CARB LOW NO_X DEMONSTRATION PROGRAM - UPDATE

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HDDECS - Gothenburg

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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
DAAAC	=	Diesel Aftertreatment Accelerated Aging Cycles Consortium (SwRI)

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*

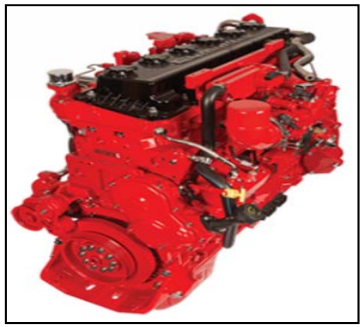
Program Engines

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**
- **<u>Incorporates waste heat recovery – turbo-compound (TC)</u>**

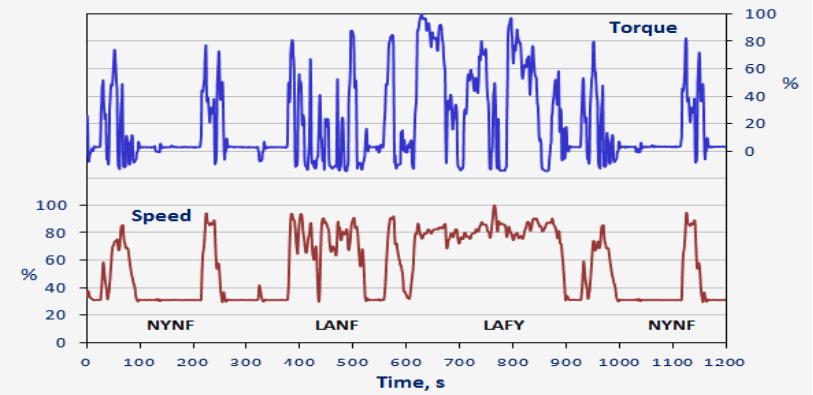
CNG – 2012 Cummins ISX12G

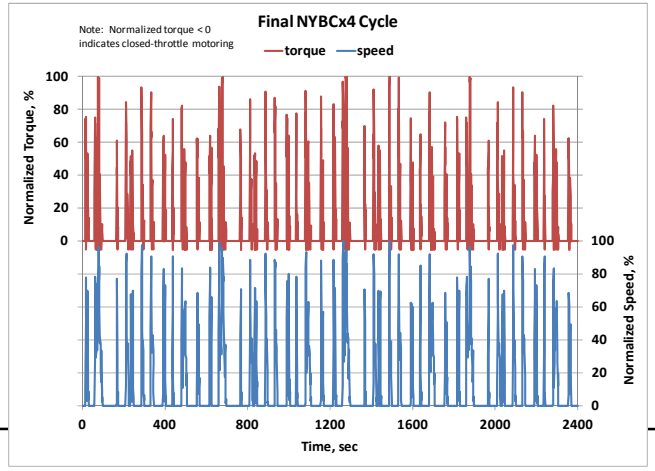
- **A stoichiometric engine with cooled EGR and TWC**
  - 250 kw @ 2100 rpm
  - 1700 Nm @ 1300 rpm
- **Suitable for a variety of vocation types**



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)





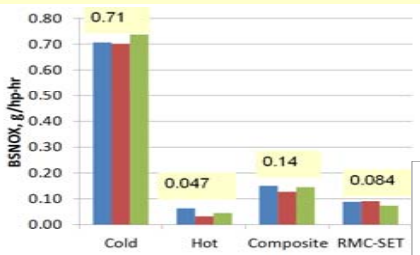
Baseline Emissions

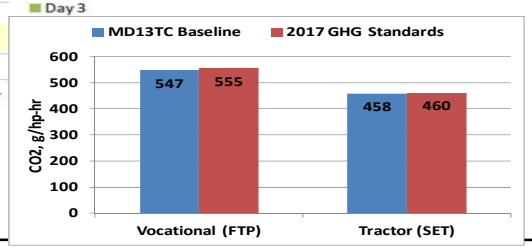
Diesel (2014)

	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 NH3, Tailpipe N_2O ~ 0.05 g/hp-hr

