Sustained Low Temperature NOx Reduction (SLTNR)

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PM068

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Overview

Timeline

- Project 02/03/2015
- Project 12/31/2017
- Percent complete 85%

Budget

- Total project funding
  - DOE share 1.2M
  - CMI share 1.2M
- Funding received FY 2016
  - $643,857
- Funding for FY 2017
  - $439,838.00

Barriers

- Barriers addressed
  - Reductant Delivery at low temperature
  - NOx reduction over 90% at low temperature
  - favorable NO_2/NOx for fast SCR reaction at low temperature

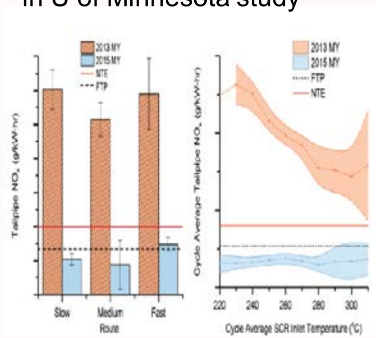
Partners

- Pacific Northwest National Lab
- Johnson Matthey Inc.
- Cummins Inc. (Project Lead)

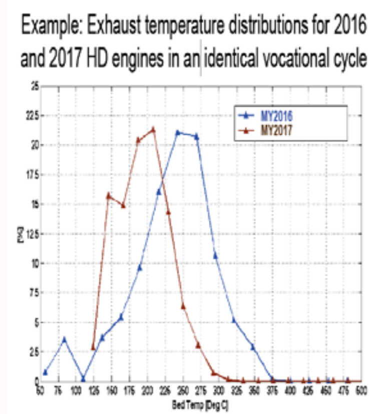
SLTNR Initiatives

Current
Application Challenge

Example: Regulation cycle vs. real world low load cycle in U of Minnesota study



Near Term
Application Challenge



Long Term
Application Challenge

Example: Fuel Efficiency, CARB, In-use Compliance

			SuperTruck 1 2010-2014		SuperTruck 2 (pending) 2016-2021
Major Objective	Metric	Condition / Reference	Program Requirement	Cummins-Peterbilt Team Actual	Program Requirement
1	Engine BTE	Demonstrate, at Cruise Point	50.0%	51.1%	55.0%
2	Vehicle FTE Improvement (Drive Cycle)	Demonstrate Improvement vs. MY2009	50.0%	76.0%	> 100%
3	Vehicle FTE Improvement (24 hour Cycle)	Demonstrate Improvement vs. MY2009	68.0%	86.0%	Actual Program Targets and Intermediaries pending Program Award Selections / Final Details
4	Engine BTE (Stretch Goal)	Define Pathway(s), at Cruise Point	55.0%	Two Viable paths, one Diesel, one Dual Fuel	SuperTruck II will have an increased emphasis on Cost Effectiveness and Commercial Viability

System Solution Challenge

- ➢ Cold start
- ➢ **Sustained low temperature**

Chemical and Engineering Challenge

- ➢ **SCR self-inhibition at low temperature**
- ➢ **Unfavorable NO_2/NOx at low temperature**
- ➢ **DEF deposit at low temperature**

Collaboration Partners

- **Department of Energy**
- **Cummins, Inc.**
- **Pacific Northwest National Laboratory**
- **Johnson Matthey, Inc.**

CMI leads the SLTNR program with the focus on system integration, model simulation, on-engine demo and commercial viability assessment, including NH3 delivery system, DOC system, and SCR system

PNNL supports SCR development to carry out fundamental studies on critical catalyst features needed to enhance LT SCR performance; and to make recommendations on formulations

JMI provides development and application support of aftertreatment catalysts, including powder, core and full size prototypes. JMI also provides aftertreatment modeling support. JMI commercial DOC and SCR catalyst as baseline

Relevance and Project Objectives

Sustained Low Temperature NOx Reduction >90% at SCR inlet 150°C

Develop **SCR catalyst** that enables sustained 90% conversion of NOx entering the SCR catalyst at 150°C

Develop an integrated system capable of providing needed **NO_2/NOx** ratio at SCR inlet 150°C

Develop an appropriate means to robustly **deliver reductant** under sustained operation at SCR inlet 150°C

Develop a model to assess the **commercial viability** of the proposed SLTNR system and **on-engine demonstration** of the developed prototype system

Acknowledgement

- ***Vehicle Technologies Office, Department of Energy:*** Jerry Gibbs
- ***National Energy Technology Laboratory:*** Walter (Jerry) Parker
- ***"DeNOx" research team at Pacific Northwest National Lab:*** Feng Gao, Márton Kollár, Yilin Wang, János Szanyi, Chuck Peden, George Muntean, Mark Stewart, Yong Wang
- ***Catalyst support team at Johnson Matthey:*** Howard Hess, Hai-ying Chen, Zhehao Wei, Joseph Fedeyko, Sampling Team, Balaji Sukumar
- ***Integration support at Cummins :*** Aleksey Yezerets, Michael Cunningham, John Heichelbech, Neal Currier, Krishna Kamasamudram, Ashok Kumar, John Luo, Venkata Lakkireddy, Anand Srinivasan, Saurabh Joshi, Yadan Tang, Johnny Cai, John Henderson, Enoch Nanduru, Vinay Joshi, Samuel Johnson, Rei Tangko , Rohan A Siddhanthi, Krishna Chilumukuru
- ***Test Cell Support***: Analytical Engineering, Inc.
- ***Design & Fabrication:*** Cole Tech

