ARB Low NOx Demonstration Program Update

SOUTHWEST RESEARCH INSTITUTE®

November 3, 2016

Agenda

- Program Objectives and Structure
- Engines
- Test Cycles
- Baseline Emissions
- Diesel Program
  - Timeline
  - Engine Calibration
  - Aftertreatment Development
  - Final Configuration and Results
- CNG Program
  - Approach and Configuration
  - Results
- Catalyst Aging Approach
- Follow-on Program Scope

List of Acronyms

ASC	=	Ammonia Slip Catalyst
AT	=	Aftertreatment
DOC	=	Diesel Oxidation Catalyst
DPF	=	Diesel Particular Filter
EHC	=	Electrically Heated Catalyst
EO	=	Engine-out
HD1	=	Heated Dosing 1 (full flow)
HD2	=	Heated Dosing 2 (partial flow)
LO-SCR	=	Light-off SCR (close coupled)
MB	=	Mini-burner
NH3	=	Gaseous NH3 dosing
PAG	=	Program Advisory Group
PNA	=	Passive NOx Adsorber
SCR	=	Selective Catalyst Reduction
SCRF	=	SCR on Filter
TC	=	Turbo-compound

Program Outline

- Part 1 (Low NO_X Feasibility Demonstration)
  - today's discussion……
  - started October 2013
  - technical completion November 2016
  - CARB funding $1.6M
  - Additional support funding
    - MECA - $600K (aftertreatment screening and aging)
    - SwRI Internal R&D - $ 500K (controls development)

- Part 2 (Low Load Duty Cycle NO_X Control)
  - planned start November 2016
  - planned completion June 2018
  - CARB funding $1M

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*

Program Engines

Diesel - 2014 Volvo MD13TC (Euro VI)

- A diesel engine with cooled EGR, DPF and SCR
  - 361kw @ 1477 rpm
  - 3050 Nm @ 1050 rpm
- Representative platform for future GHG standards for Tractor engines
- Incorporates waste heat recovery – turbo-compound (TC)

CNG – 2012 Cummins ISX12G

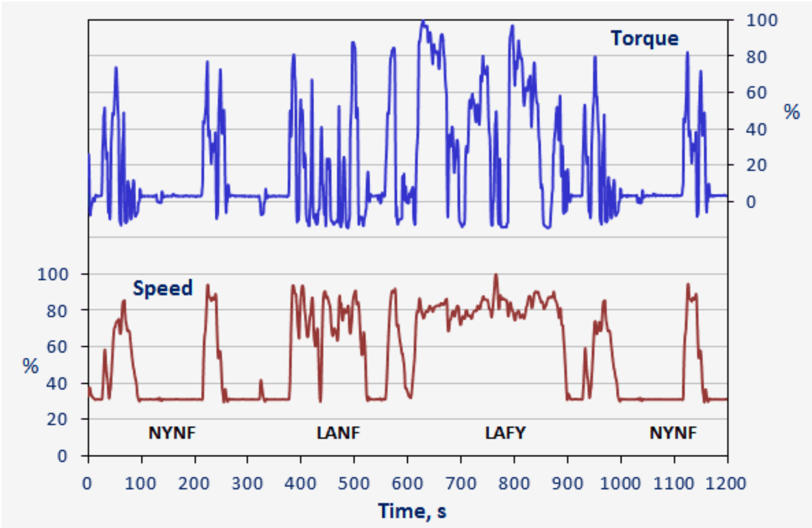
- A stoichiometric engine with cooled EGR and TWC
  - 250 kw @ 2100 rpm
  - 1700 Nm @ 1300 rpm
- Suitable for a variety of vocation types

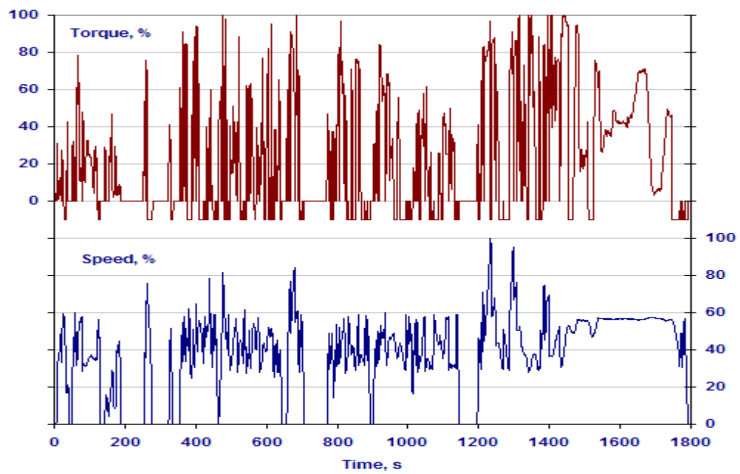
Main Program Tasks

- Measure baseline emissions
  - Certification cycles: CARB Idle, FTP, RMC-SET, and WHTC
  - Low-load vocation cycles: NYBC, ARB Creep, and OCTA
- Develop engine and aftertreatment control strategies using:
  - A diesel engine provided by Volvo Group
  - A CNG engine provided by Southwest Research
  - Aftertreatment control systems provided by MECA
- Screen potential aftertreatment control strategies with a hot gas transient reactor (HGTR) burner system developed by Southwest Research
- Select final engine and aftertreatment control strategies
  - Representative aging of final systems
- Demonstrate the low NOx emissions with the final strategies

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)

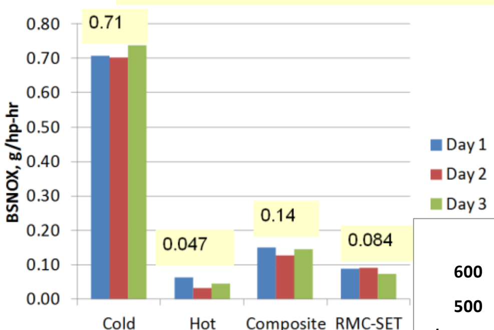
Baseline Emissions

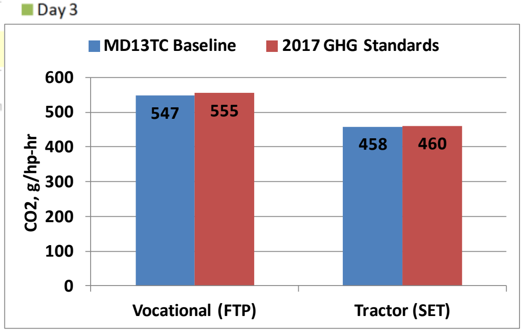
Diesel (2014)