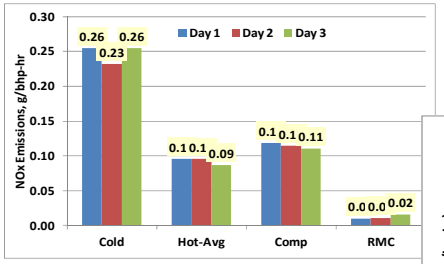


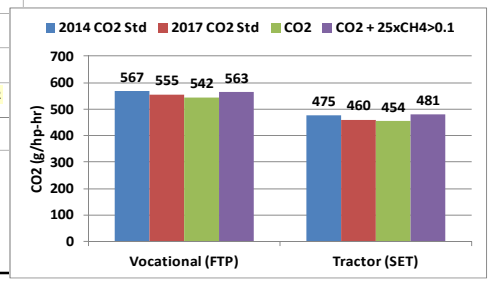


CNG (2012)

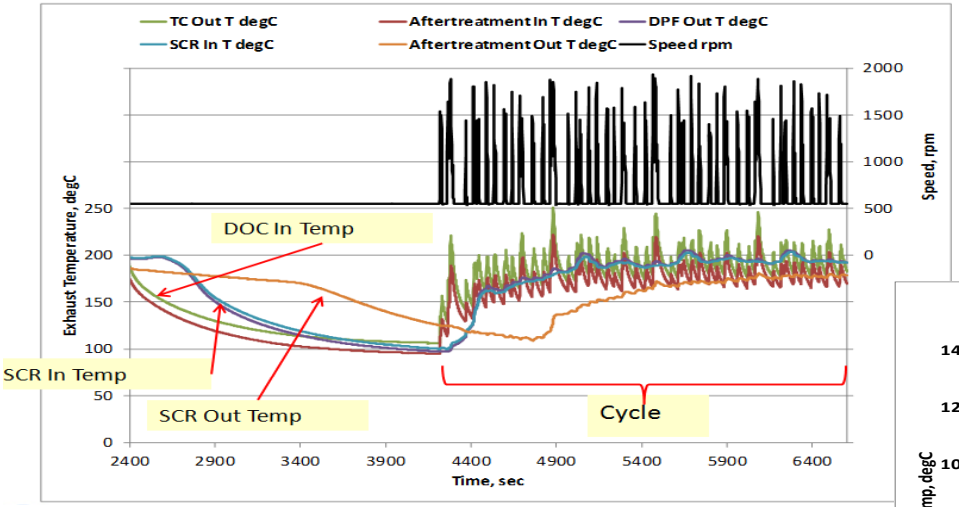
	Tailpipe NOx, g/hp-hr	
	FTP	**RMC**
Average	**0.115**	**0.012**
SD	**0.003**	**0.003**
COV	**2.7%**	**21.3%**
SD % Std	**1.5%**	**1.3%**