2016 Milestones Completed

	2016 Milestones	% Completion
Mar 2016	Major review complete for reductant delivery system design (high risk item requires iterative generations)	100%
Mar 2016	Alpha formulation (LT SCR) prototype parts available for reactor testing	100%
May 2016	Model based design of DOC and testing completion to confirm system meets NO_2/NOx target	100%
Jun 2016	Model developed for alpha formulation LT SCR and directed the sizing of prototype system	100%
Jun 2016	Initial commercial viability analysis completed and recommendation made for prototype SLTNR system to test	100%
Jun 2016	Finalize the plan on design, hardware procurement and testing	100%
Nov 2016	Recommendation made to improve SCR catalyst formulation into beta version	100%
Dec 2016	Sub system build complete and ready for engine testing	100%

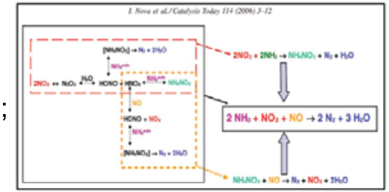
2017 Milestones

	2017 Milestones	% Completion
April , 17	Selections of SLTNR systems for additional testing and final demonstration	100%
June, 17	JMI delivers modified formulation	100%
September, 17	Quantify thermal stability and sulfur sensitivity of LT SCR catalyst formulations	20%
November, 17	Complete demonstration system engine performance and robustness testing	10%
December, 17	Final Review and Program Wrap up	

Technical Approach Progress – SCR Development

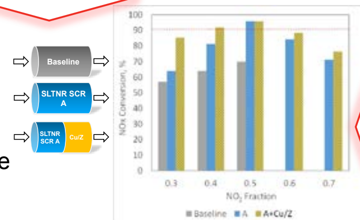
Challenges Identified For Low Temperature SCR

SCR at low temperature proceeds predominantly through the mechanism involving formation, sublimation and decomposition of AN; Self-inhibition due to AN accumulation is the key barrier for best-in-class Cu-SCR at low temp;

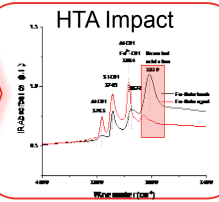


Development and optimization of formulation

PNNL/JM developed SLTNR SCR A and B with minimal NH4NO3 formation; SLTNR SCR followed by Cu/Z hybrid system proved promising for broader range of temperature inlet NO2/NOx ratio; on-going fundamental study on robustness and durability



Lab Diagnostics



Scale-up from powder to monolith by JM

Model to support system performance evaluation

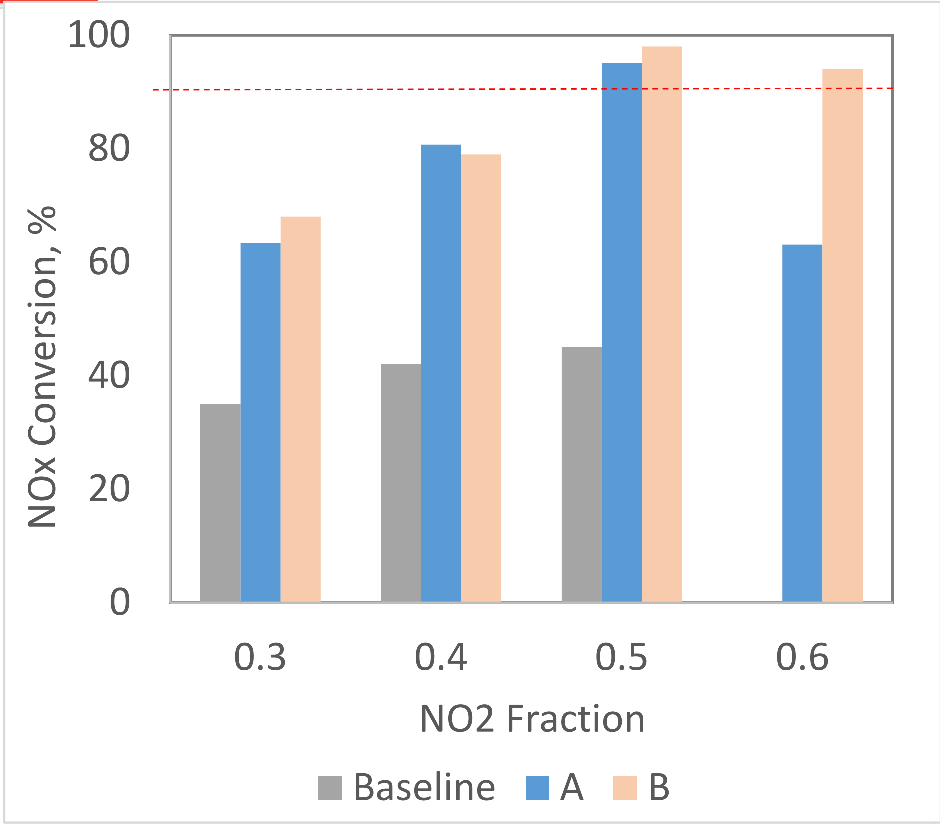
Engine Demo to quantify application potentials and gaps

