CARB Low NOx Program Update

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Integer Emissions Summit and DEF Forum

October 27, 2015

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Agenda

- Program Objectives
- Timelines
- Program Engines
- Test Cycles
- Diesel Program Update
  - Baseline
  - Engine Calibration
  - Aftertreatment Screening
- CNG Program Update

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Program Objectives

- Development target is to demonstrate 90% reduction from current HD NO_X standards
  - 0.02 g/bhp-hr
  - Aged parts
- Solution must be technically feasible for production
- *Solution must be consistent with path toward meeting future GHG standards*
  - *CO_2, CH_4, N_2O*

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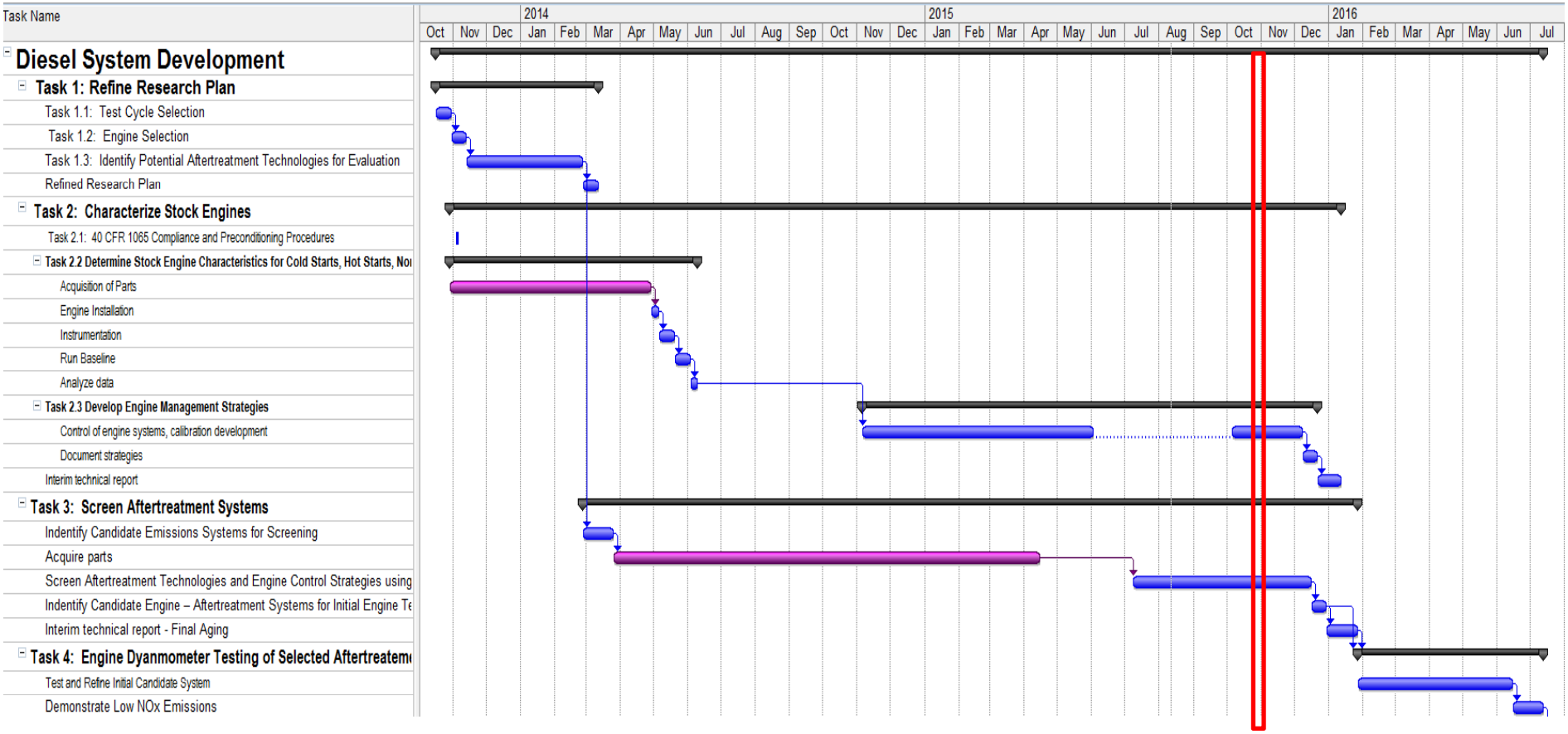
Diesel Timeline



Final Demonstration is projected for July 2016

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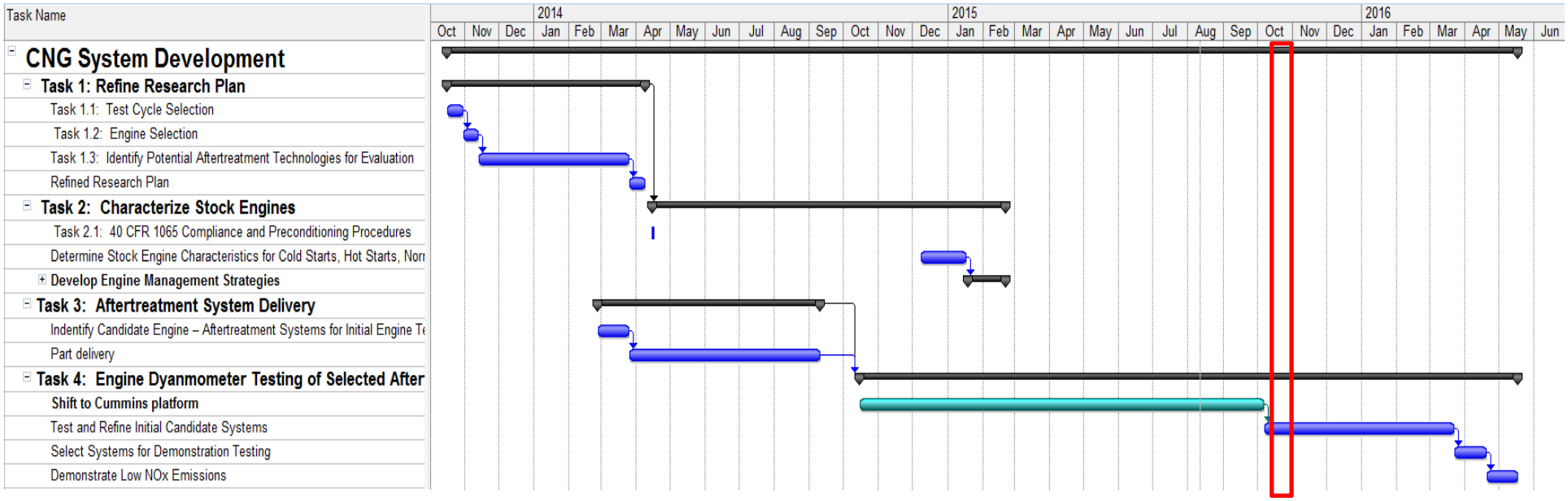
CNG Timeline