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

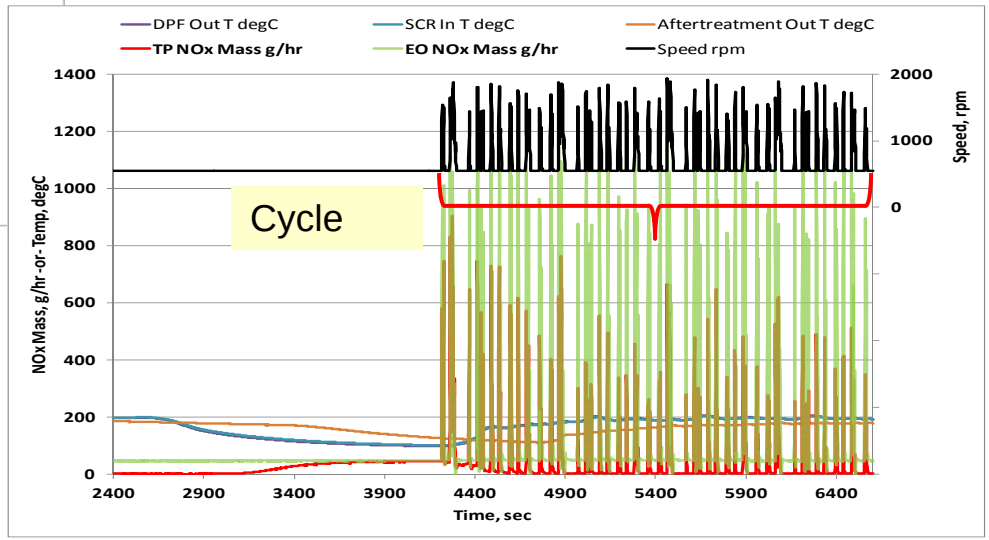




Example Vocational Cycle on Baseline 2014 Engine – NYBCx4

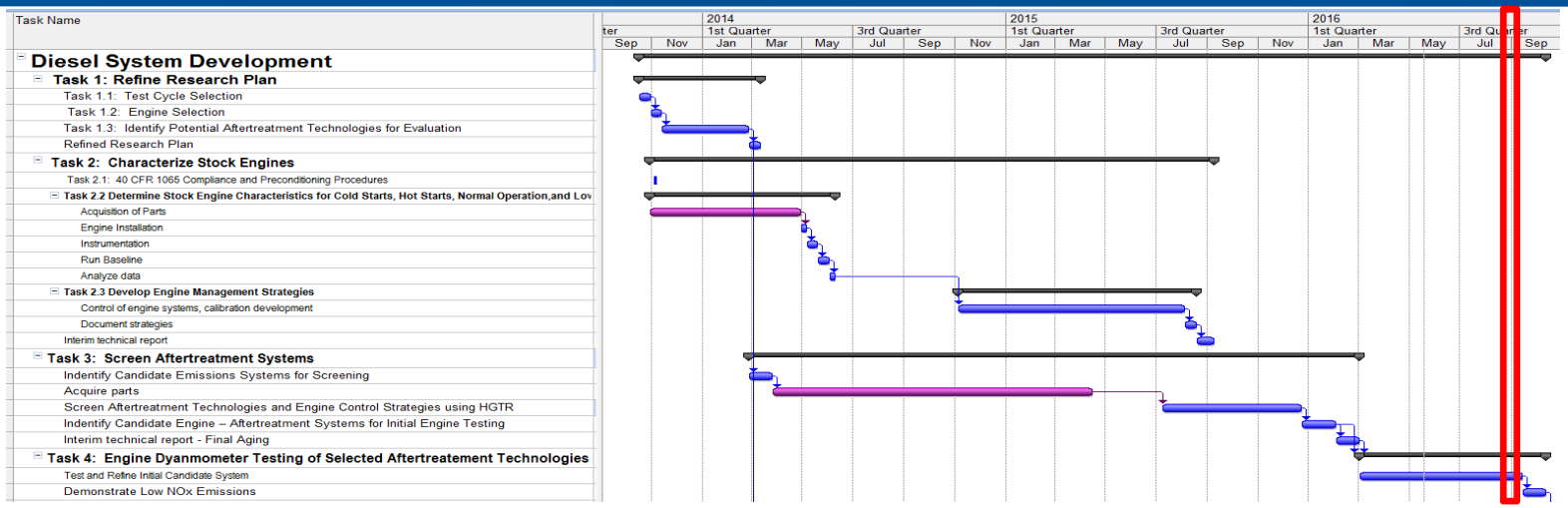


- **Preconditioned with warm-up and NYBCx4 cycle before 30-min idle segment**
- **Note that entire cycle would be below current NTE range**



- Cycle average power ~ 17kw
- EO ~ 6 g/hp-hr
- TP ~ 2.4 g/hp-hr
- 62% conversion cycle average
  - Conversion still improving at end