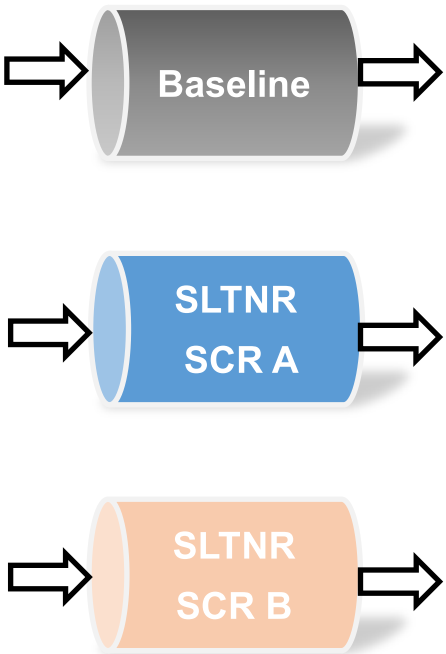
Commercial Assessment

Technical Accomplishment – SCR Component Development

Pacific Northwest NATIONAL LABORATORY · JM · Cummins

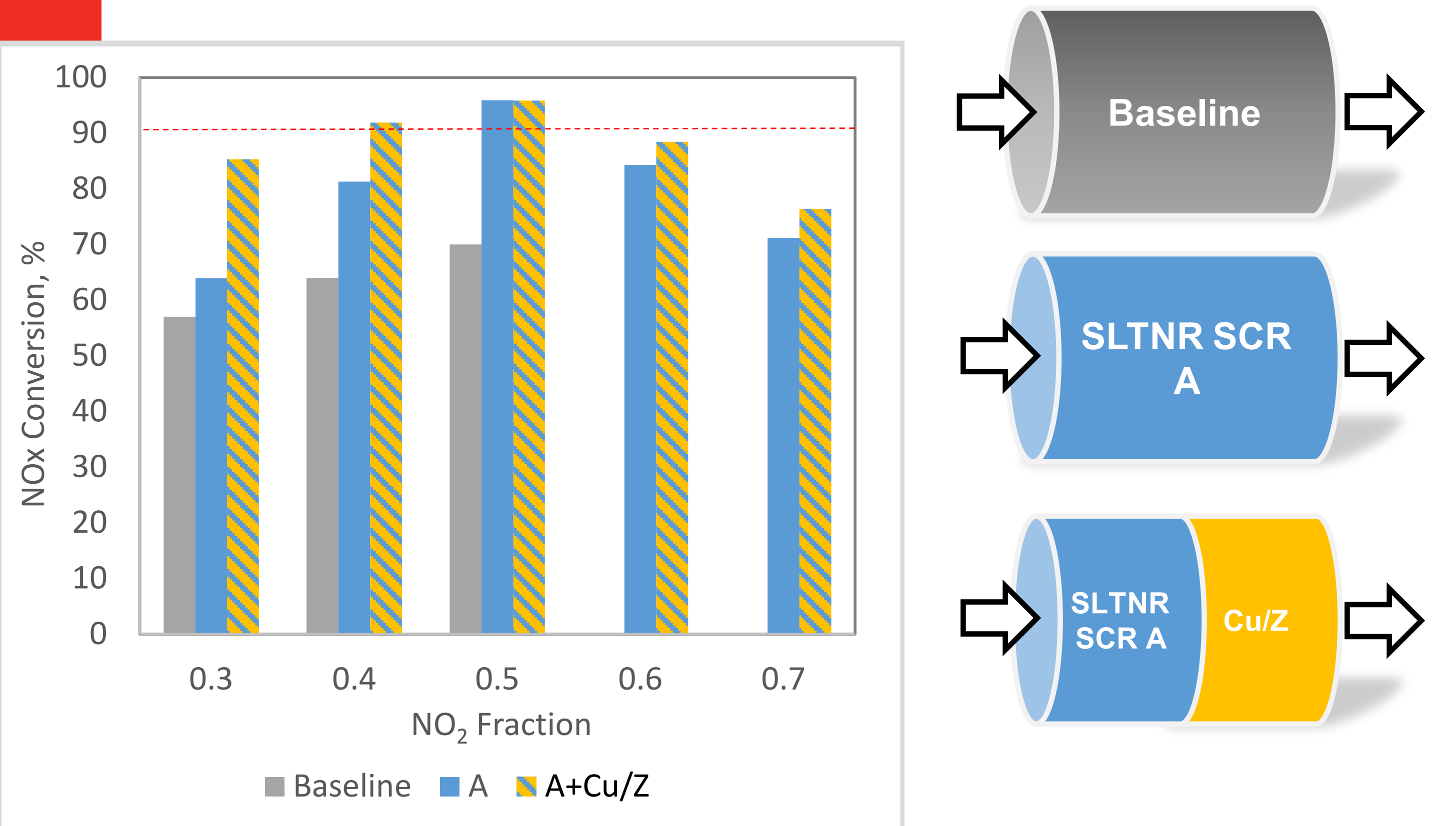
Lab testing with powder at GHSV 100,000h^{-1}, 150°C