	Tailpipe NOx, g/hp-hr	
	FTP	**RMC**
Average	**0.14**	**0.084**
SD	**0.012**	**0.0093**
COV	**8.5%**	**11%**
SD % Std	**5.9%**	**4.6%**

Engine-out NOx ~ 3 g/hp-hr

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

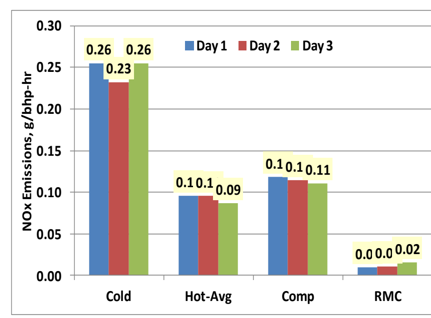


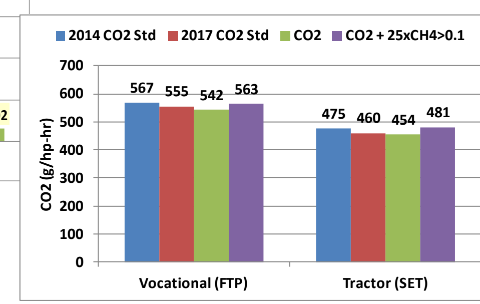


CNG (2012)

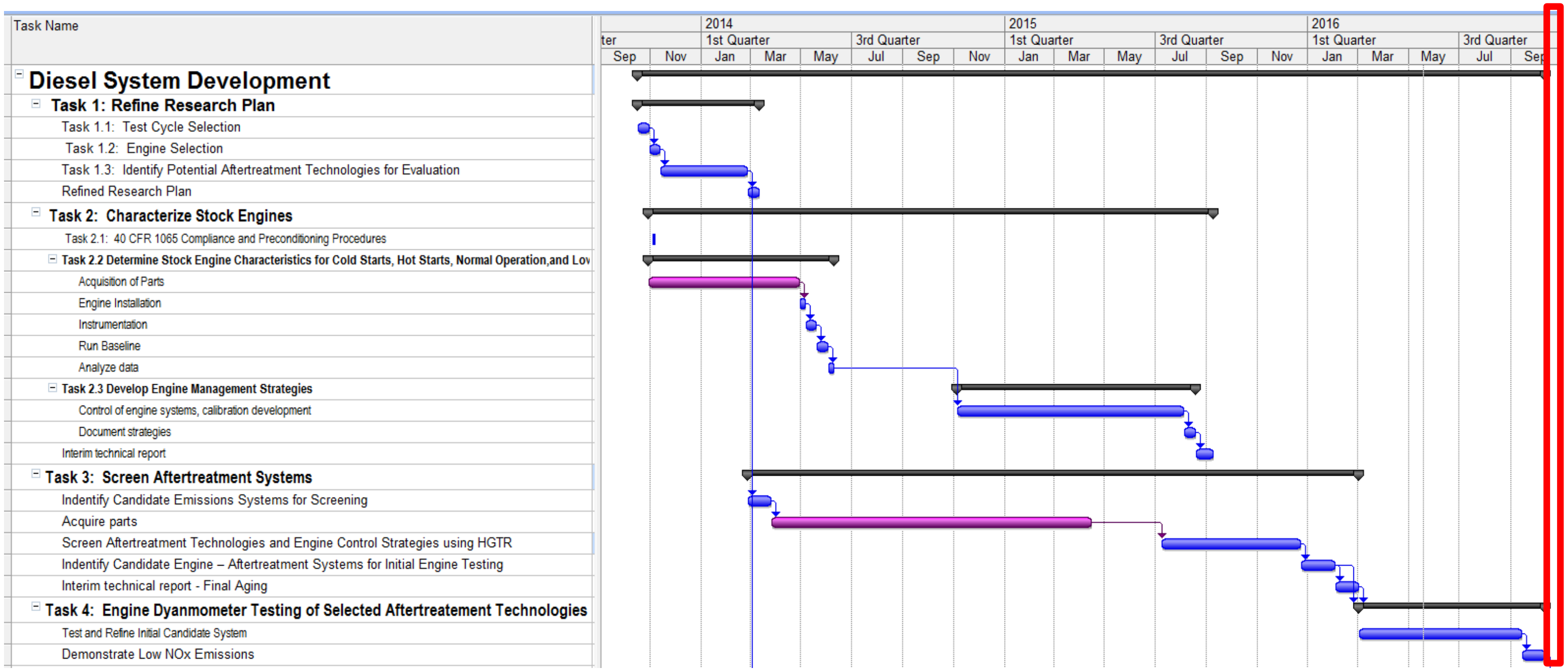
	Tailpipe NOx, g/hp-hr	
	FTP	**RMC**
Average	**0.115**	**0.012**
SD	**0.003**	**0.003**
COV	**2.7%**	**21.3%**
SD % Std	**1.5%**	**1.3%**

Tailpipe NH_3 ~ 75-100ppm
Tailpipe CH_4 ~ 1 g/hp-hr





Diesel Program Timeline



Final system selection completed
Final aging of selected system is nearly complete
Controls tuning and refinement in progress

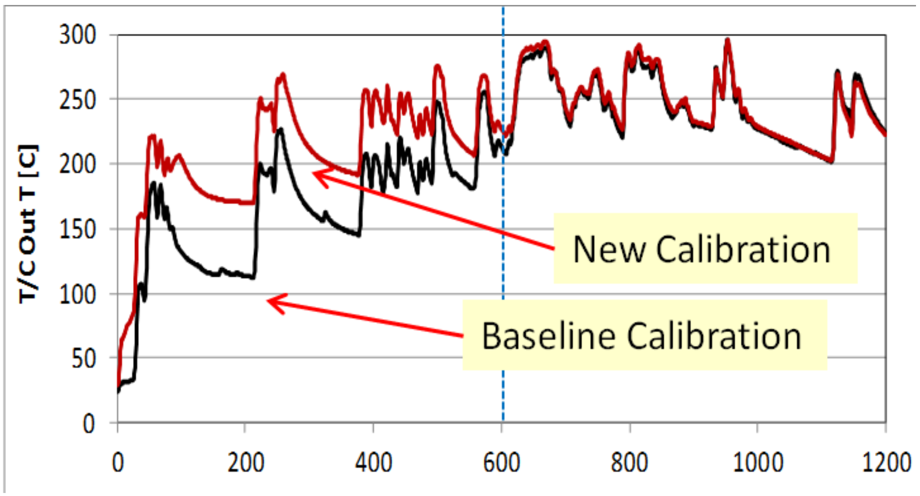
Based on aging timeline, final demonstration tests expected in November, 2016