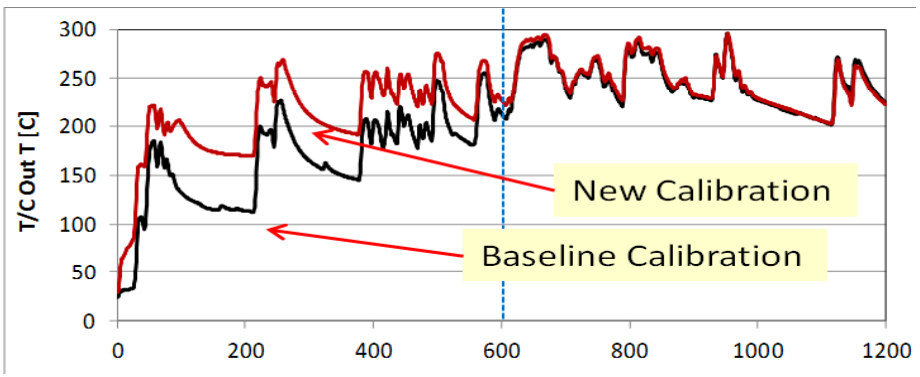
Diesel Program Timeline



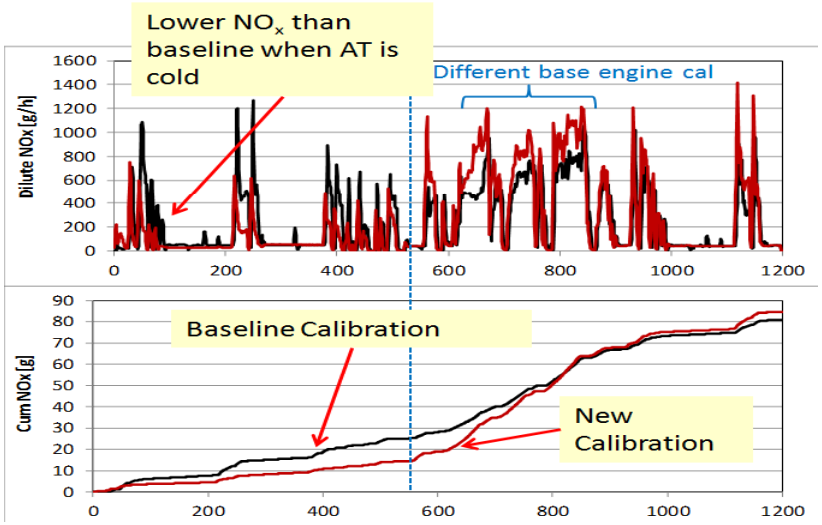
- **Final system selection completed**
- **Final aging of selected system is under way (~400 of planned 1000 hours completed)**
- **Controls tuning and refinement in progress**

- **<u>Based on aging timeline, final demonstration tests expected in October, 2016</u>**

Diesel Engine Calibration Approach



Increased Temperatures

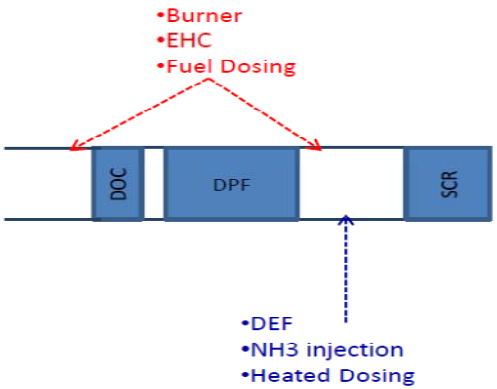


Decreased EO NO_x

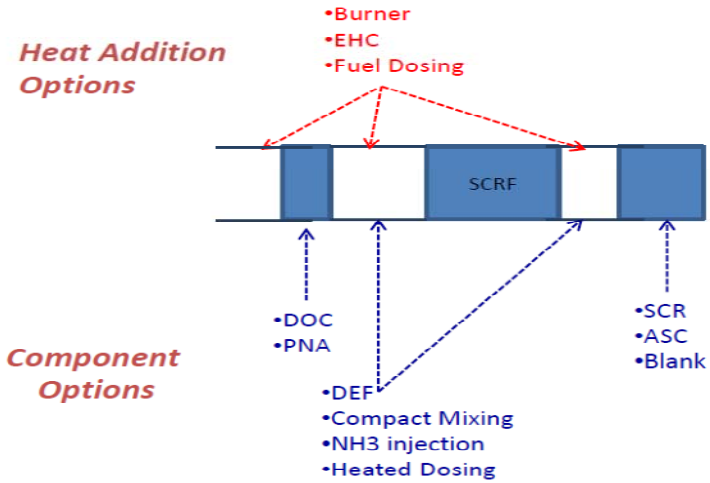
- **Modify existing engine calibration during cold-start warm-up**
  - help AT light-off and reduce NO_x until that time
  - EGR modifications, multiple injections, intake throttling, elevated idle speed
- **Release controls to baseline calibration after AT light-off**
  - maintain fuel economy and GHG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