Technical Accomplishment – SCR System Development

Lab testing with powder at GHSV 100,000h^{-1}, 175°C

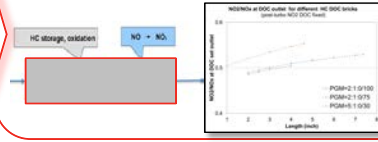


Technical Approach
– Integrated High NO_2 Strategy

Attack Approach

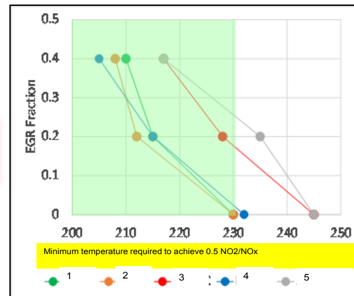
Develop DOC formulation and location together with EGR assistance to optimize NO oxidation performance

Model Based Design of DOC formulation and size



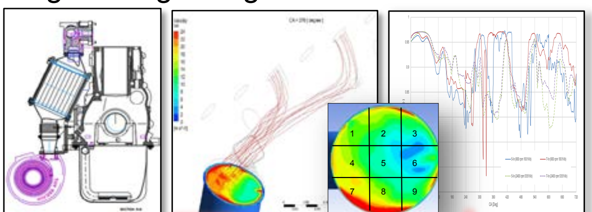
Concept System Mapping

with various PGM, location and volume



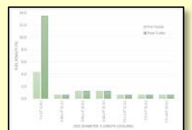
Proof of Concept Pre-turbo DOC

Engineering Design and Evaluation



GT Power

to understand impact on engine



Exhaust manifold re-design

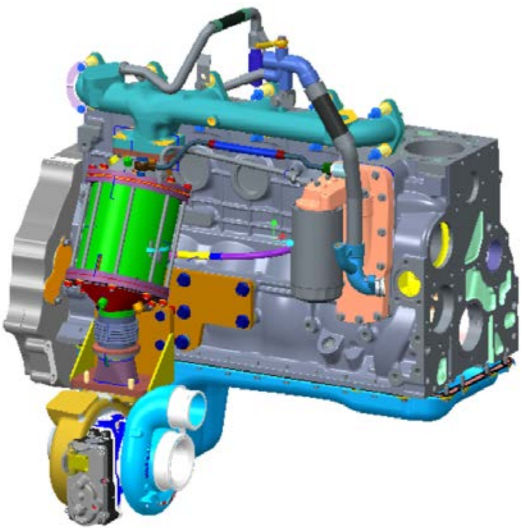
Engine Demo

Commercial Assessment

Technical Accomplishment and Progress – Integrated High NO_2 Strategy

Proof of Concept Design

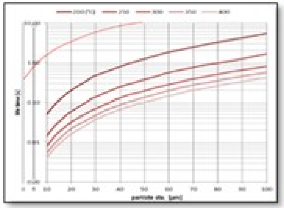
On-going: Engine test and Design optimization to improve transient response



Technical Approach–
Vaporizer Design Proof of Concept

Technology Selection

Droplet size <10micron required at 150°C to minimize deposit, which is not possible with best-in-class mechanical injectors but might be achievable with well designed vaporizer

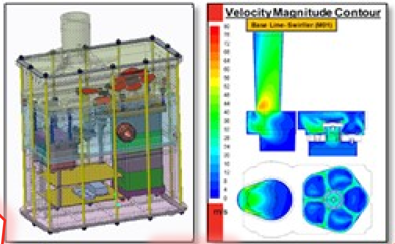


Proof of Concept (I) Preliminary Testing

Droplet Size Distribution Comparison

Averaged Derived Parameter	State of Art Mechanical Injectors	PZT
SMD (micron)	33-55	5~7
Dv90 (micron)	93-150	27