Final Demonstration is projected for May 2016

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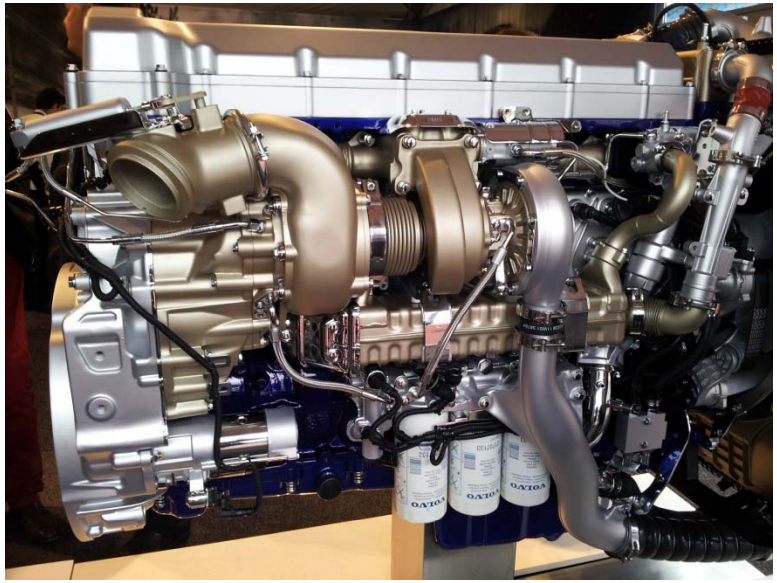
Diesel Engine

- **2014 Volvo MD13TC Euro VI**
  - Line Haul application
- Production engine in Europe at the time of selection
- Meets U.S. 2010 and Euro-VI standards
  - 361 kw @ 1477 rpm
  - 3050 NM @ 1050 rpm
  - 550 rpm idle
- Representative of direction OEM intends to pursue for future GHG standards



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Natural Gas Engine

- **2012 Cummins ISX12-G**
  - **Bus application**
- Original choice was Doosan 11-liter gas engine under development at SwRI
  - Baseline engine PM was a problem due to mechanical design issue
- SwRI decision was to change to production ISX12-G engine
  - Major additional efforts required (covered by SwRI funding)
    - 250kw @ 2100 rpm
    - 1700 NM @ 1300 rpm
    - 725 rpm idle

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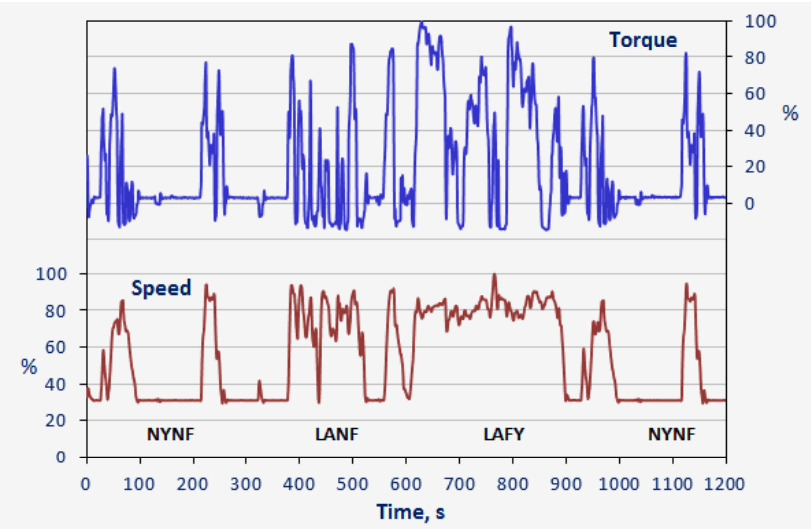
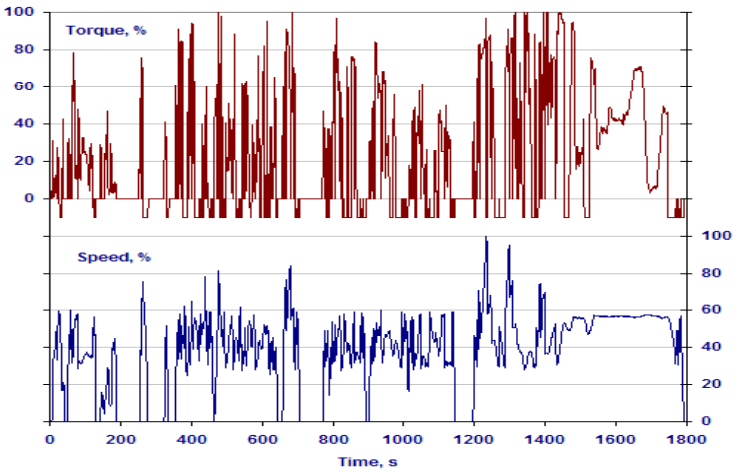
Test Cycle Selection

- Primary Cycles for Program
  - US HD FTP – primary focus
  - WHTC – "lower temperature"
  - RMC-SET – required for GHG assessment
  - CARB Idle
  - Primary Cycles are calibration focus



- Additional Vocational Cycles
  - NYBC, ARB Creep, OCTA
  - Lower load operation (drayage, etc.)
  - Demonstration only (no additional calibration)



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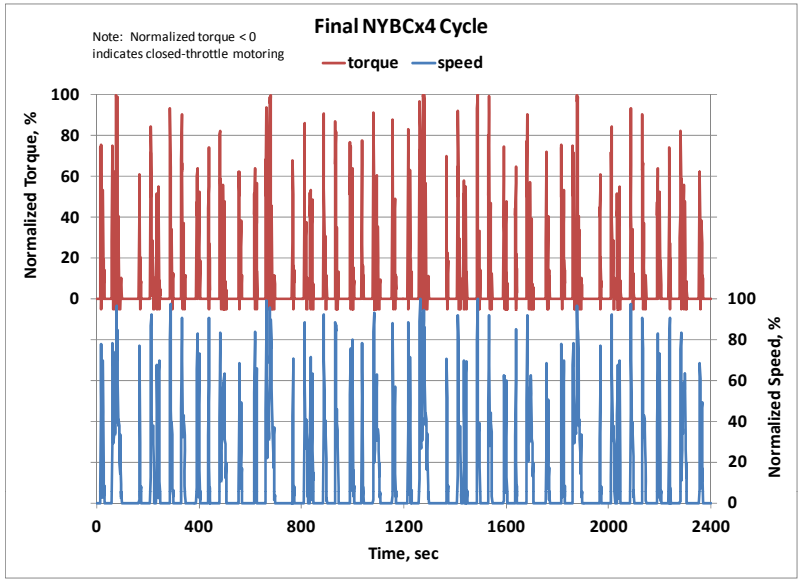
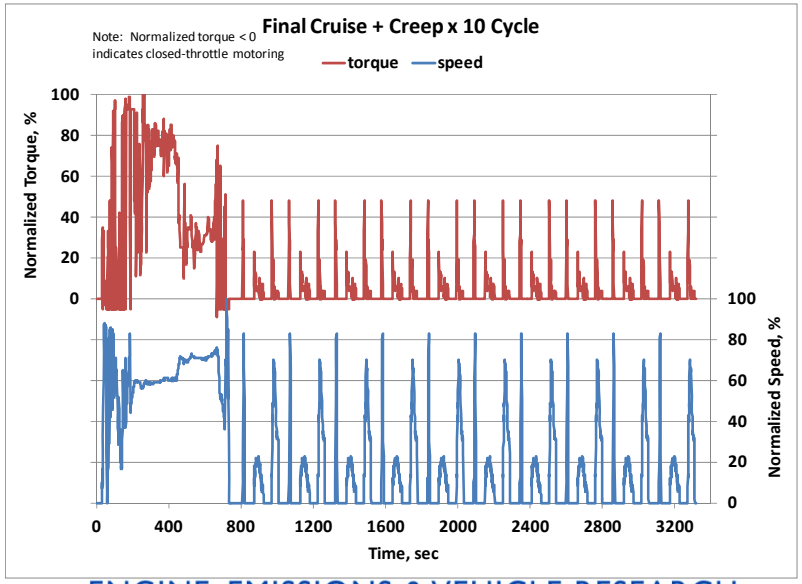
Vocational Cycles