Diesel Aftertreatment System Screening

Traditional Approach

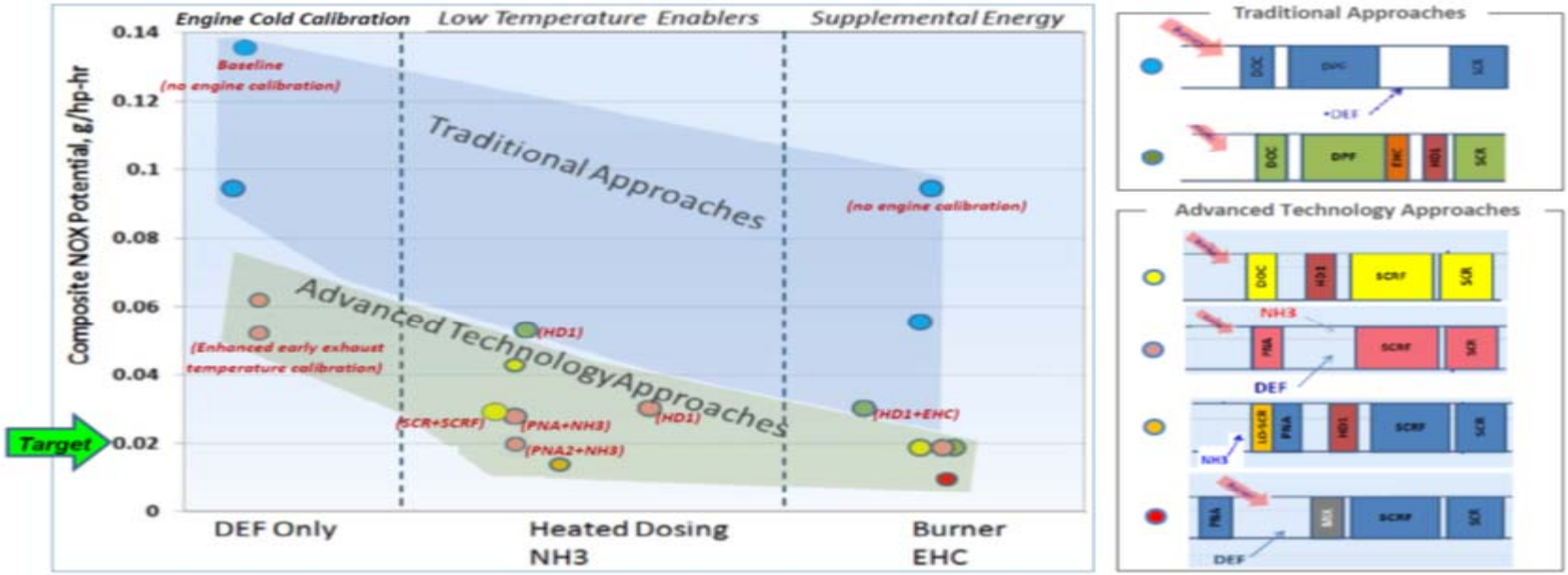


Advanced Approach



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/hp-hr

Final Technology Rankings from Screening (Incorporates stakeholder feedback)