Diesel Program Status and Remaining Tasks

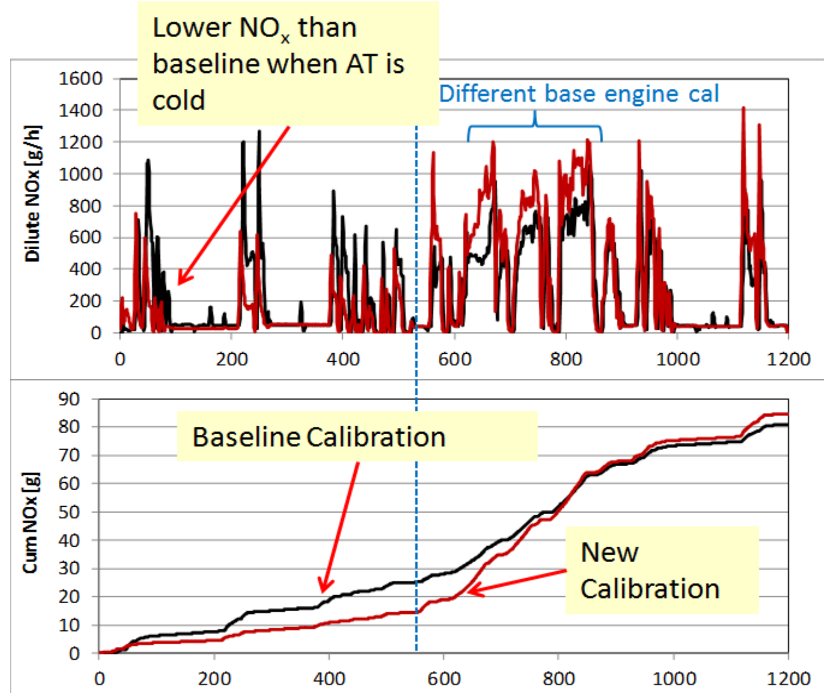
- Final Low NO_X Demonstration
  - Final down-selection completed
  - Controls tuning is in progress
  - Final demonstration testing to be completed when final aged parts available – November 2016
  - Reporting to follow in November 2016

- Aftertreatment Aging for Final Demonstration
  - Examine durability of aftertreatment parts
  - Final aging is in progress – 1000 hours planned
  - Parts should be available in November for demonstration testing

Diesel Engine Calibration Approach



Increased Temperatures



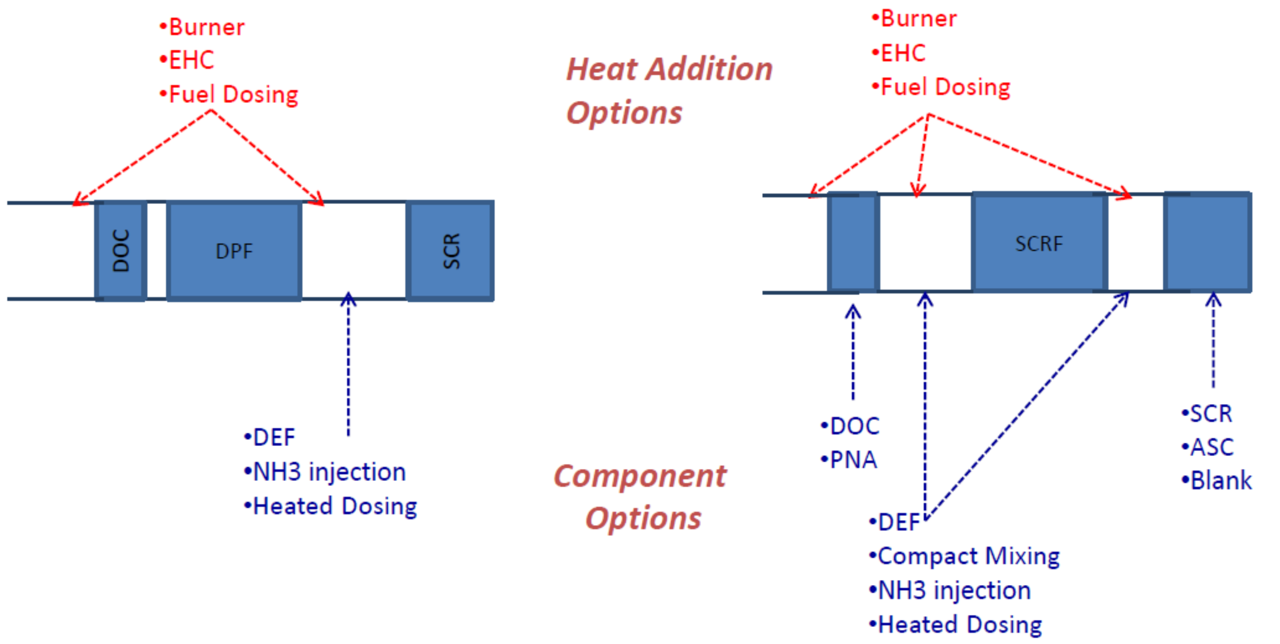
Decreased EO NO_x

- Modify existing engine calibration during cold-start warm-up
  - help AT light-off and reduce engine-out NO_x until that time
  - EGR modifications, multiple injections, intake throttling, elevated idle speed
- Release controls to baseline calibration after AT light-off
  - maintain fuel economy and GHG
- Minimal modifications during warmed-up operation