- NYBC x4
  - Cool start (after 30 min idle)
  - Highly transient light-load (41 min)
- Cruise + Creep Cycle
  - 50mph Cruise 20min + Creep x10 (42min)
  - Warm start
  - Test temperature maintenance
- OCTA Cycle
  - 20min + 31.8 min
  - Typical vocational (drayage) operation





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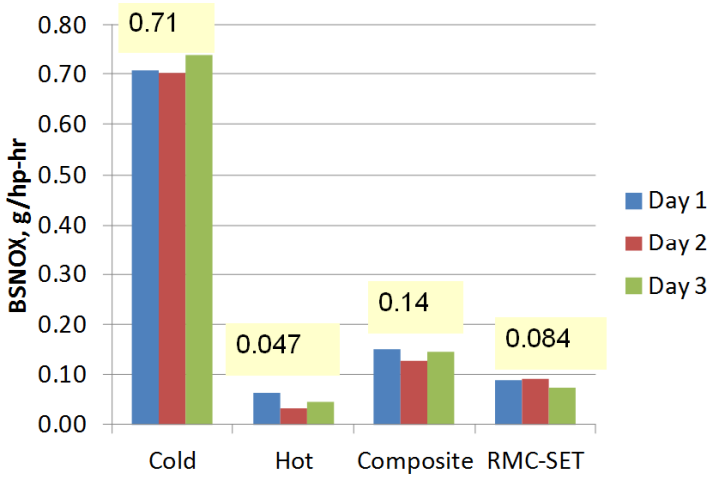
Diesel Baseline – Tailpipe Emissions

	Composite FTP Tailpipe, g/hp-hr				
	NOx	PM	NMHC	CO	CO2
Average	**0.14**	0.001	0.0004	1.0	547.1
SD	**0.012**	0.0003	0.0003	0.09	1.84
COV	**8.5%**	24%	88%	8.8%	0.3%
SD % Std	**5.9%**	2.5%	0.2%	0.6%	n/a

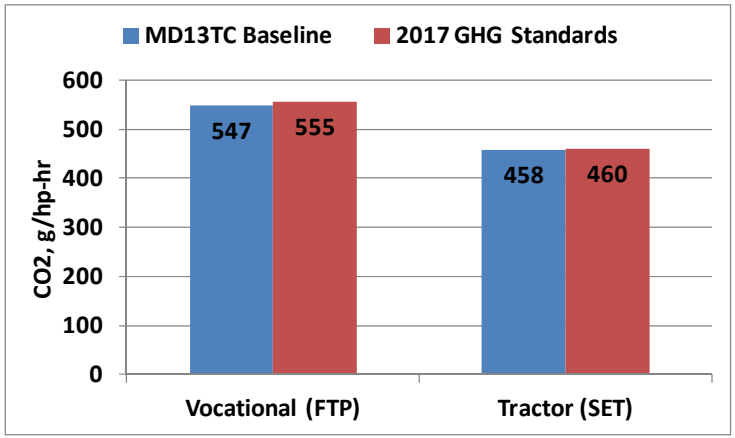
No tailpipe NH_3
Tailpipe N_2O ~ 0.03 g/hp-hr



Engine-out NOx ~ 3 g/hp-hr

	RMC-SET Tailpipe, g/hp-hr				
	NOx	PM	NMHC	CO	CO2
Average	**0.08**	0.002	0.003	0.02	457.7
SD	**0.009**	0.0014	0.0003	0.001	0.72
COV	**11.0%**	70%	9%	5.9%	0.2%
SD % Std	**4.6%**	13.6%	0.2%	0.0%	n/a

No tailpipe NH_3
Tailpipe N_2O ~ 0.05 g/hp-hr



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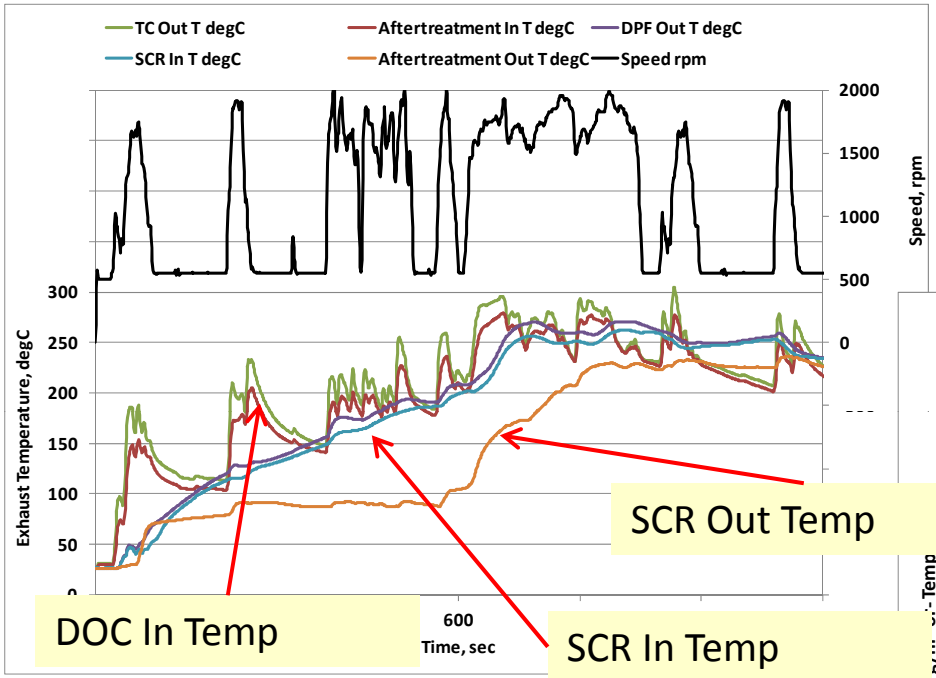
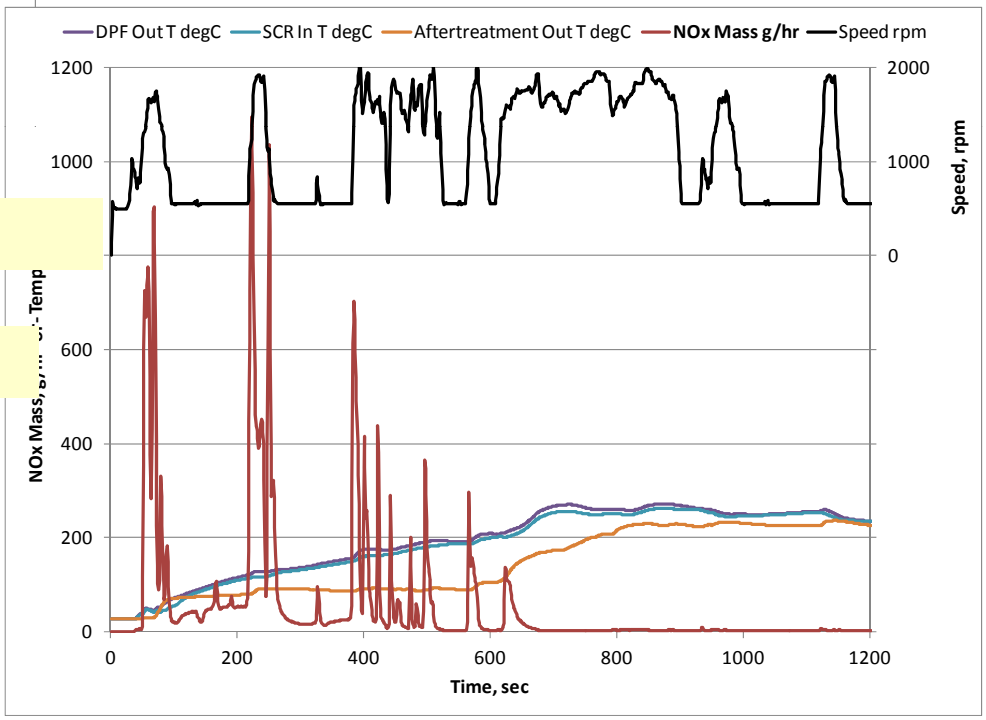
Diesel Baseline – Cold-Start Temperatures and NOx