Proof of Concept (II) Component Design



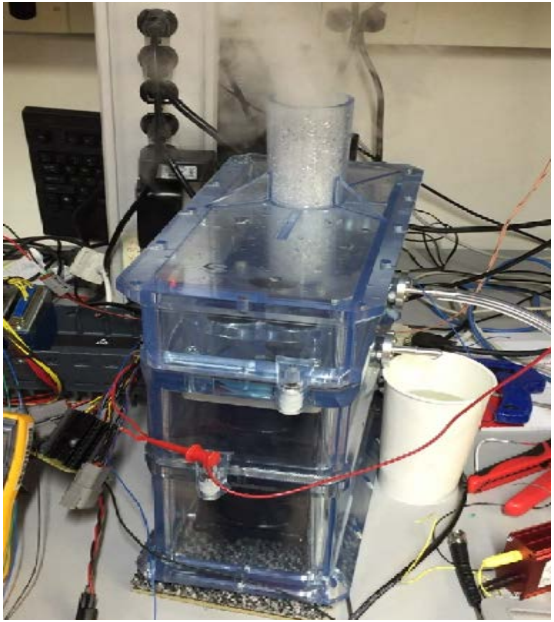
Proof of Concept (III) System Design

Key challenges: metering control, integration, and robustness

Engine Demo to quantify application potentials and gaps

Commercial Assessment

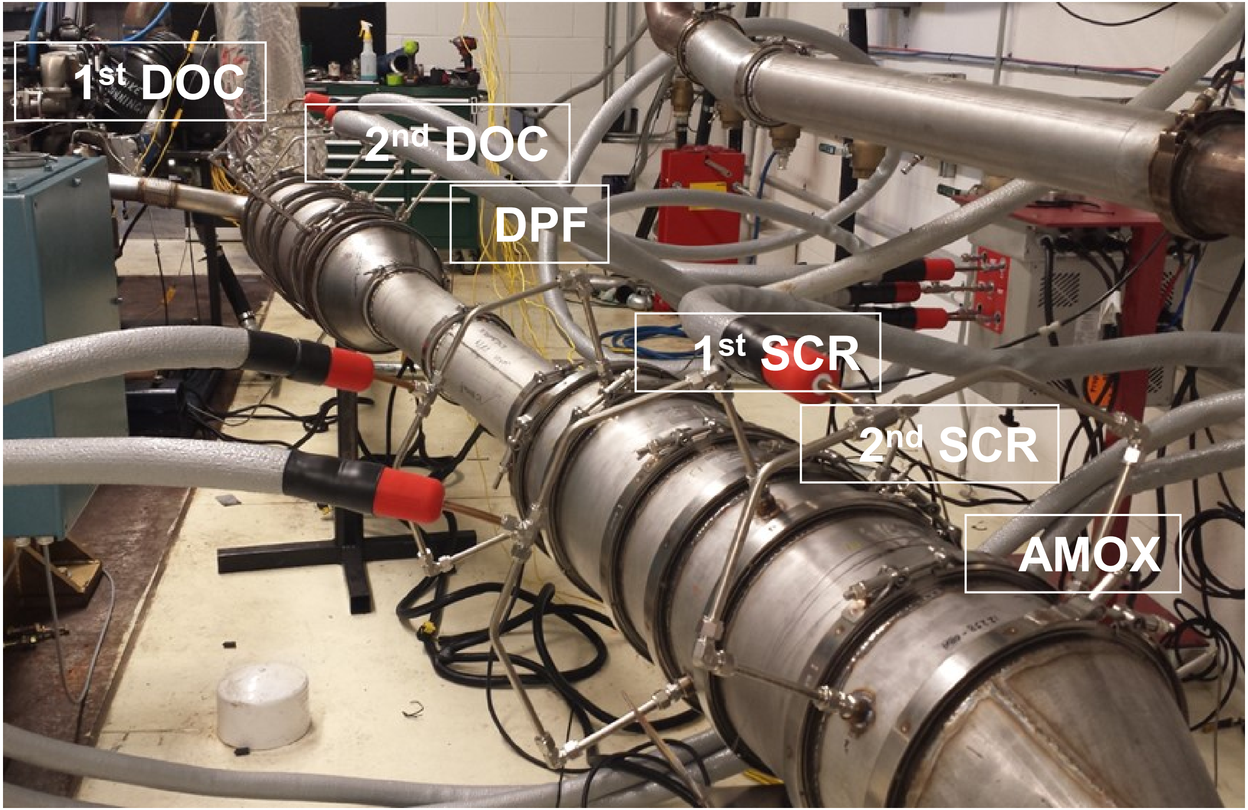
Technical Accomplishment and Progress – Proof of Concept Prototype DEF Vaporizer



Critical Functions and Entitlements	Current Product	SLTNR vaporizer
Min dosing temp (C)	190	(1)
Droplet size (SMD microns)	33	3
Droplet size (DV90 microns)	93	27
Max DEF flow rate (l/hr)	4(2)	0.7(3)