Diesel Aftertreatment System Screening

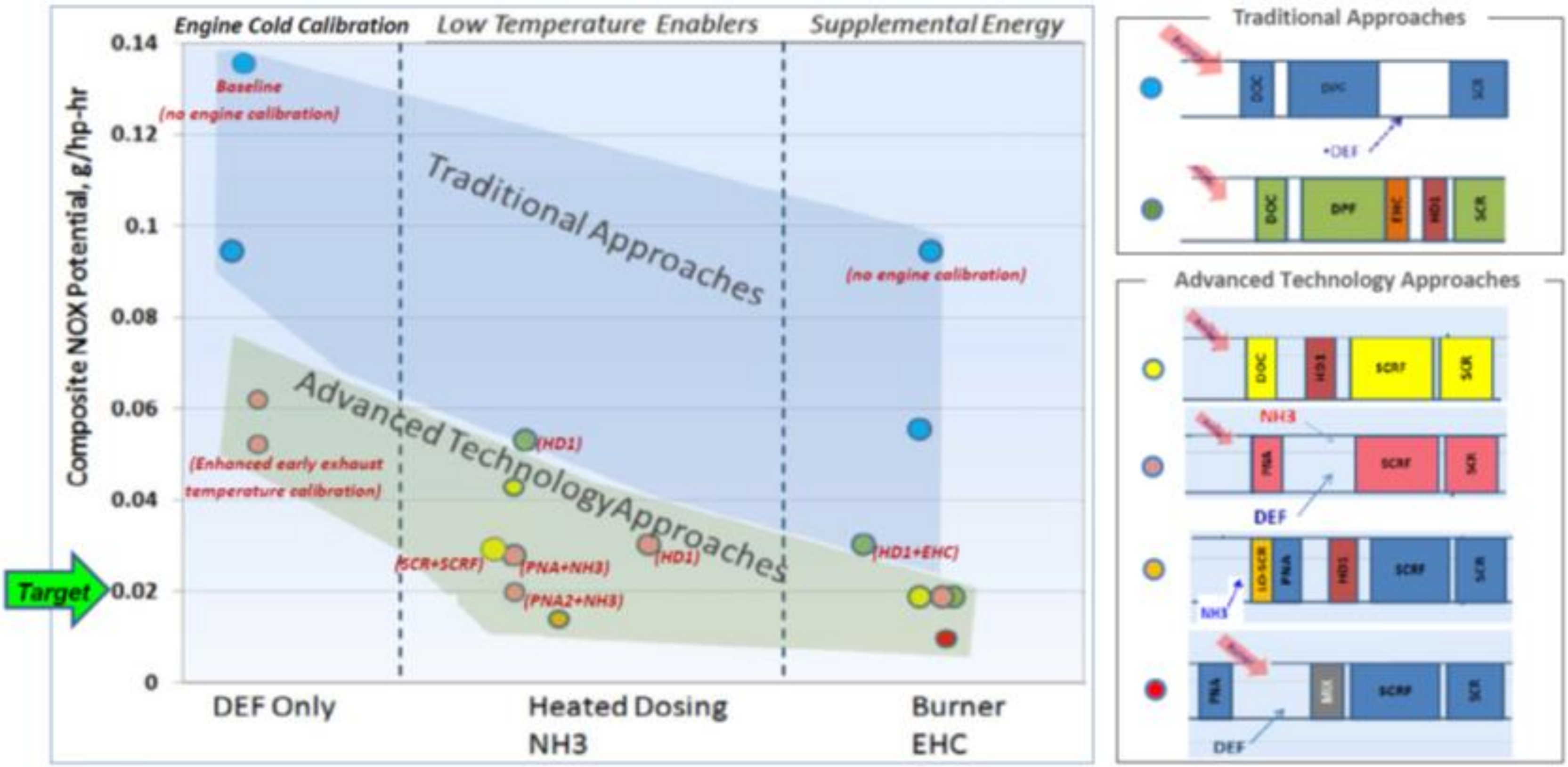
Traditional Approach

Advanced Approach



Examined 33 out of 500 possible configurations of component and heat addition options

Screening Test Results for Diesel Aftertreatment System Configurations



Acronyms

DOC: diesel oxidation catalyst; ***DPF***: diesel particulate filter; ***SCR***: selective catalyst reduction; ***Burner***: 10kw mini-burner; ***EHC***: electrically heated catalyst; ***HD1***: heated DEF dosing; ***SCRF***: SCR catalyst coated DPF; ***PNA***: passive NOx adsorber; ***PNA2***: PNA with altered catalyst formulation; ***NH3***: gaseous ammonia injection; ***LO-SCR***: close-coupled light-off SCR

Multiple potential pathways to achieve NOx emissions below 0.02 g/bhp-hr

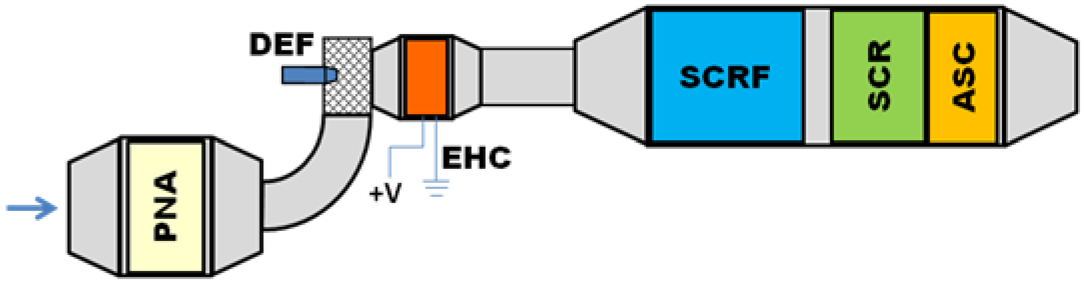
Final Technology Rankings from Screening (Incorporates stakeholder feedback)

System	Composite NO_x Potential	Potential Composite FTP Penalty, %	Durability	Complexity	Cost
PNA + HD1 + SCRF + SCR/ASC	0.02	0.9	8/ 13.3	10/10	4/9.8
NH3 + LO SCR + PNA + HDI + SCRF + SCR/ASC (HD1)	0.016	0.95	12/20.7	11/56	11/12.5
EHC/DOC + DEF + SCRF + SCR + SCR/ASC - *(underevaluation)*	///	1.05	7/9.4	7/9	4/6.2
PNA + MB + DEF + SCRF + SCR/ASC	0.01	1.04	13 /16.2	10/13.1	9/12.5
MB + DOC + DEF + SCR + SCRF + SCR/ASC	0.019	1.04	9/10.7	8//10	8/7.7
MB + DOC + DEF + SCRF + SCR + SCR/ASC	0.018	1.04	9/10.7	8//10	8/7.7
DOC + MB + SCRF + SCR + SCR/ASC - *(not evaluated)*	//////////////////	1.04	9/10.7	8/10	7/7.7
MB + DOC + DPF + SCR + SCR/ASC	0.025	0.62	6/6.4	6/7	7/6.3
EHC/DOC + DPF + HD1+ SCR + SCR/ASC - *(not evaluated)*	//////////////////	0.98	5/8.6	6/9	5/8.4
PNA + HD1 + SCRF + SCR/ASC	0.029	0.9	8/13.3	5/13	4/9.8
PNA + NH3 + DEF + SCRF + SCR/ASC	0.031	0.72	8/13.4	8/13	7/12.3
NH3 + LO SCR + DOC + DPF + HD1 + SCR+SCRF + SCR/ASC *(not evaluated)*	//////////////////	0.65	4/15.2	9/16	10/12.4
DOC + DPF + EHC + HD1 + SCR + SCR/ASC	0.033	1.2	2/7.2	2/7	6/7.7
Base engine, stock calibration 4852 g *Base engine, CC1: 4973 g*					