Engine-Out NOx = 2.9 g/hp-hr
TP NOx = 0.7 g/hp-hr
Conversion = 75%



Average AT inlet = 196°C
First 200 secs = 99°C
Time to 180°C
- AT Inlet – 230 secs (380)
- <u>SCR Inlet – 550 secs</u>

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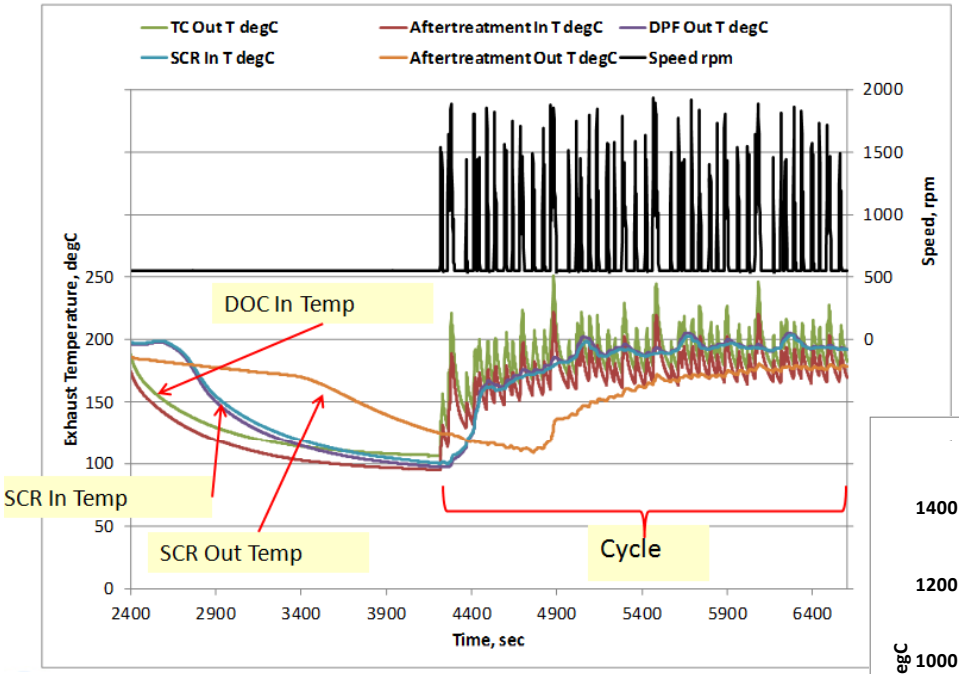
Example Vocational Cycle – NYBCx4

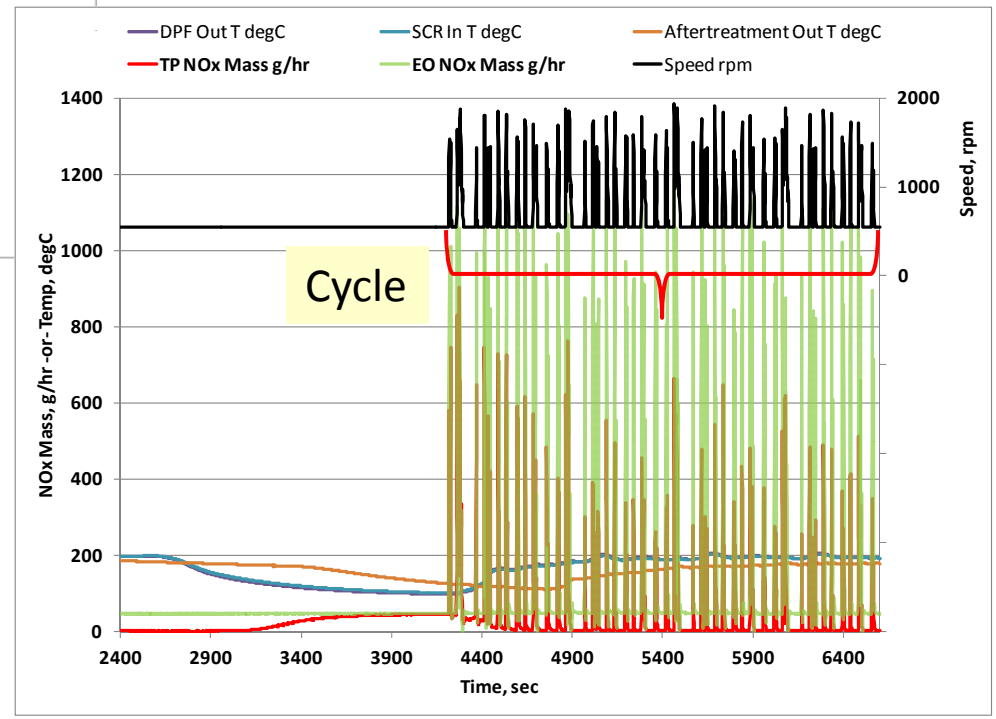


- Preconditioned with warm-up and NYBCx4 cycle before 30-min idle segment
- Note that entire cycle would be below current NTE range

Cycle average power ~ 17kw

EO ~ 6 g/hp-hr
TP ~ 2.4 g/hp-hr
62% conversion cycle average

Conversion still improving at end



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Cold-start Engine Calibration Strategy

- Engine measures for reducing cold-start emissions focused on increasing exhaust temperature and reducing engine-out NOx during SCR warm-up

- Engine-based measures utilized:
  - Multiple in-cylinder injections (7th injector available)
  - Early and increased EGR
  - Elevated idle speed
  - Intake throttling (exhaust throttle available)