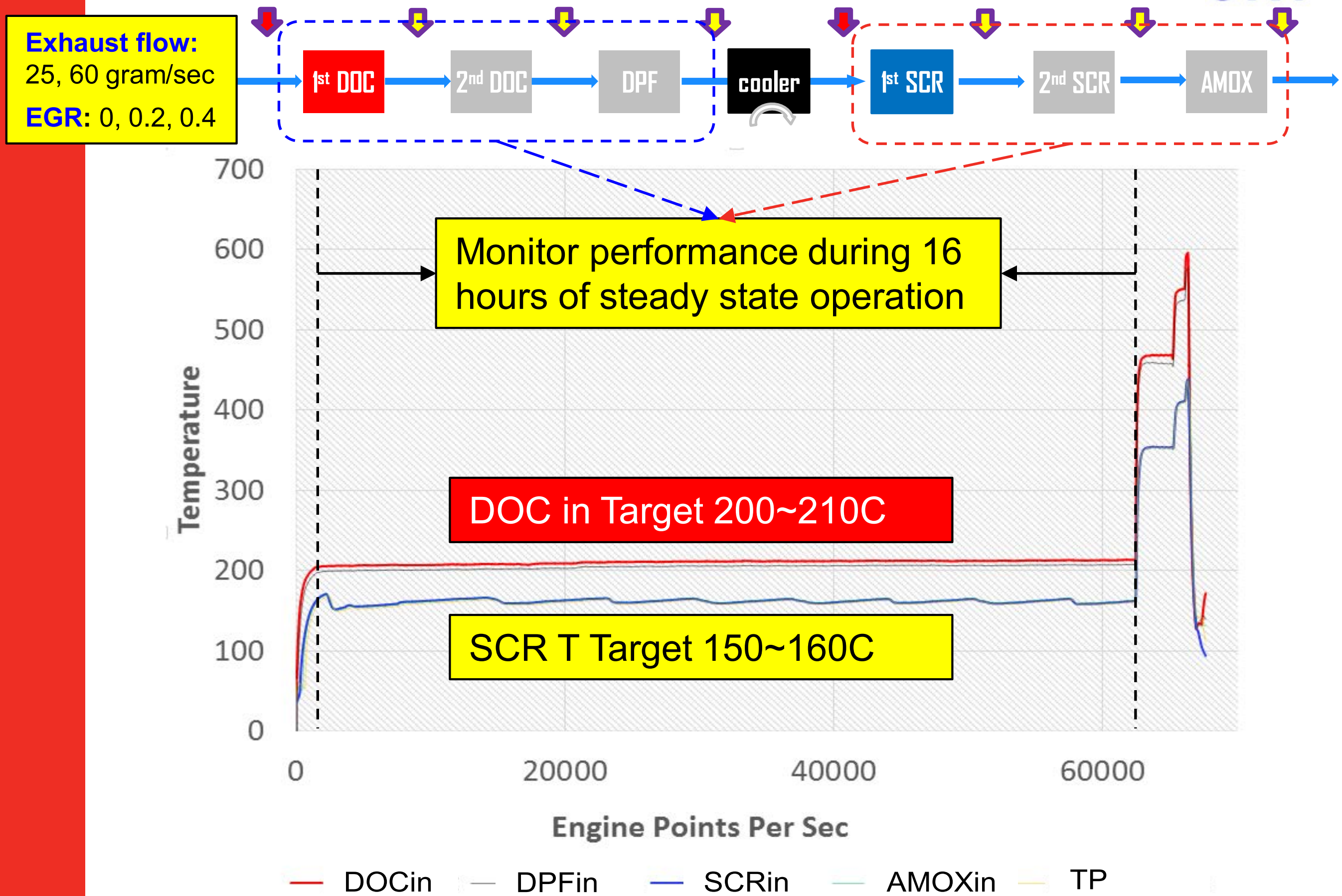
(1) To be evaluated by engine test
(2) Based on ISB with EGR at rated
(3) 0.7 l/hr might be sufficient for SLTNR condition

Technical Accomplishment and Progress – Prototype Engine Test



Performance Evaluation Protocol

ISB 6.7L, 360HP, ANR ~1.0



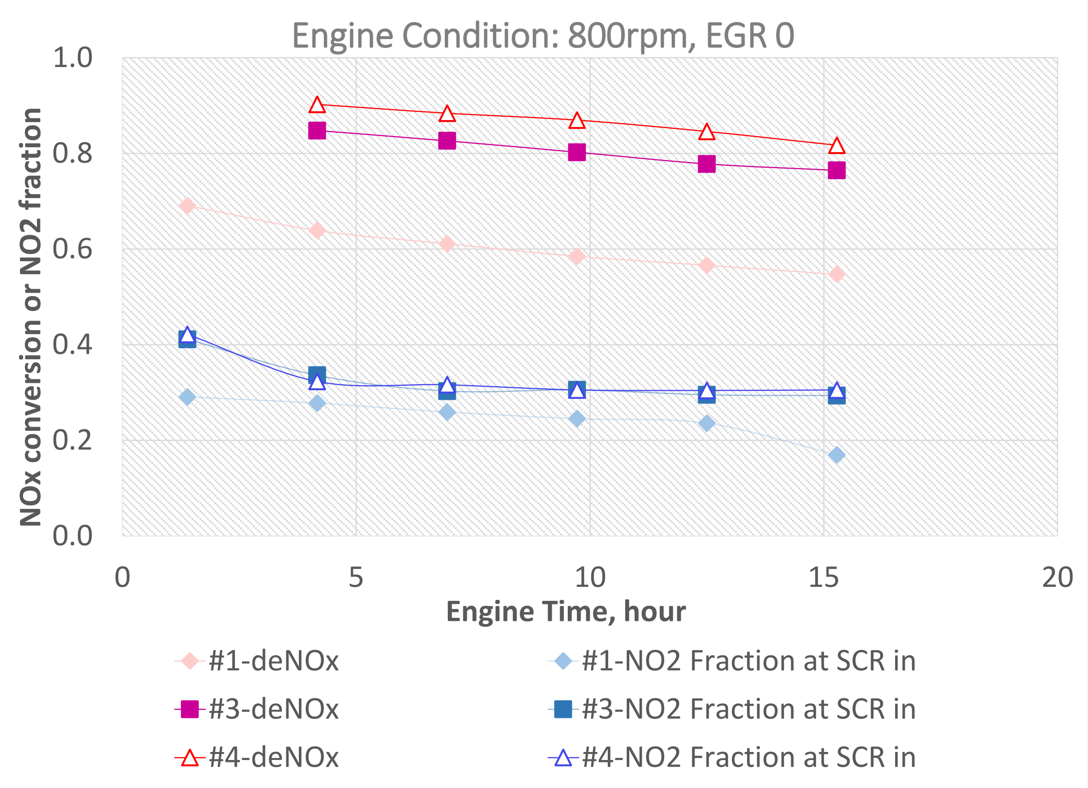
Architectures Evaluation With Incremental Introduction of SLTNR Technology

