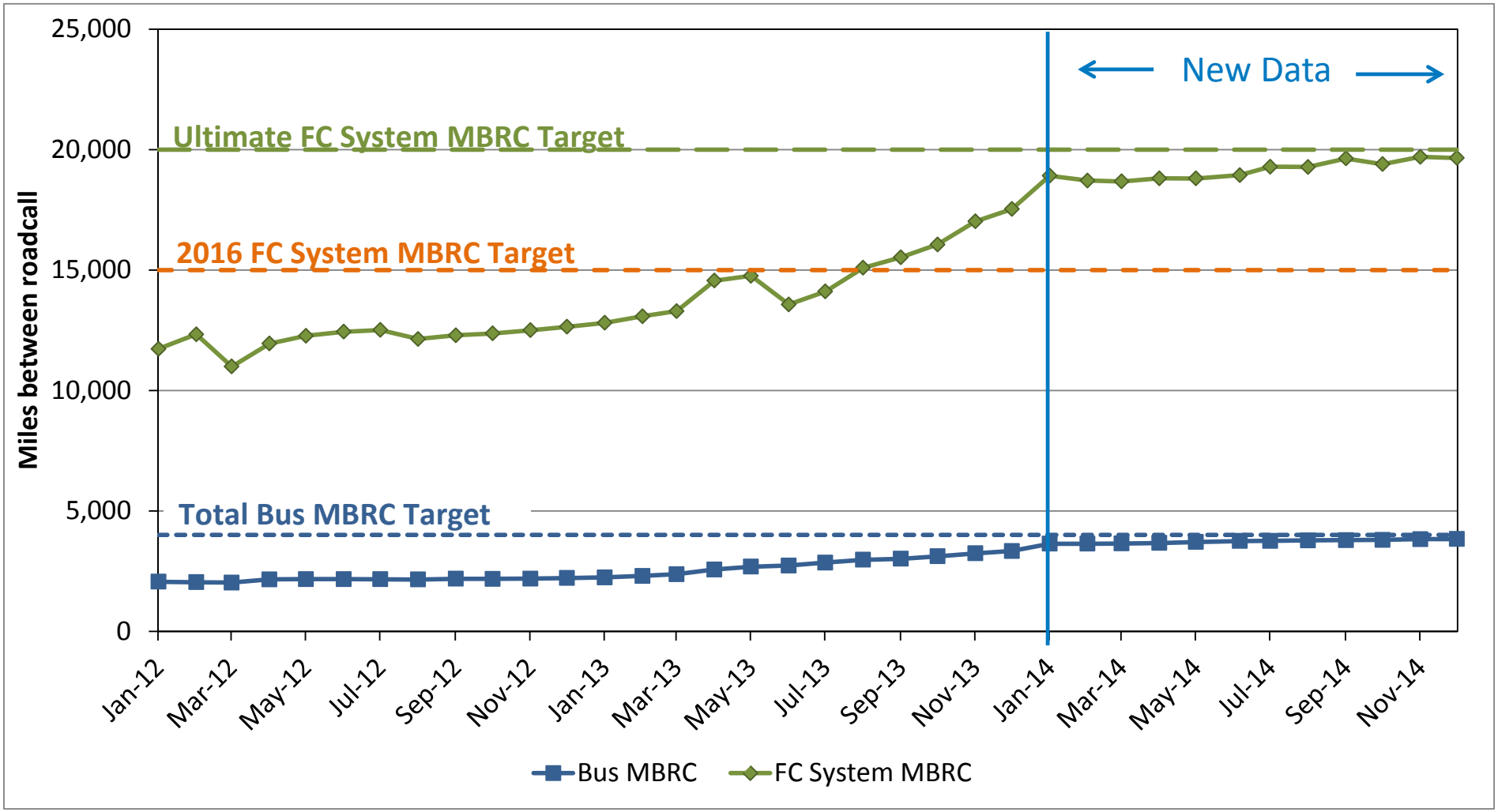
FCEB: 7.26

Diesel: 4.29

CNG: 3.43

Highly variable depending on duty cycle: average