- Based on 2016 PAG forum and low NO_X device survey
- Engine cell objective was to evaluate in order until reaching a viable solution to 0.02 g/hp-hr at minimum fuel penalty / cost / complexity

Summary of Results with First AT Config. (not selected for Final Demo)

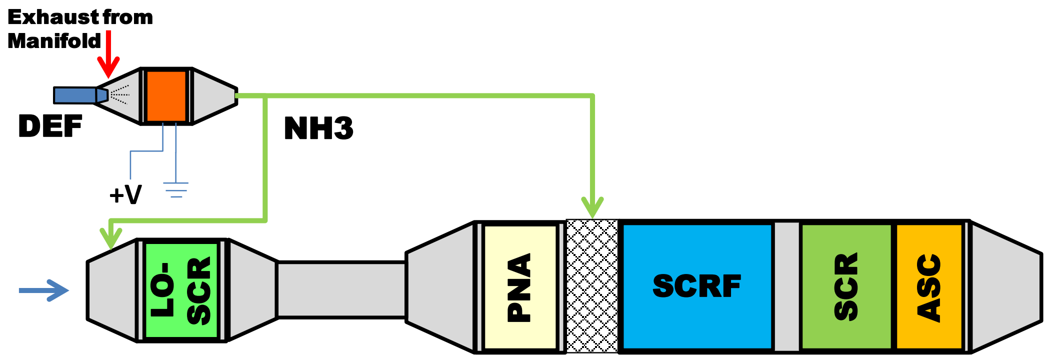
- Configuration 1 – PNA2+HD1+SCRF+SCR+ASC



  – 0.025 to 0.03 g/hp-hr composite with original 2kw EHC-HD1
  – 0.022 to 0.025 g/hp-hr with larger 6kw EHC-HD1 (additional 3% BSFC on cold-start)
    - **would likely be below 0.02 for a non-TC engine**
  – More heat needed to get below 0.02 on current engine (we project 10kw)
- Advantages –simplest AT system architecture
- Why not select it ?
  – Efficiency – fuel penalty required to get below 0.02 is too large
    - 22% conversion of fuel energy to heat, likely 2.5%+ FTP composite GHG impact
  – Complexity – electrical heat at 10kw requires significant electrical system infrastructure changes

Summary of Results with Second AT Config (not selected for Final Demo)

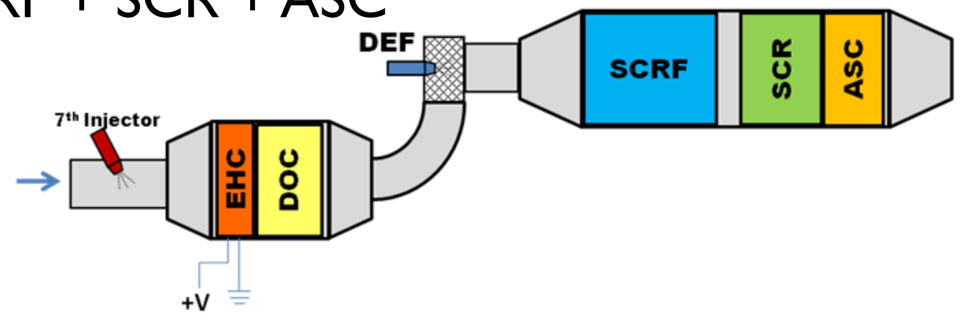
- Configuration tested – NH3+LOSCR+PNA2+HD1+SCRF+SCR+ASC
- Long term implementation = <u>HD2+LOSCR+PNA2+SCRF+SCR+ASC</u>
  - multipoint dosing is required for this to work



  - 0.022 to 0.025 g/hp-hr observed using the 3” zeolite LO-SCR catalyst
    - **<u>would likely be below 0.02 on a non-TC engine</u>**
- Advantages – lower GHG penalty – on order of 1%
- Why not select it ?
  - Time – requires implementation of HD2 to be practical and more development to reach robust controls – we did not have time to complete these efforts
  - Long term sulfur management of LO-SCR needs evaluation (time)

EHC/DOC (Not Evaluated on Engine)

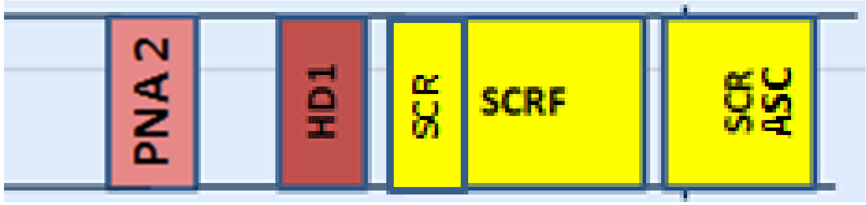
- The next ranked item on the list was
  - EHC/DOC + DEF + SCRF + SCR + ASC



- We examined EHC/DOC concept in HGTR cell to look at heat generation potential
  - potential was good but not sufficient for low TC-engine temperatures
  - lack of PNA in this system, sufficient rapid heat potential not there for 0.02
- Significant additional calibration effort to try this but low success probability for this TC engine – time was not available

Summary of Results with Third AT Config (not selected for Final Demo)

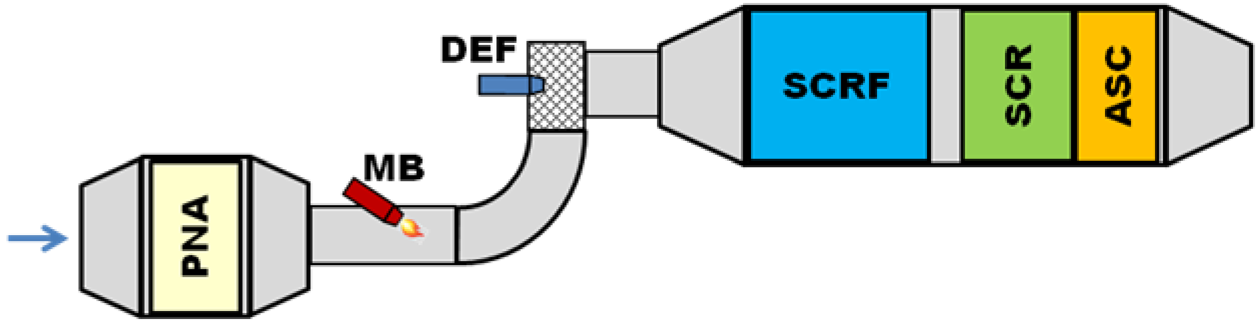
- Configuration tested –PNA2+HD1+SCR+SCRF+SCR+ASC
  - ran HD1 at 3.5 kw heat level