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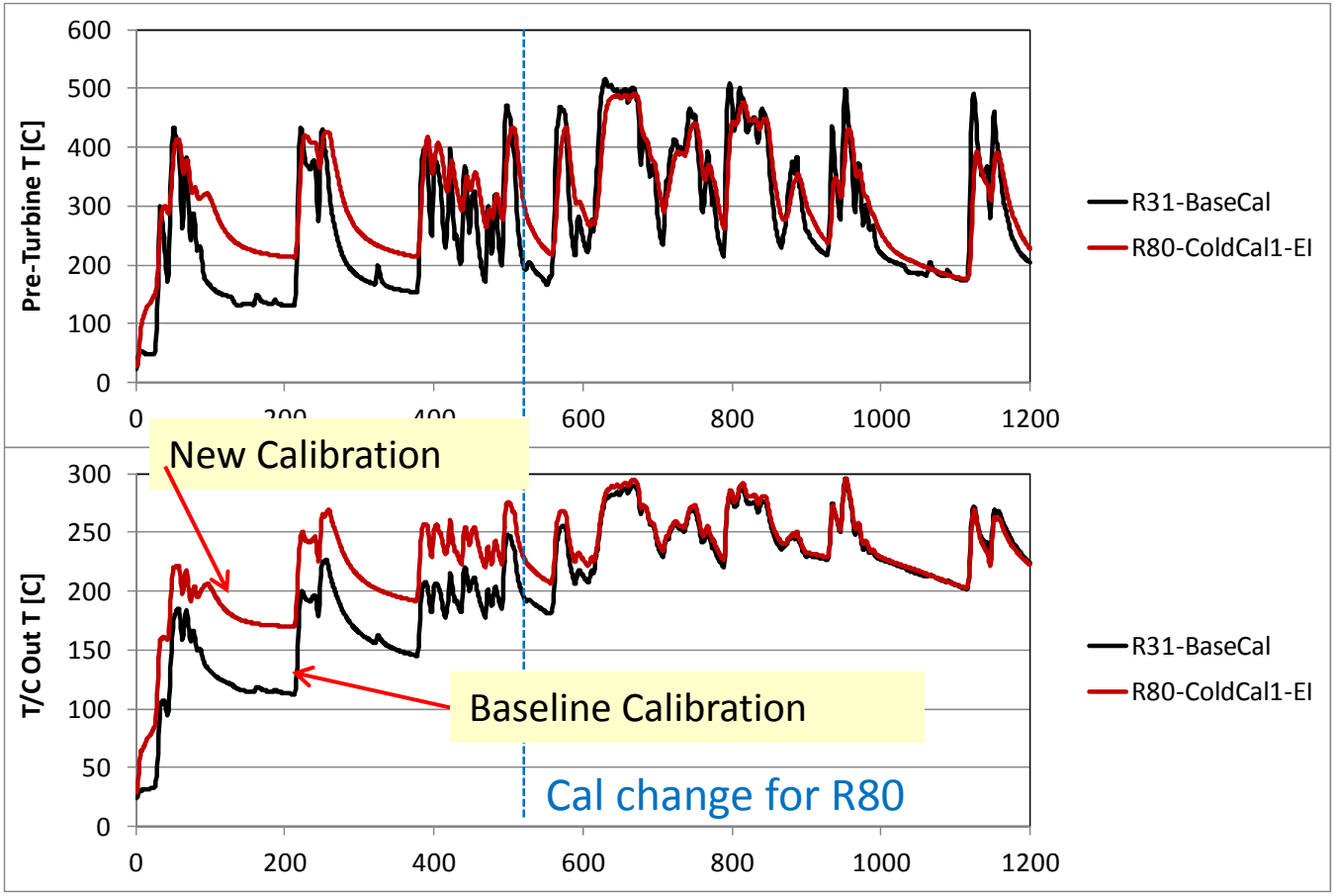
Modified Cold-Start Calibration – Temperatures



For R80, switch from Cold Cal 1 to Base Cal occurred during the 30 sec idle period after 525 sec

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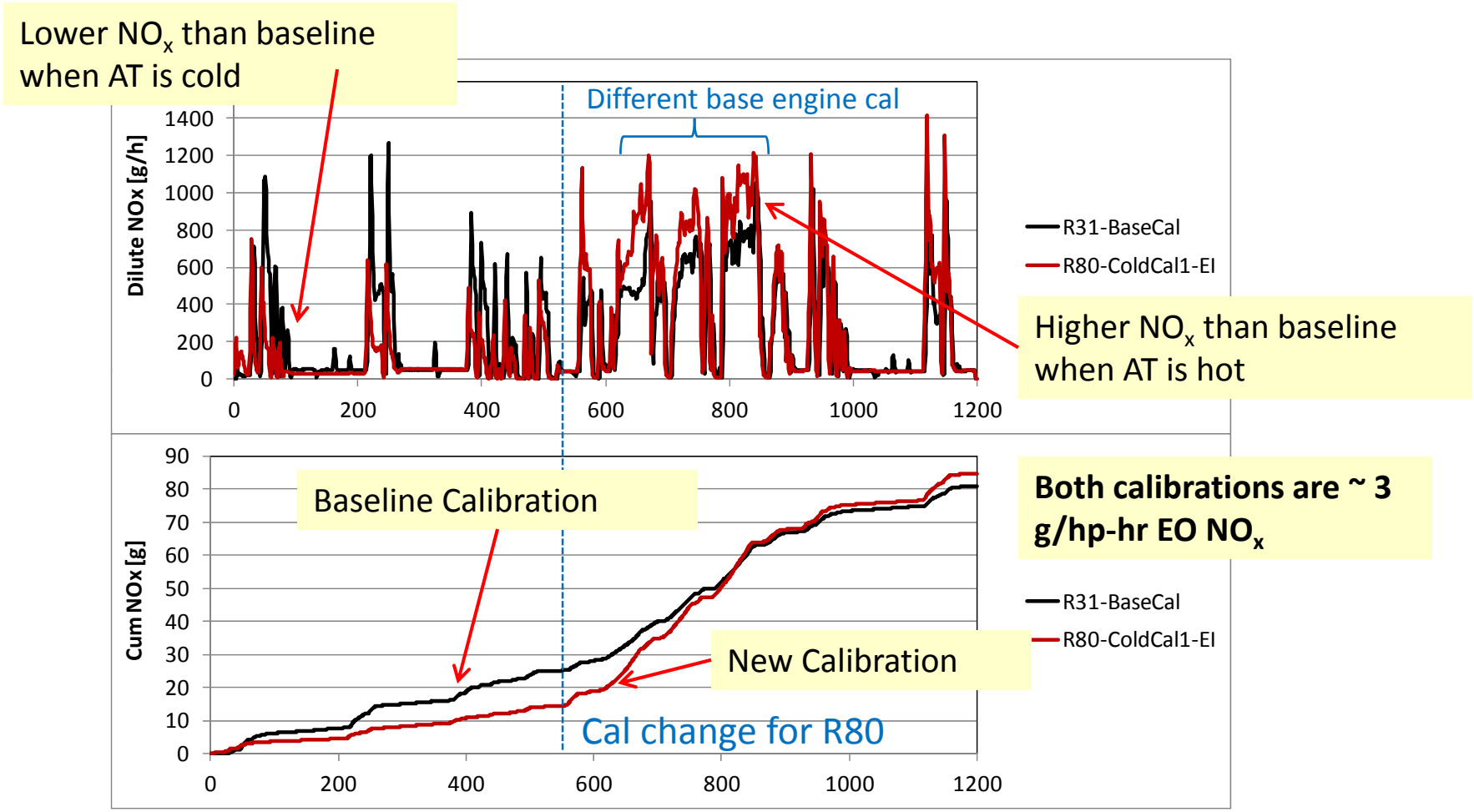
Modified Cold-Start Calibration - NO_x