speed, terrain, auxiliary loads

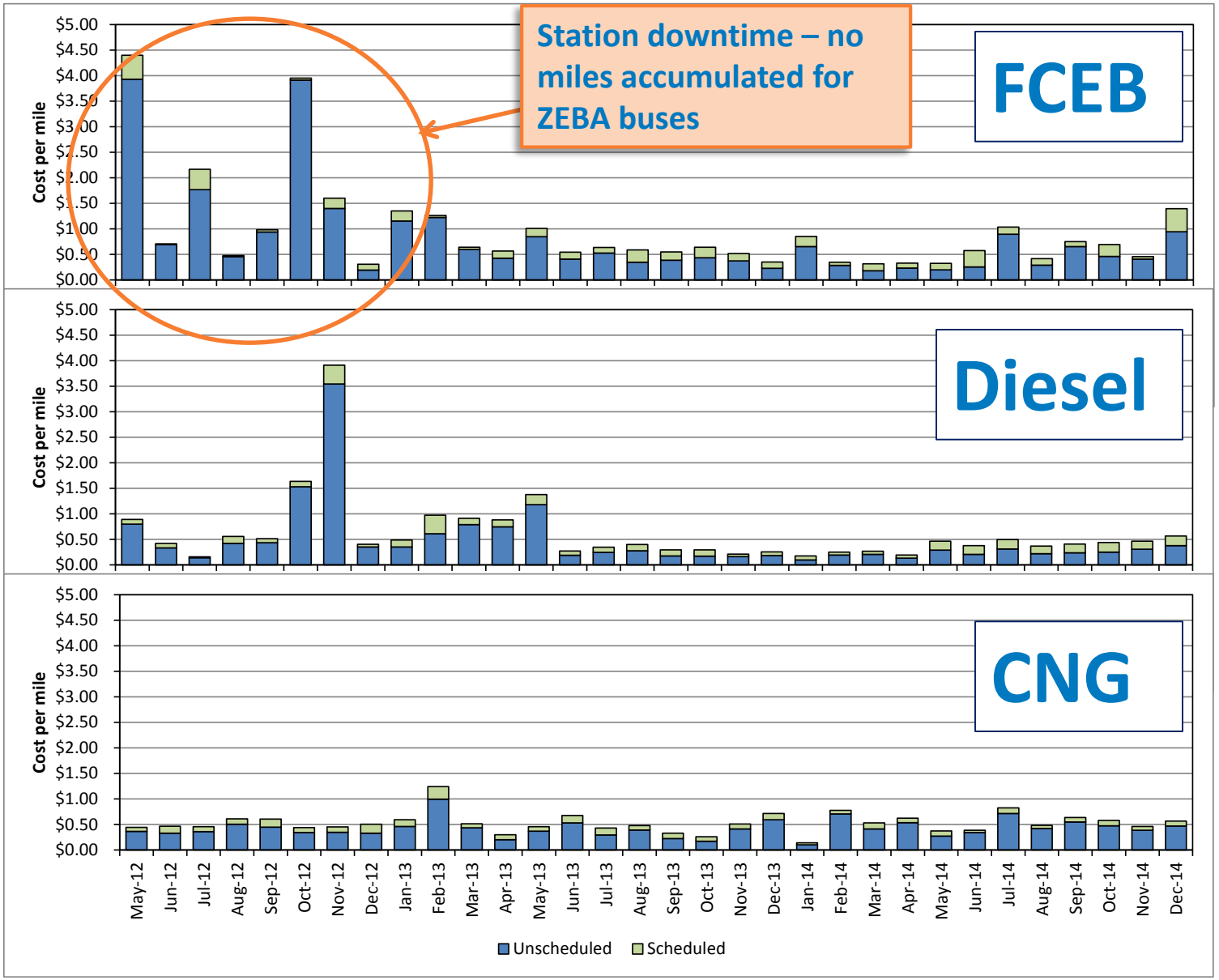
Reliability: Miles Between Roadcall (MBRC)