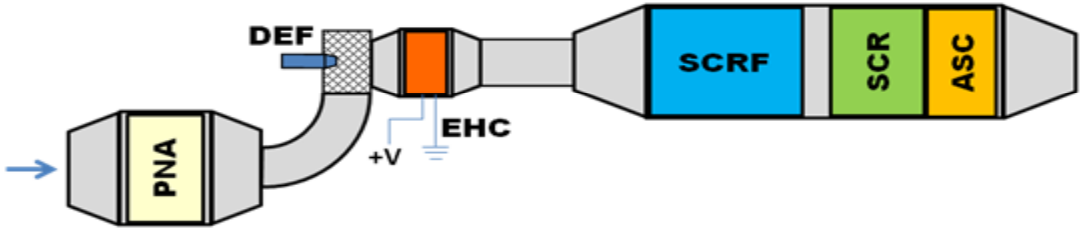
System	Composite NO_x Potential	Potential Composite FTP Penalty, %	Durability	Complexity	Cost
PNA + HD1 + SCRF + SCR/ASC	0.02	0.9	8/ 13.3	10/10	4/9.8
NH3 + LO SCR + PNA + HDI + SCRF + SCR/ASC (HD1)	0.016	0.95	12/20.7	11/56	11/12.5
EHC/DOC + DEF + SCRF + SCR + SCR/ASC - *(under evaluation)*	///	1.05	7/9.4	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 Feb 2016 workshop and Program Advisory Group stakeholder feedback

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)

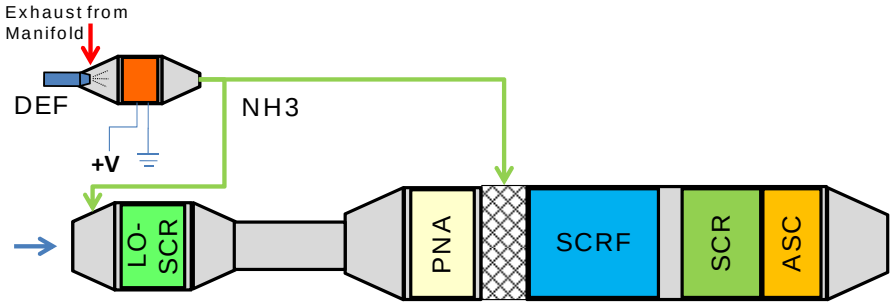
- **Configuration 1 – PNA2+HD1+SCRF+SCR+ASC**



  - 0.025 to 0.03 composite with original 2kw EHC-HD1
  - 0.022 to 0.025 composite with larger 6kw EHC-HD1 (additional 3% BSFC on cold-start)
- **<u>would likely be below 0.02 for a non-TC engine</u>**
  - More heat needed to get below 0.02 on current engine (10kw projected)
- **Advantages – simplest AT system architecture**
- **Why not select it ?**
  - <u>Efficiency</u> – 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)

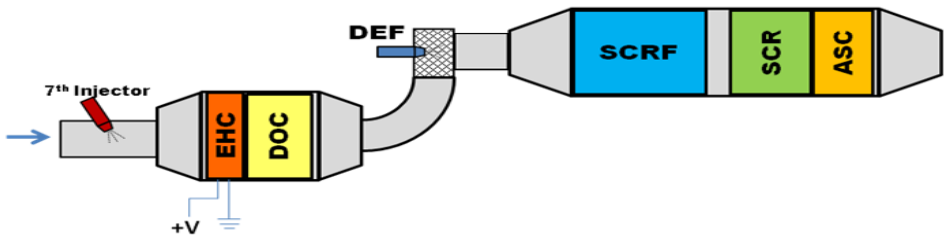
- **Configuration 2 tested – NH3+LOSCR+PNA2+HD1+SCRF+SCR+ASC**
- **Long term implementation = <u>HD2+LOSCR+PNA2+SCRF+SCR+ASC</u>**
  - multipoint dosing is required for this concept to work



  - 0.022 to 0.025 composite 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 – time not available 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**

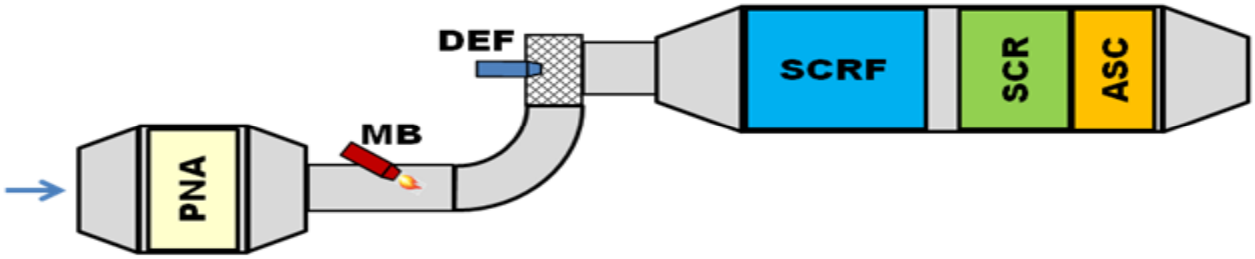
Summary of Results with Third AT Config (not selected for Final Demo)