For R80, switch from Cold Cal 1 to Base Cal occurred during the 30 sec idle period after 525 sec

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Cold FTP Emissions Summary

Run	Cal.	Cum EO Thermal Energy (0-525 s)	Cum EO NOx (0-525 s)	Cycle BSNOx	Cycle BSFC	Cycle BSPM
		[MJ]	[g]	[g/hp-hr]	[g/kWh]	[g/hp-hr]
31	**Base**	**31.4**	**24.8**	**2.98**	**241**	**0.19**
86	Cold Cal 1 - Base Idle	26.9	13.2	2.81	239	0.22
82	**Cold Cal 1 – Elev Idle**	**31.5**	**14.2**	**3.04**	**247**	**0.20**
R82 equivalent to R80 in Calibration. R82 includes air gap insulated manifold and downpipe						

Engine calibration changes currently result in 0.4% penalty to Composite BSFC (2.5% on cold-start FTP) with R82 (elevated idle version)

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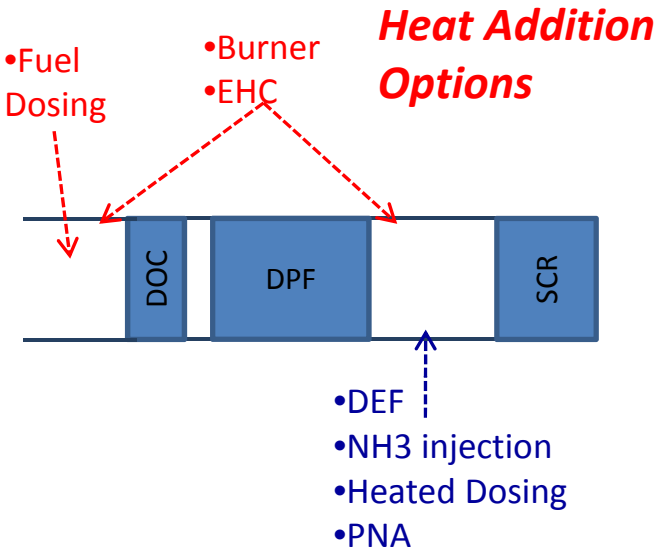
Aftertreatment Technology Approaches

Traditional Approach



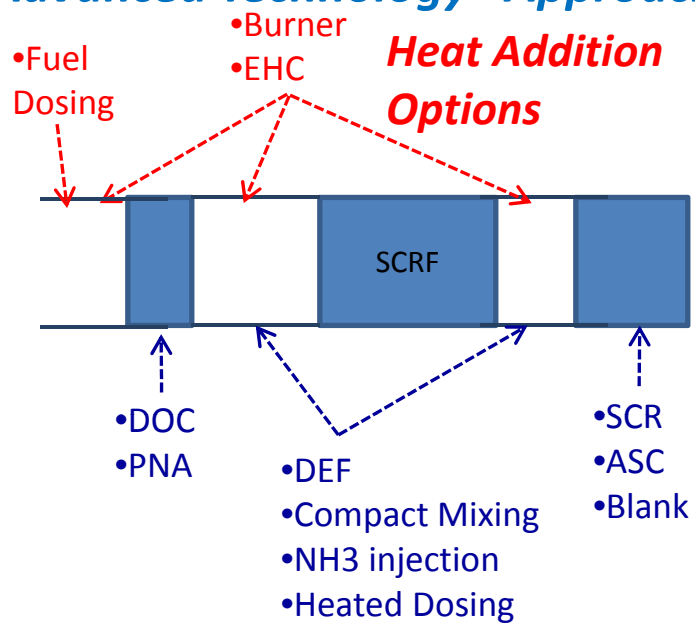
Advantages

- Retains passive regeneration of filter

Disadvantages

- Large thermal mass upstream of SCR

"Advanced Technology" Approach



Advantages

- Low upstream thermal mass, Rapid light-off

Disadvantages

- Competition for NO2 reduces passive regeneration

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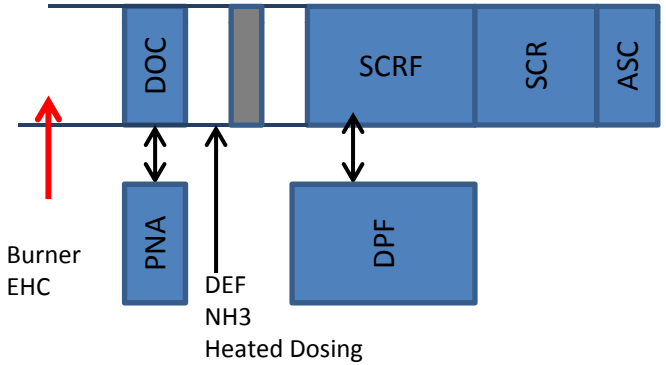
Technology Screening

- **Primary objective is to provide information for the technology down selection for final demonstration**
  - Performance achieved
  - Repeatability of performance
  - Fuel economy impact of solution
  - Simplicity of Solution



- *Goal is to evaluate combinations of Advanced and Traditional technology systems and production viable modifiers to assess the potential Low NOX performance of various combinations of technologies and strategies*

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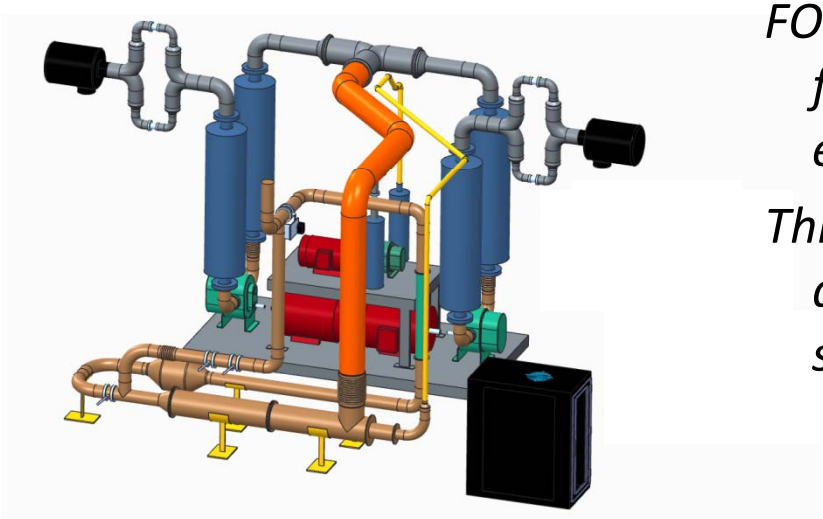
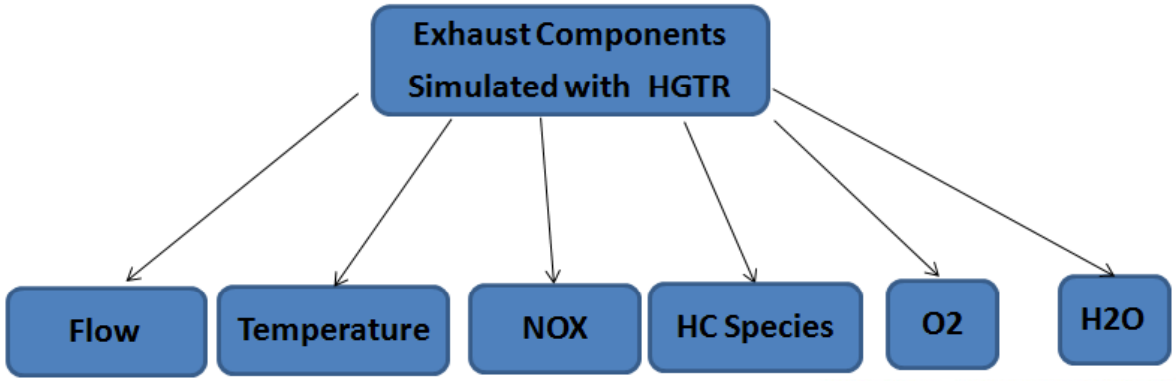
HGTR – Hot Gas Transient Reactor



FOCAS-HGTR is a computer controlled diesel-fuelled burner system, designed to simulate the exhaust conditions of a wide range of engines.