FC System MBRC surpasses 2016 target, approaching ultimate target

Accomplishments : Progress Toward Targets

Scheduled and Unscheduled Maintenance Costs per Mile



Monthly high and low

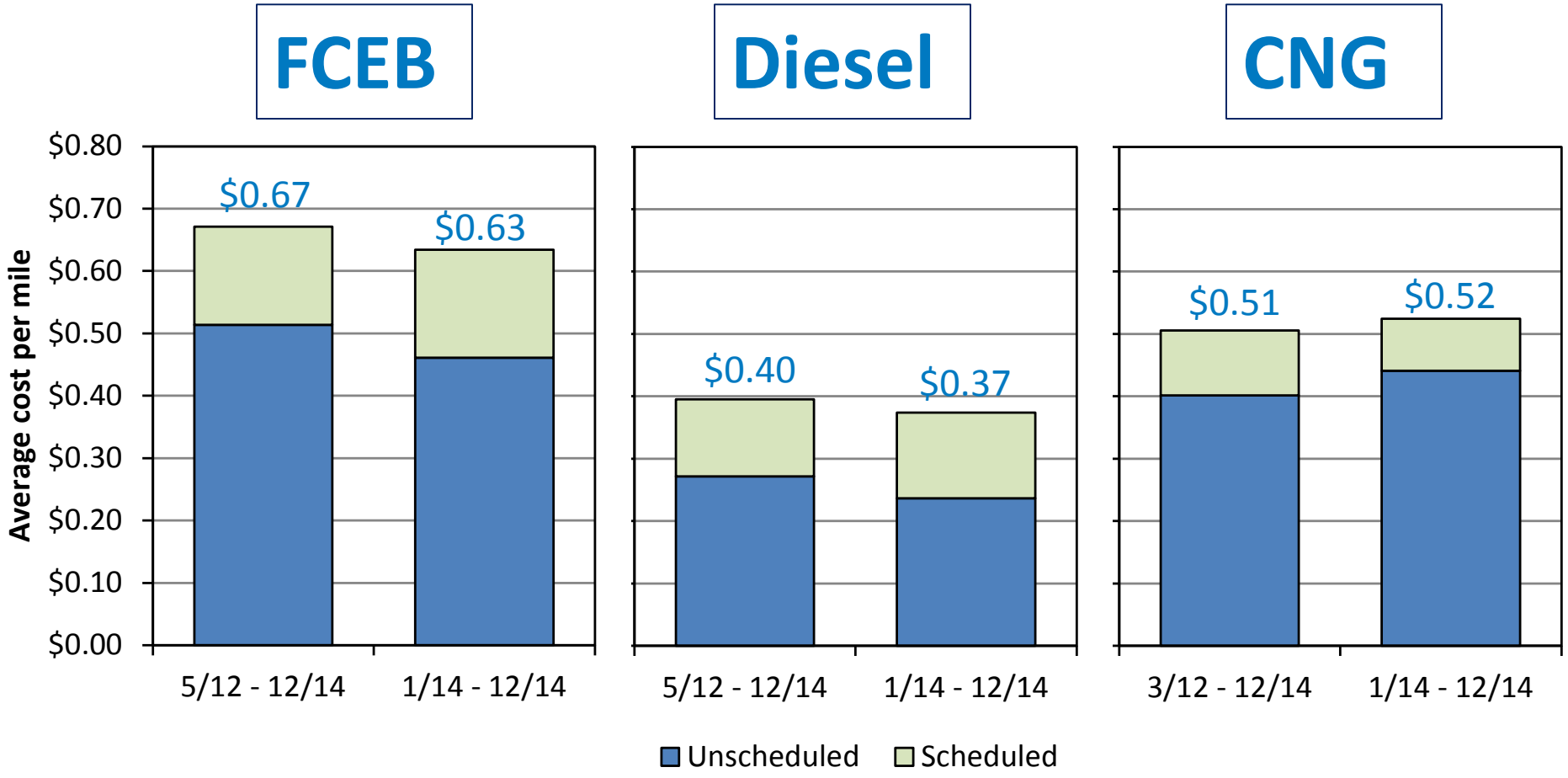
$4.40
$0.31

$3.91
$0.16

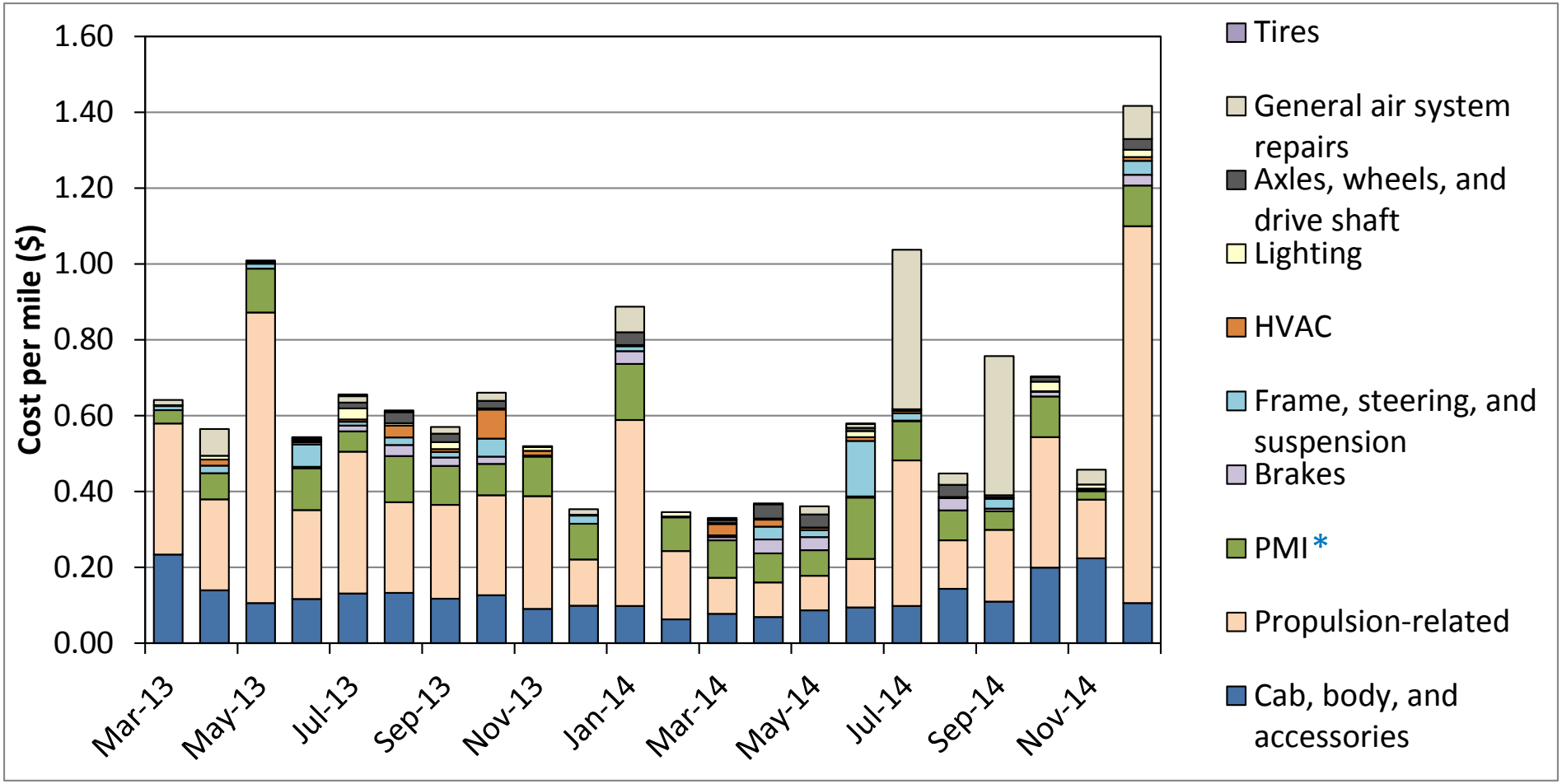