  - 0.022 to 0.025 observed using the 3" zeolite LO-SCR catalyst at position shown (about 1% additional fuel penalty on cold-start over engine cal alone)
  - net GHG effect less than 6kw EHC even with increased SCRF regeneration frequency
- Advantages – lower GHG penalty than high-power EHC, simpler than LO-SCR with multi-point dosing
- Why not select it ?
  - Time – need to try larger SCR upstream of SCRF, requires more fabrication and time is not available to try different formulations from suppliers to find optimal configuration

Final AT Configuration: Mini-burner

- Primary configuration tested –PNA2+MB+SCRF+SCR+ASC



- Results on engine are well below 0.02 g/hp-hr with catalysts used for screening analysis
  - Composite ~ 0.012 g/hp-hr
- Advantages – lower GHG penalty than full EHC, less backpressure and controls complication than LO-SCR
- Impact on GHG from baseline including engine calibration
  - 2% on FTP – 0.5% engine cal, 0.5% SCRF regen, 1% mini-burner
    - hot-start optimization may reduce this some
  - < 0.5% on RMC-SET – SCRF regen only

Preliminary FTP Test Data Sets with Final Diesel Configuration

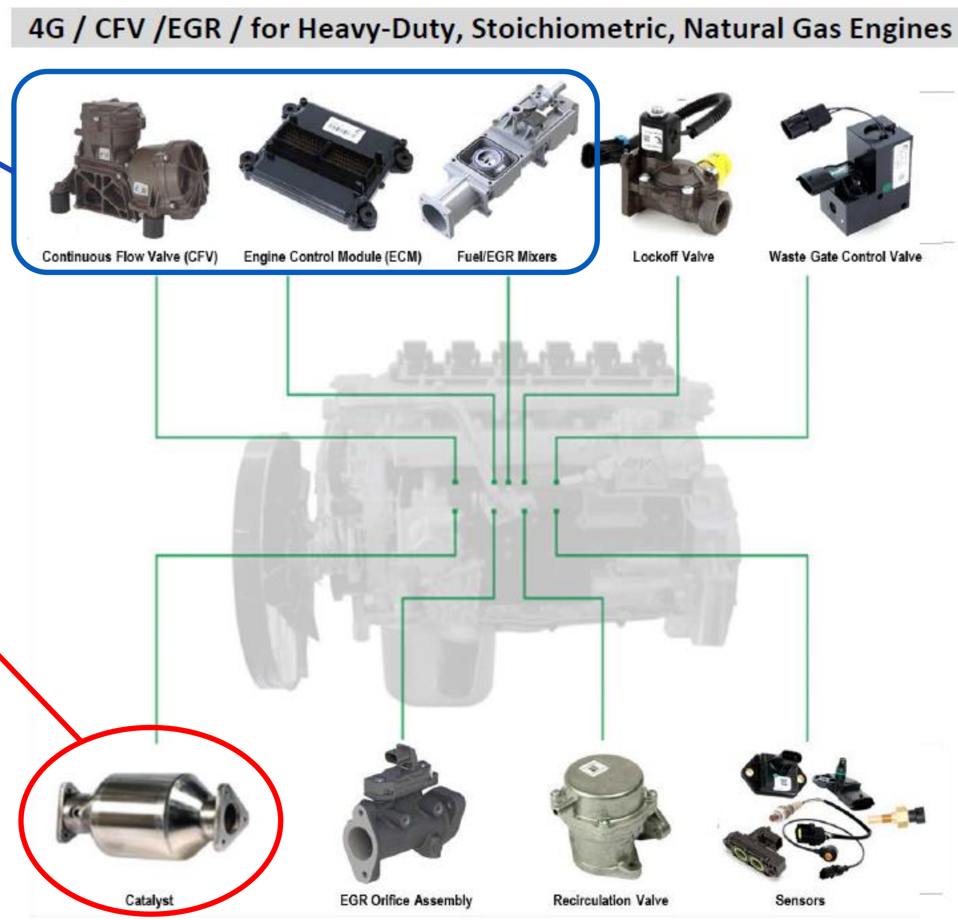
		Tailpipe FTP BSNOx, g/hp-hr					
	Run	Cold	Hot 1	Hot 2	Hot 3	Composite	Hot Average
Development Parts (Oven Aged)	1	0.025	0.010	0.010		0.012	0.010
	2	0.027	0.009	0.009	0.010	0.012	0.009
	3	0.024	0.008	0.009	0.009	0.010	0.009
	Avg	**0.025**				**0.011**	**0.009**
	SD	**0.0015**				**0.0010**	**0.0007**
Degreened Parts before Final Aging		**0.027**	**0.005**	**0.004**	**0.006**	**0.008**	**0.005**

- Engine-out NO_x is 2.9 g/hp-hr
- Cold-start conversion = 99%
- Hot-start conversion = 99.7%

- N_2O is 0.07 to 0.08 g/hp-hr
- Data will be updated with Final Aged parts in November…

CNG Low Emissions Approach

- Replace engine controls with a system by EControls by ENOVATION CONTROLS
  - Key Components for accurate fuel control
- Catalysts supplied by MECA members
  - EHC
  - Light-off catalyst
  - Advanced TWC
  - Close-coupled catalyst