- **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 impact 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 composite FTP – 0.5% engine cal, 0.5% SCRF regeneration, 1% mini-burner (including air)
    - hot-start optimization may reduce this some
  - < 0.5% on RMC-SET – SCRF regeneration only

Preliminary FTP Test Data Sets with Final Diesel Configuration

	Run	Cold	Hot 1	Hot 2	Hot 3	Composite	Hot Average
Development Parts	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
Average		**0.025**				**0.011**	**0.009**
SD		**0.0015**				**0.0010**	**0.0007**
Degreened Prior to Aging		**0.027**	**0.005**	**0.004**	**0.006**	**0.008**	**0.005**

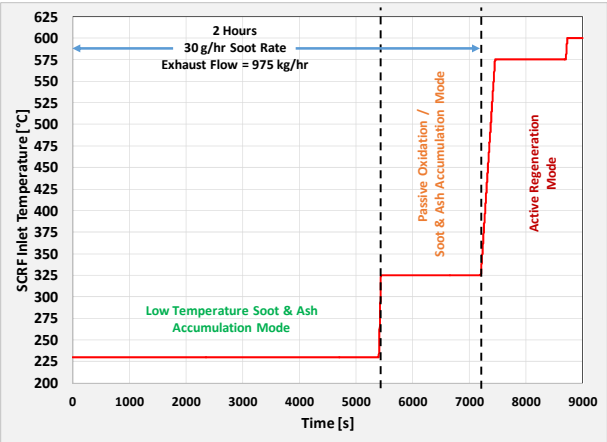
- **Engine-out NO_x is 2.9 g/hp-hr**
- **Cold-start conversion = 99%**
- **Hot-start conversion = 99.7%**

	BSCO2, g/hp-hr		
	Cold	Hot	Composite
Baseline Engine	574	543	547
Current with MB	600	547	555
% change	4.5%	0.7%	1.4%

- **N_2O is 0.07 to 0.08 g/hp-hr**
- **Data will be updated with Final Aged parts in October...**

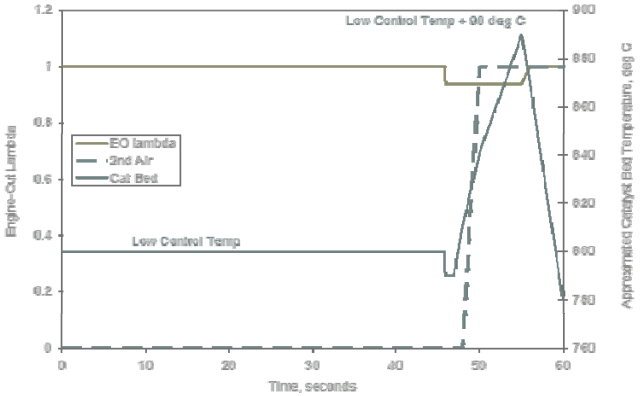
Final Aging Approaches

DIESEL



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

CNG



- **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**
- **Program focus will be 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

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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APPENDIX – CNG RESULTS

CNG Low Emissions Approach

- **Replace engine controls with a system by**
  - 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 (Aged)