$1.24
$0.14

Accomplishments : Progress Toward Targets

Scheduled and Unscheduled Maintenance Costs per Mile



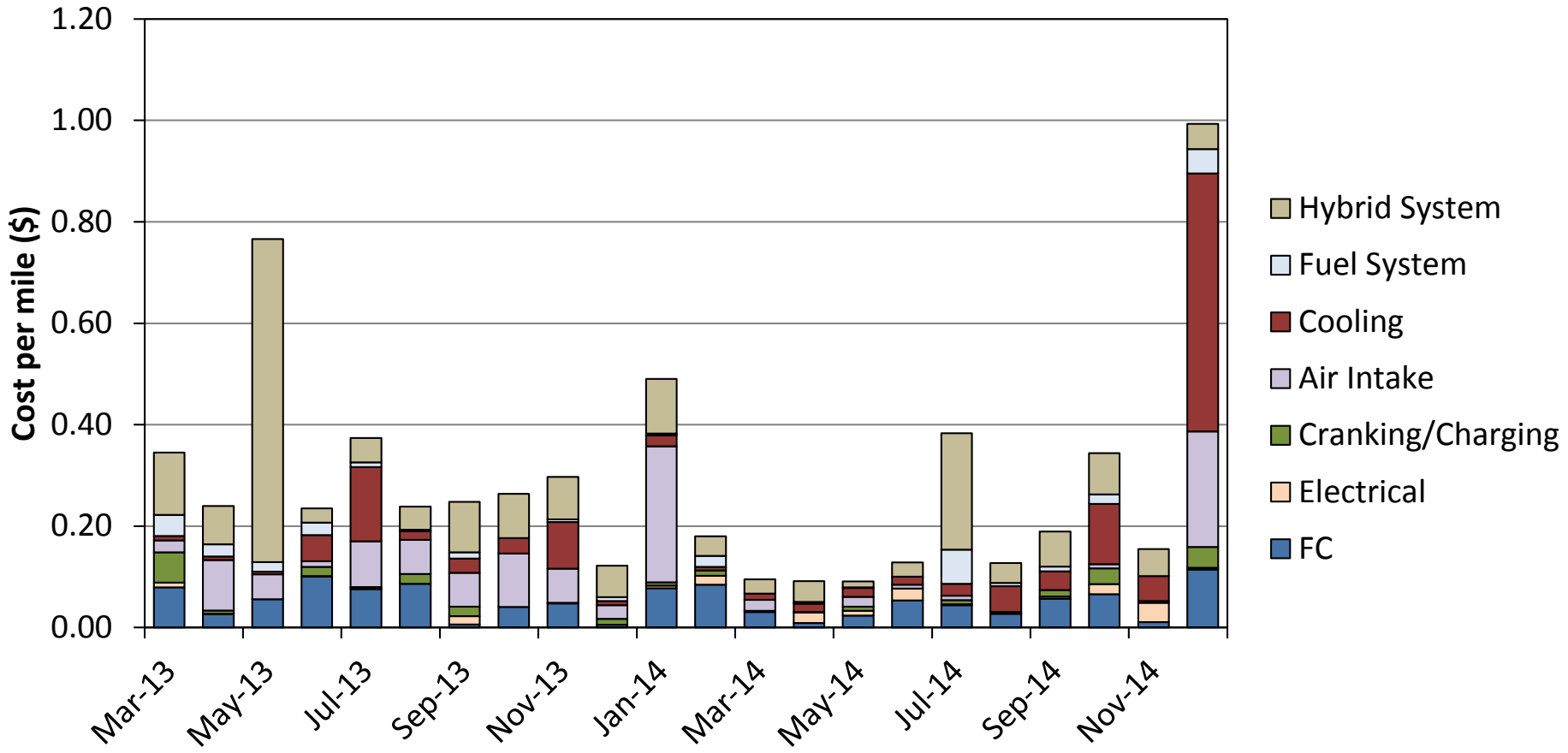
Maintenance Cost per Mile by System



Propulsion system costs make up 46.9% of total maintenance costs followed by Cab, body, and accessories at 19.6%

*PMI – Preventative Maintenance Inspection

Propulsion System Cost per Mile by Sub-System



FC System costs are only 8.3% of total maintenance costs
Costs are high for some components:
Inverter replacement for 1 bus in May 2013
Coolant system issues with 2 buses in December 2014