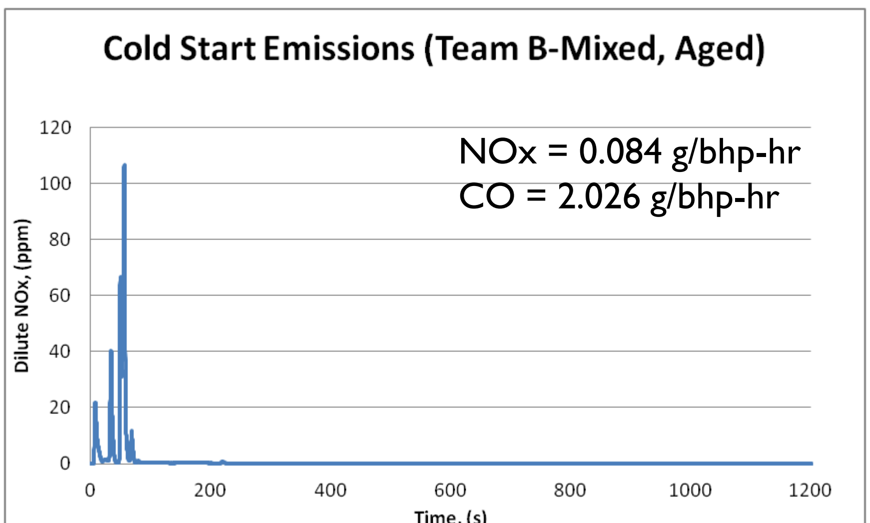
CNG Engine Final AT Configuration

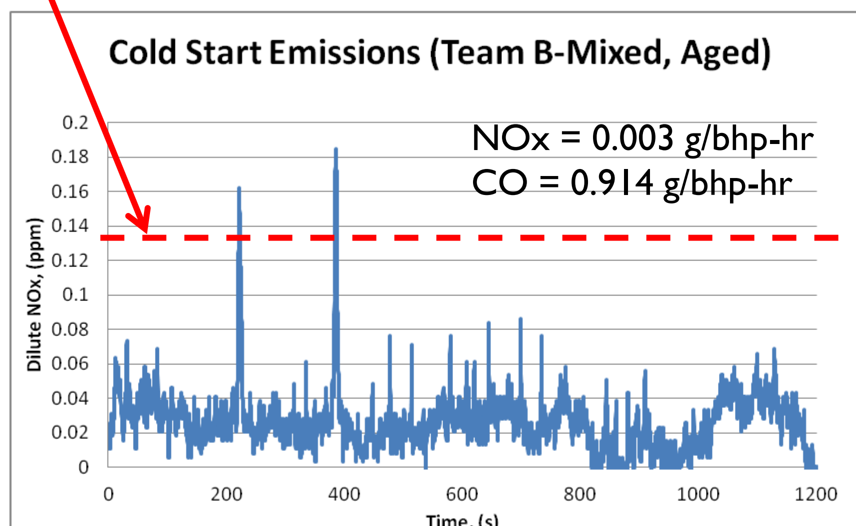
- Final system selection *Updated Calibration*
  - Close-Coupled from the two catalyst setup for **cold start**
  - Under-floor TWC from single setup for **space velocity**

Total SVR ~ 2.4

Close-Coupled Under-body

(0.136 ppm average composite NOx over the FTP results in 0.015 g/bhp-hr NOx)





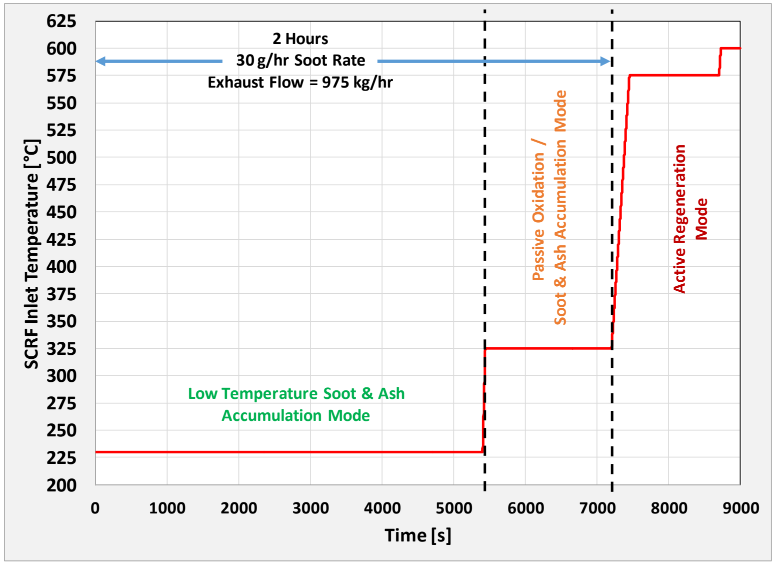
Final CNG Calibration FTP Results (Final Engine Aged parts) – average of 5 runs

		NO_x	CO	THC	CH_4	CO_2	BSFC	PM	NH_3 Avg
Cold Avg	Raw	0.065	3.549	0.210	0.216	590.1	0.500		
	Dilute	0.068	3.359	0.228	0.212	595.3	0.504	0.0016	40.3
Hot 1 Avg	Raw	0.000	1.592	0.129	0.151	539.1	0.455		
	Dilute	0.001	1.608	0.138	0.151	543.9	0.459	0.0013	60.4
Hot 2 Avg	Raw	0.000	1.495	0.126	0.148	537.2	0.453		
	Dilute	0.001	1.507	0.127	0.148	541.5	0.457	0.0012	52.5
Hot 3 Avg	Raw	0.000	1.470	0.113	0.133	537.3	0.453		
	Dilute	0.001	1.489	0.112	0.135	541.3	0.457	0.0012	49.8
Composite Avg.	**Raw**	**0.009**	**1.803**	**0.135**	**0.154**	**545.2**	**0.460**		
	Dilute	**0.010**	**1.790**	**0.140**	**0.154**	**549.7**	**0.464**	**0.0012**	**52.3**
Baseline – Composite	**Dilute**	**0.115**	**2.956**	**--**	**0.956**	**541.8**	**--**	**0.002**	**75.8**

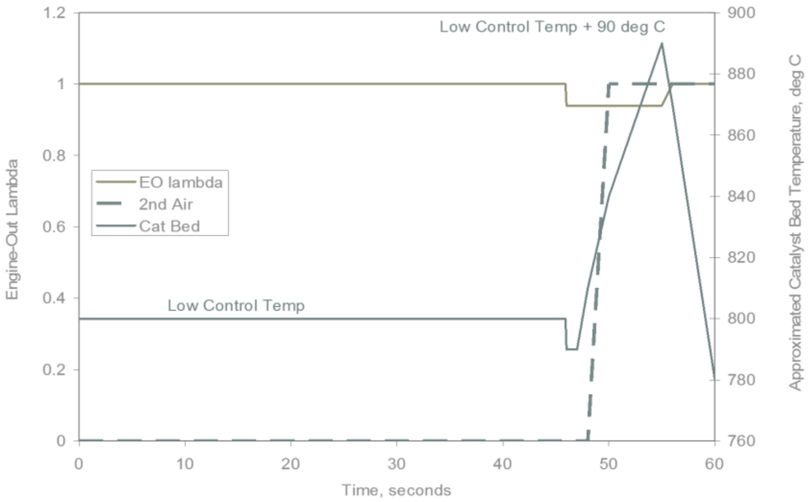
- Note cycle average NH_3 on FTP is ~ 50ppm
  - This is above the design target of 10ppm but this is due to a controller shortcoming
    - Current controller does not have robust oxygen storage model (typical technology for LD)
  - We did not have time / scope to incorporate this into current controller but it is production feasible to do so