This is a full size, continuous gas reactor which accommodates testing of full-sized catalyst systems

Independent control of exhaust gas variables



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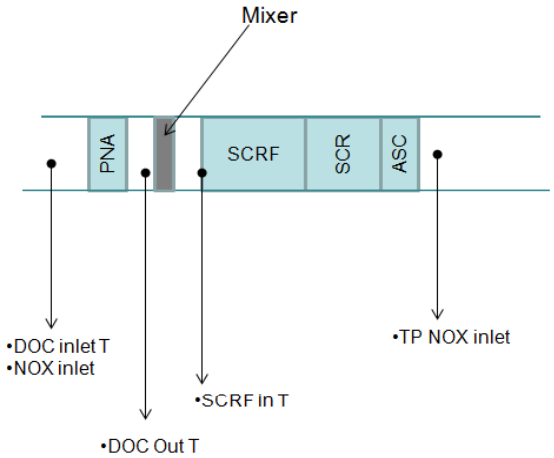
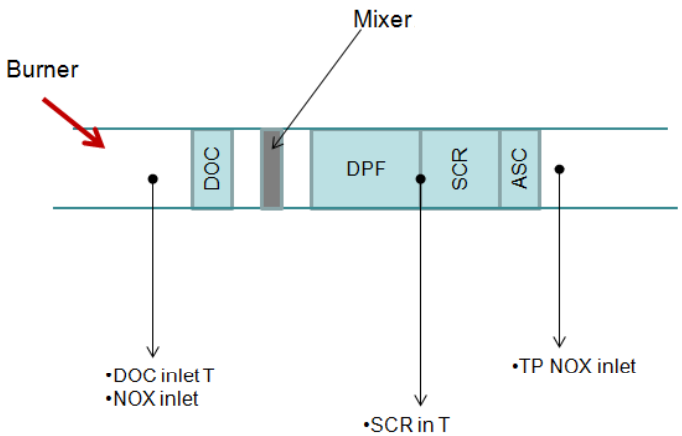
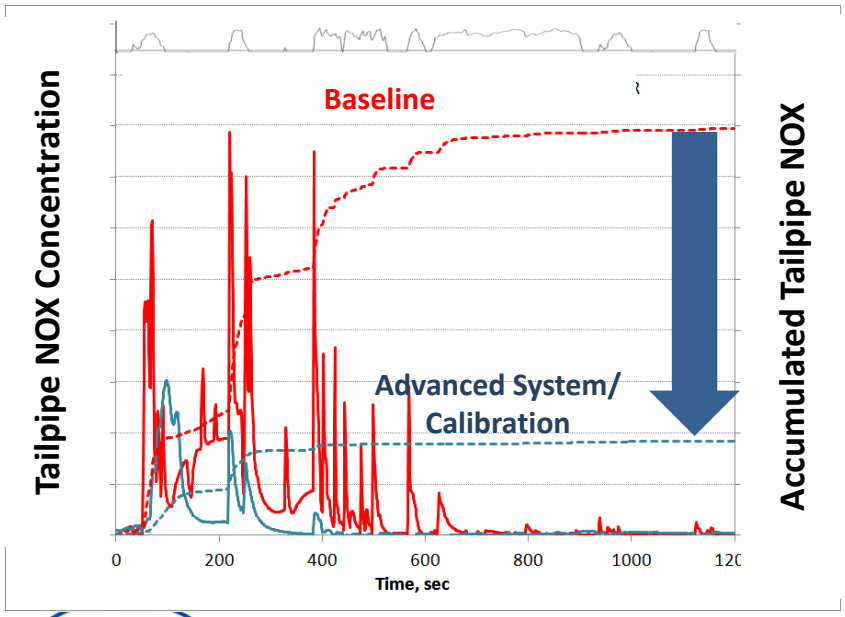
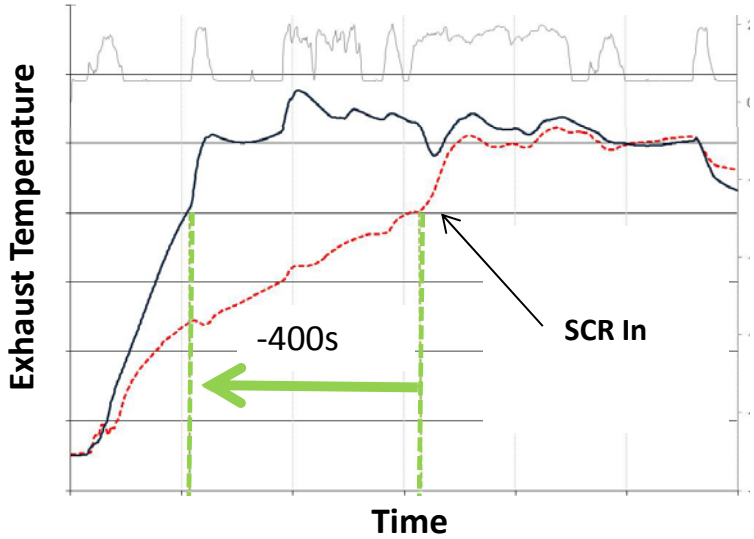
Sample of Approaches Tested