Accomplishments and Progress:
Responses to Previous Year Reviewers' Comments

- **Please highlight which systems had the least and greatest maintenance costs.**
  - Maintenance costs by system are included in the presentation. (Slide 14-15)
- **Would be useful to know if MBRC is prescribed by the manufacturer and if they are being overly conservative**
  - The MBRC targets were developed with industry input (primarily transit agencies) and are based on standard diesel technology. Actual MBRC varies by agency and depends on the diligence of maintenance practices at a depot. (i.e. maintaining scheduled PMs)
- **Would add information from other countries to gauge how close to commercialization this technology may be.**
  - We participate in International Fuel Cell Bus Workshops to share data with demonstrations outside the United States. Any detailed analysis/comparisons would require access to data (with similar metrics) from international projects which is currently not available and out of scope of this project.
- **NREL should continue to work with different configurations of FCEBs**
  - NREL is now collecting data on battery-dominant FCEBs, but does not have enough data to present results yet.
  - NREL is focused on manufacturer teams that intend to commercialize a product.

Collaborations

- **Transit agencies provide data on buses, fleet experience, and training, and review reports**
  - California: AC Transit, Golden Gate Transit, Santa Clara VTA, SamTrans, SunLine, UC Irvine
  - Alabama: Birmingham-Jefferson County Transit Authority
  - Texas: Capital Metro, Austin
  - Massachusetts: Massachusetts Bay Transportation Authority
- **Manufacturers provide some data on buses and review reports**
  - Bus OEMs: Proterra, Van Hool, New Flyer, ElDorado National
  - FC OEMs: Ballard, Hydrogenics, Nuvera, 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**
- **Improve integration/optimization of systems and components**
- **Transition build process with OEM taking the primary role for bus production**
- **Develop robust supply chain for components and parts**
- **Increase learning curve for maintenance staff—training and tools**
- **Reduce cost, both capital and operating**

Proposed Future Work

Fuel Cell Electric Bus Evaluations for DOE and FTA

Demonstration	State	City	# Buses	2014		2015				2016				2017			
				3	4	1	2	3	4	1	2	3	4	1	2	3	4
ZEBA Demonstration *	CA	Oakland	12	AC Transit													
American Fuel Cell Bus (AFCB) *	CA	Thousand Palms	1	SunLine													
	NY	Ithaca	1						TCAT								
	OH	Canton, Cleveland	2							SARTA/GCRTA							
	CA	Irvine	1				UCI										
AFCB (TIGGER)	MI	Flint	1					Flint MTA									
	CA	Thousand Palms	3	SunLine													
Birmingham FCEB *	AL	Birmingham	1	BJCTA													
Massachusetts AFCB *	MA	Boston	1				MBTA										
Advanced Composite FCEB *	TX	Austin	1			Capital Metro											
	DC	Washington							DCDOT								
Next-gen Compound Bus *	CA	San Francisco	1						SFMTA								
Battery Dominant AFCB *	CA	Thousand Palms	1							SunLine							
AFCB (LoNo)	CA	Thousand Palms	5									SunLine					
	OH	Canton	5									SARTA					

Jun 2015

* 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
- Diesel hybrid with fuel cell primarily for accessories

Proposed Future Work

- **Remainder of FY 2015**
  - Complete following data analyses/reports:
    - AC Transit, ZEBA Demo Report, Apr 2015
    - SunLine AFCB Report, May 2015
    - Birmingham FCEB Report, August 2015
    - 2015 Annual Status Report, Sep 2015
  - Begin data collection on FCEBs in Boston, Ithaca, University of California Irvine
- **FY 2016**
  - 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
  - Policy making organizations
  - Funding organizations
- **No technology (hardware/software) is developed through this project**

Summary

Documented progress toward targets:

	Units	Current Status	2016 Target	Ultimate Target
Bus lifetime	Years / miles	5/100,000	12/500,000	12/500,000
Powerplant lifetime[1]	Hours	1,000 –19,000	18,000	25,000
Bus availability	%	70	85	90
Roadcall frequency[2] (Bus/fuel cell system)	Miles between roadcall	4,256 / 18,896	3,500/15,000	4,000/20,000
Operation time	Hours per day/ days per week	19/7	20/7	20/7
Maintenance cost	$/mile	0.67	0.75	0.40
Fuel economy	Miles per diesel gallon equivalent	7.26	8	8
Range	Miles	220 – 310	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