Final Aging Approaches

DIESEL



CNG



- Based on SwRI DAAAC Protocol
- Thermal acceleration – full useful life (FUL) of Active Regeneration events
- Chemical acceleration – increased oil consumption engine
  - 25% of FUL exposure
- 1000 total hours planned

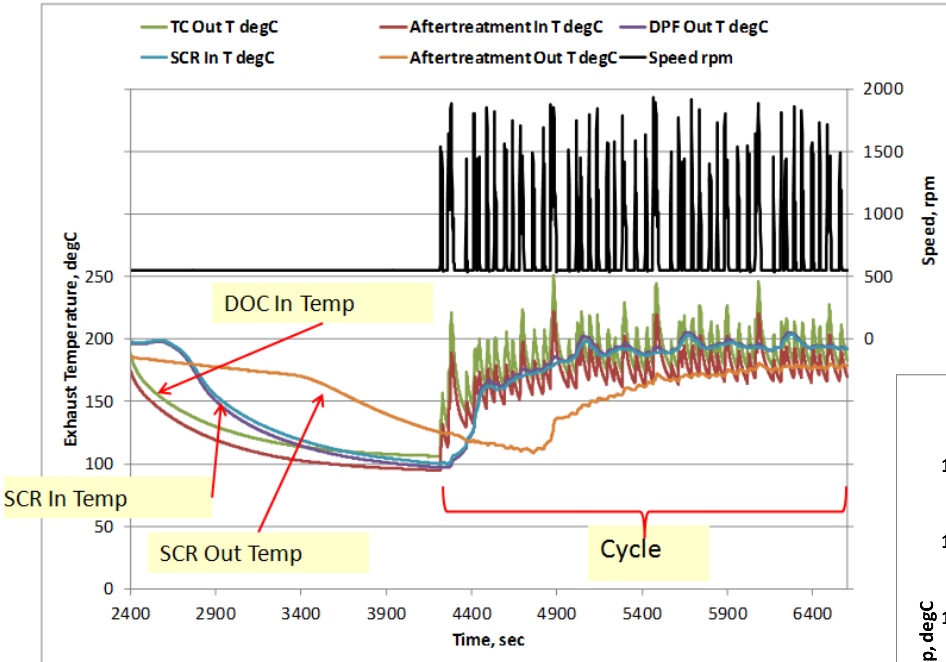
- Acceleration based on Standard Bench Cycle (SBC) approach
  - Accepted for gasoline TWC aging
- Calculations based on California bus field cycle
- SBC with 90degC exotherm, LCT = 875degC
  - 137 hours at 903degC Reference Temperature

Follow On Program Scope

- Next program to follow-on from current ARB Demonstration Program already awarded - $1M in additional funding
- Part 2 Program focus is Low-temperature and Low Load (urban) Vocational duty cycles

- Key Topics
  - Development of Low-Load duty cycle profiles
    - Development of a Heavy-Duty Low Load Cycle
  - Re-calibration of ARB Diesel Demonstration Engine to achieve low NO_x on Low Load profiles
    - What is the impact on GHG for this kind of control ?
  - Appropriate load metrics for in-use testing at Low Load

Example Vocational Cycle on Baseline 2014 Engine – NYBCx4

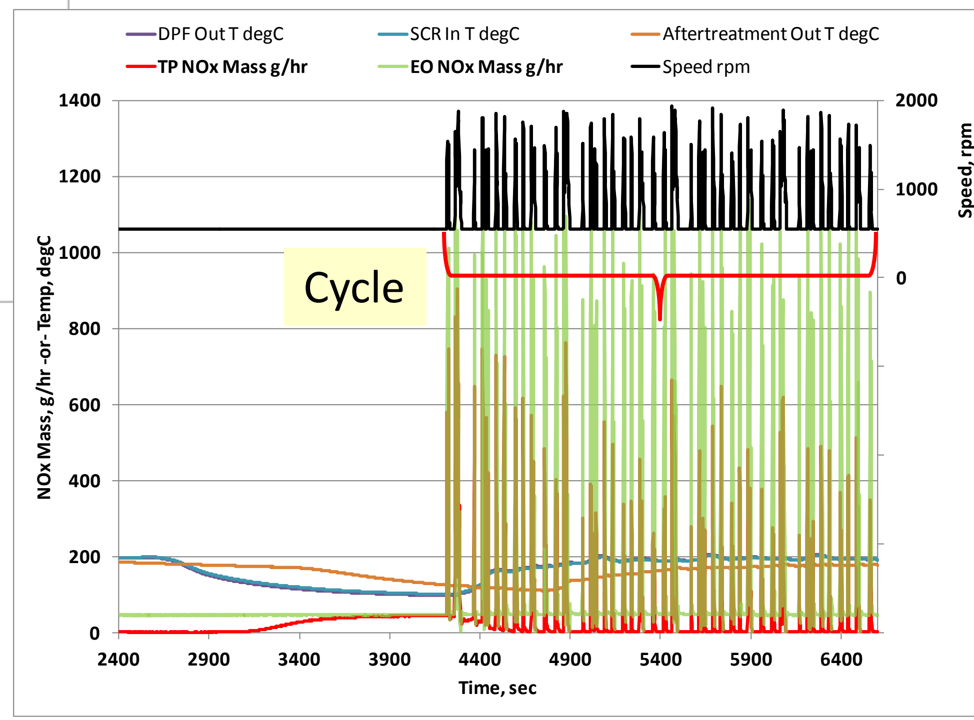


- Preconditioned with warm-up and NYBCx4 cycle before 30-min idle segment
- Note that entire cycle would be below current NTE range

Cycle average power ~ 17kw

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

Conversion still improving at end



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

More Information

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

- SwRI Contact
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