CFTP







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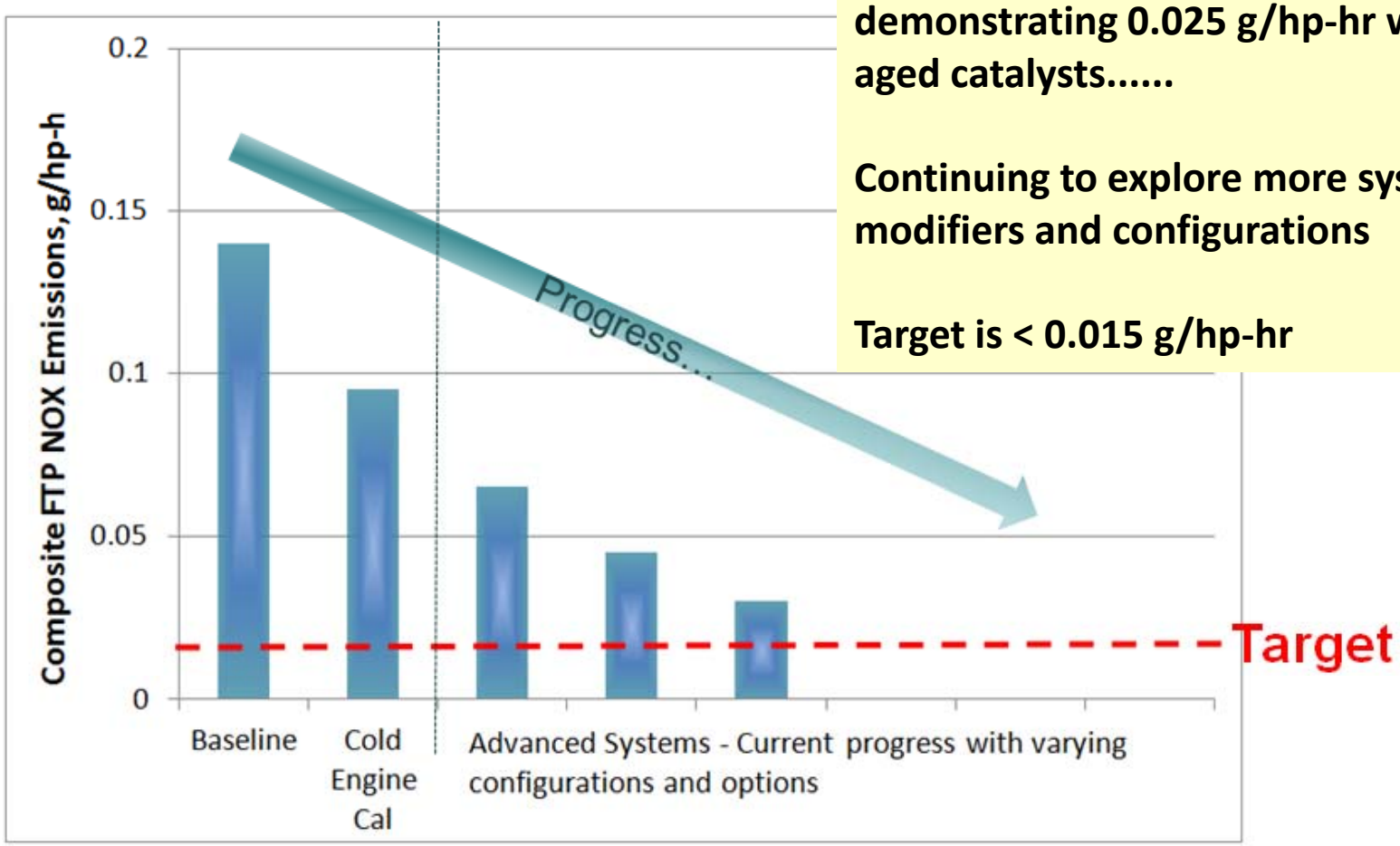
Current Screening Progress



Screening Phase 1 systems are demonstrating 0.025 g/hp-hr with aged catalysts……

Continuing to explore more system modifiers and configurations

Target is < 0.015 g/hp-hr

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Final Calibration and Demonstration

- Selected technology(s) will be moved to engine January 2016
  - Full Aged systems installed on engine
  - Engine calibrations will be tested and tuned to develop final calibration
  - Reserved system submitted for final aging
- Final systems to be aged on engine
  - Draft aging protocol will be finalized once technology is down-selected
  - Target is full useful life
- Final Low NOx Demonstration Mid-Year 2016

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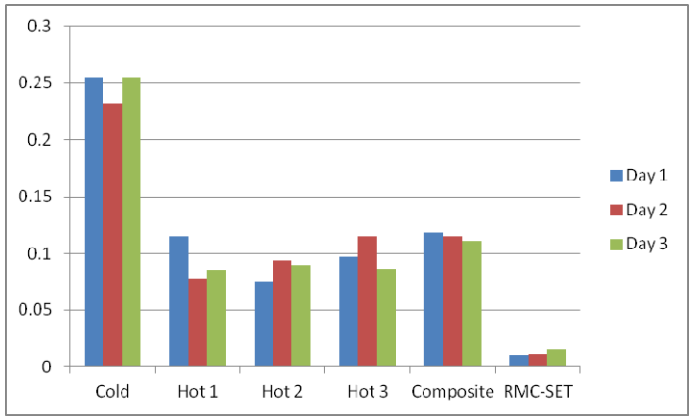
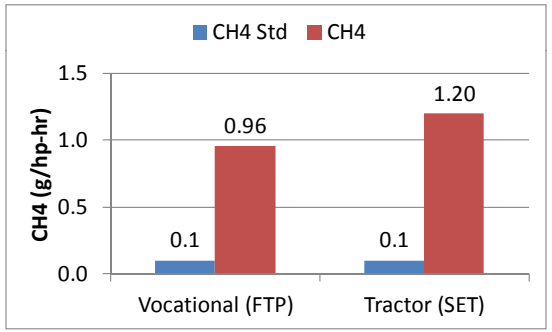
CNG Engine Baseline

	Composite FTP Tailpipe, g/hp-hr				
	NOx	PM	NMHC	CO	CO2
Average	0.115	0.002	0.124	2.96	541.8
SD	0.00305	0.00008	0.00234	0.43951	2.948
COV	2.7%	3.3%	1.9%	14.9%	0.5%
SD % Std	1.5%	0.8%	1.7%	2.8%	n/a

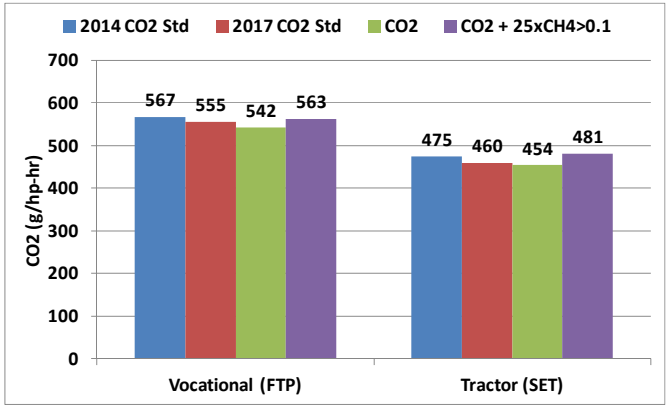
Tailpipe NH_3 ~75 ppm
Tailpipe N_2O ~ 0.003 g/hp-hr





	RMC-SET Tailpipe, g/hp-hr				
	NOx	PM	NMHC	CO	CO2
Average	0.012	0.0006	0.090	1.56	453.8
SD	0.00262	0.00005	0.00163	0.27939	1.014
COV	21.3%	7.4%	1.8%	17.9%	0.2%
SD % Std	1.3%	0.5%	1.2%	1.8%	n/a

Tailpipe NH_3 ~160 ppm
Tailpipe N_2O 0.000 g/hp-hr



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CNG Status and Plan

- Engine change to Cummins ISX-12G required change of controls hardware
- Installation of controls is now complete and calibration is starting
- Three different TWC-based catalyst systems are supplied by MECA members
  - One will be chosen after short screening process
- Calibration to reach 0.02 g/hp-hr will proceed with final demonstration planned mid-2016

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Acknowledgements

- California Air Resources Board
- Program Partners
  - Volvo
  - Manufacturers of Emission Controls Association (MECA)
    - MECA member companies who have provided emission control hardware
  - E-Controls (CNG engine controls)
- Program Advisory Group members

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More Information

- California ARB website
  - http://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm

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