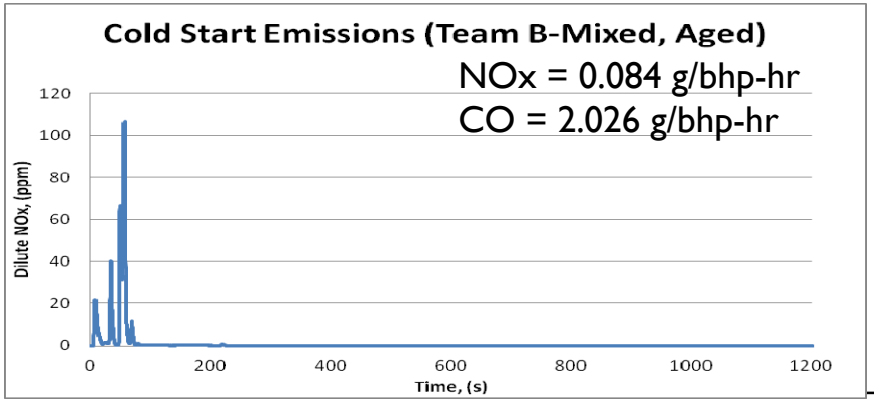
- **Final system selection**
  - Close-Coupled from the two catalyst setup for **cold start**
  - Under-floor TWC from single setup for **space velocity**

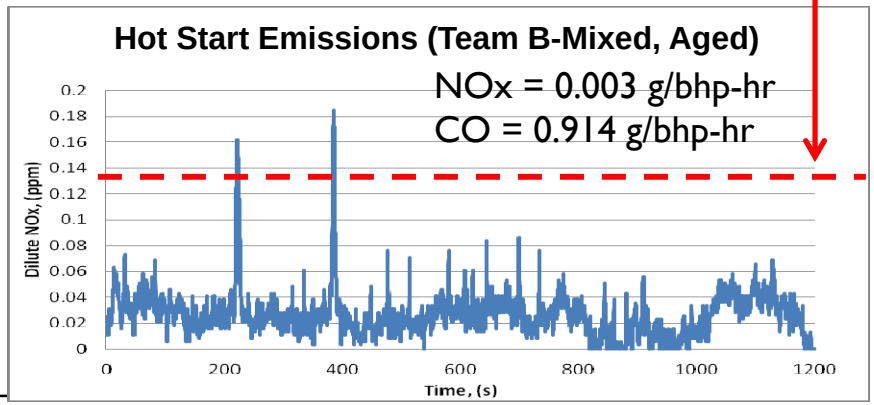
Total SVR ~ 2.4

Close-Coupled

Under-body

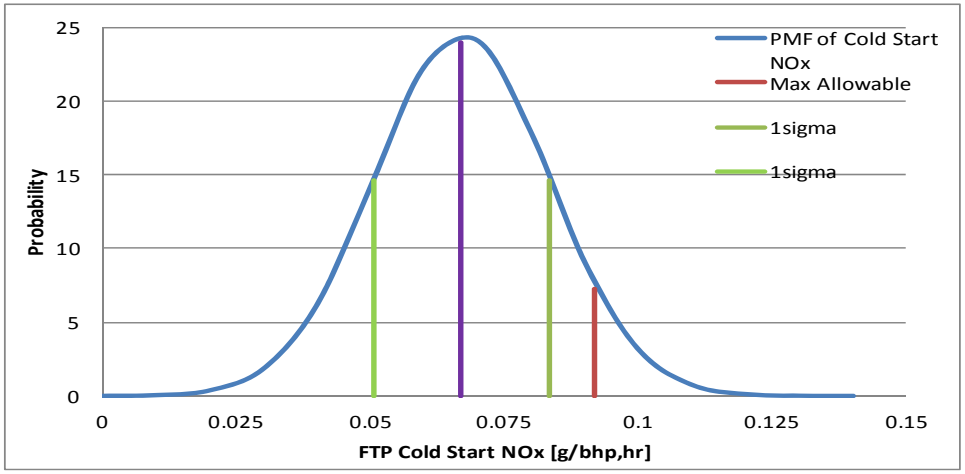
(0.136 ppm average composite NOx over the FTP results in 0.015 g/bhp-hr NOx)





Final CNG Calibration FTP Results (Aged parts)

- **Cold-start FTP**
  - Avg = 0.067 g/hp-hr
  - SD = 0.016 g/hp-hr
- **Hot-start FTP**
  - Avg = 0.005 g/hp-hr
  - SD = 0.003 g/hp-hr
- **Composite = 0.014 g/hp-hr**



- **Note cycle average NH_3 on FTP is ~ 25ppm**
  - This is above the design target of 10ppm but that 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