Architecture #1	Baseline DOC	Baseline NH3 Dosing	Baseline SCR
Architecture #2	DOC GEN1	Baseline NH3 Dosing	Baseline SCR
Architecture #3	DOC GEN1	Baseline NH3 Dosing	SCR GEN1
Architecture #4	DOC GEN2	Baseline NH3 Dosing	SCR GEN1
Architecture #5	DOC GEN2	Baseline NH3 Dosing	SCR GEN2
Architecture #6	DOC GEN2	Baseline NH3 Dosing	SCR GEN3
Architecture #7	DOC GEN2	Vaporizer	SCR GEN3
Architecture #8	DOC GEN3	Vaporizer	SCR GEN3

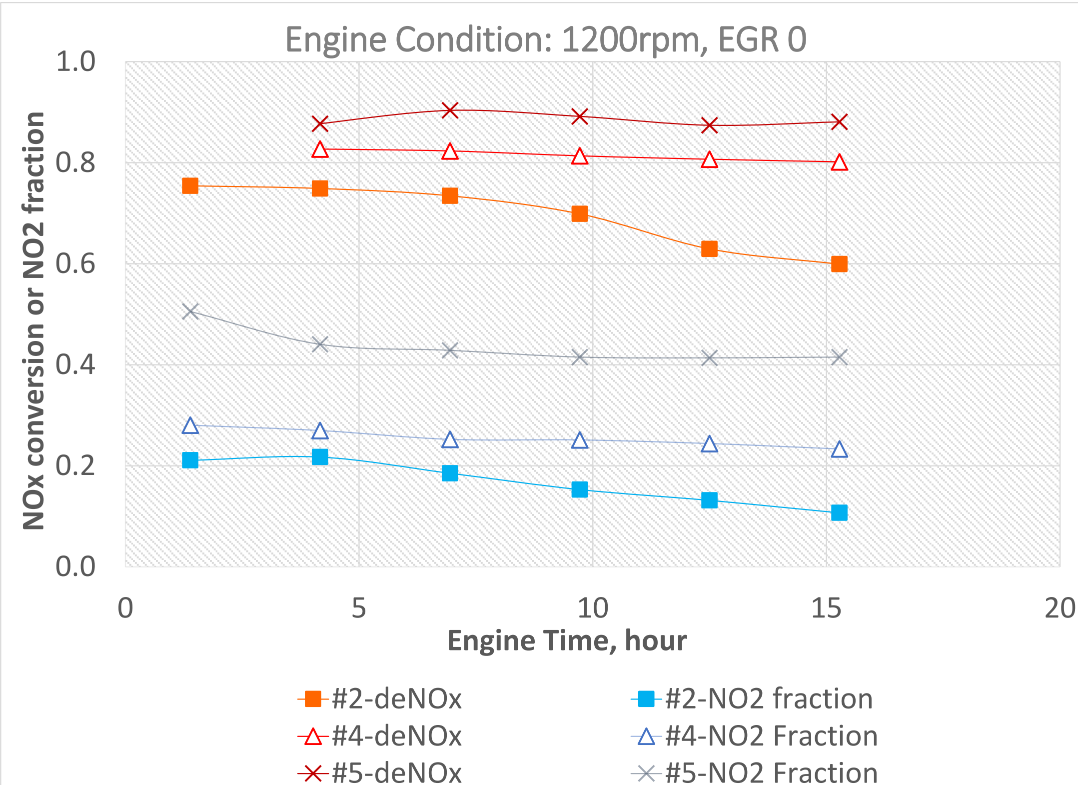
Architectures Evaluation With Incremental Introduction of SLTNR Technology

Time Bar				
	Architecture #1	Baseline DOC	Baseline NH3 Dosing	Baseline SCR
	Architecture #2	DOC GEN1	Baseline NH3 Dosing	Baseline SCR
	Architecture #3	DOC GEN1	Baseline NH3 Dosing	SCR GEN1
	Architecture #4	DOC GEN2	Baseline NH3 Dosing	SCR GEN1
	Architecture #5	DOC GEN2	Baseline NH3 Dosing	SCR GEN2
On-going	Architecture #6	DOC GEN2	Baseline NH3 Dosing	SCR GEN3
Q2’17	Architecture #7	DOC GEN2	Vaporizer	SCR GEN3
Q3’17	Architecture #8	DOC GEN3	Vaporizer	SCR GEN3

Architecture #1	Baseline DOC	Baseline NH3 Dosing	Baseline SCR
Architecture #3	DOC GEN1	Baseline NH3 Dosing	SCR GEN1
Architecture #4	DOC GEN2	Baseline NH3 Dosing	SCR GEN1

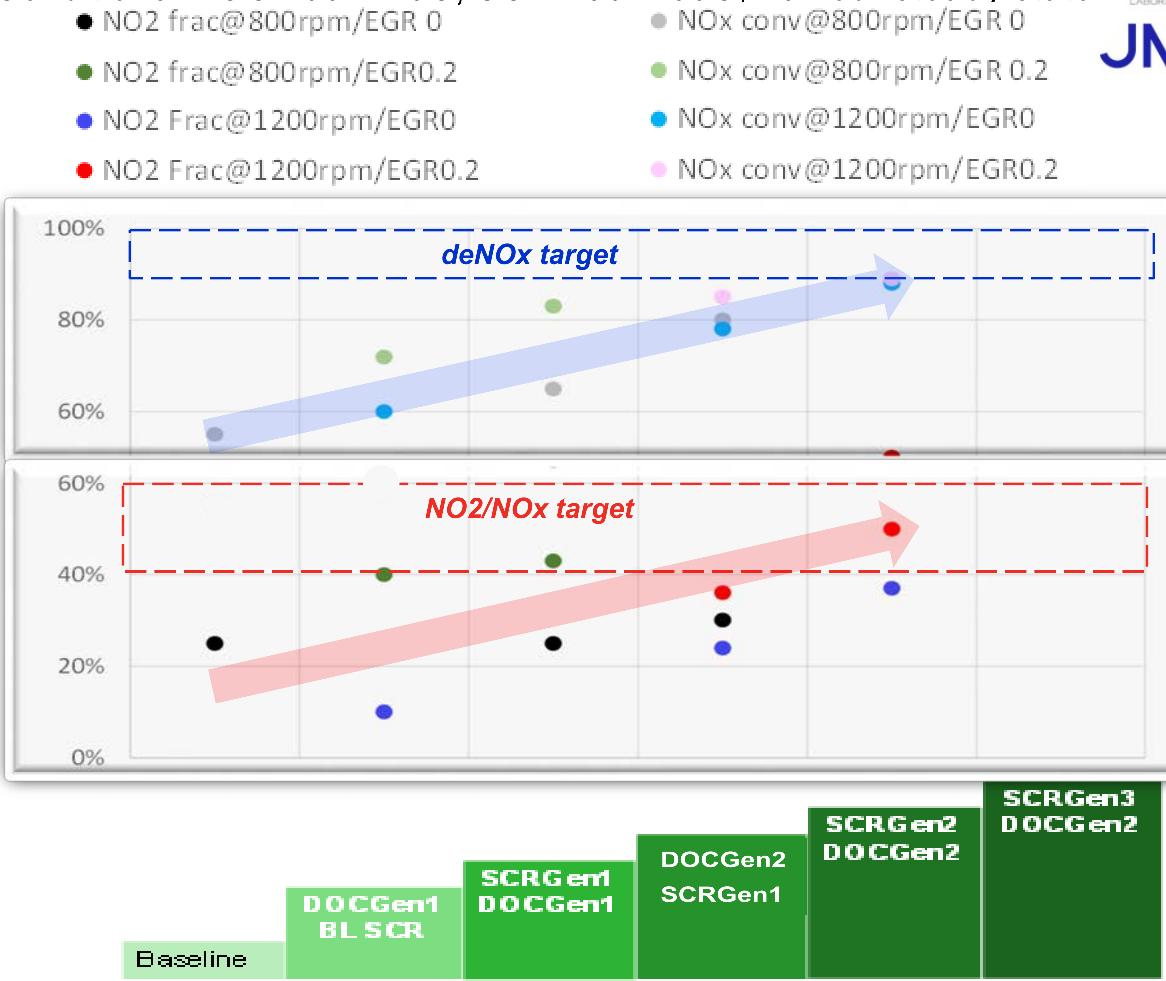


Architecture #2	DOC GEN1	Baseline NH3 Dosing	Baseline SCR
Architecture #4	DOC GEN2	Baseline NH3 Dosing	SCR GEN1
Architecture #5	DOC GEN2	Baseline NH3 Dosing	SCR GEN2



Incremental Performance Improvements

Conditions：DOC 200~210C; SCR 150~160C; 16 hour steady state



Commercial Assessment Summary

Aspect	Evaluation Criteria / Baseline	Current Feasibility	2 Yr. Potential	4 Yr. Potential	6 Yr. Potential	8 Yr. Potential
Initial Purchase Price						
System Cost	Current cost of baseline system = 1x	Rate with a feasibility percentage utilizing baseline and anticipated system cost				
Operating Cost						
Active regen frequency (reduced passive regeneration)	Time between active regens over operating duty cycle	Rate with a feasibility percentage utilizing baseline system values and anticipated performance of final system				
Fluid Economy over drive cycle	Fuel + Urea consumption over cold FTP + warm FTP					
Fluid Economy over low temperature operation	Fuel + Urea consumption over low temperature cycle					
Backpressure	Exhaust manifold pressure at rated temperature and flow					
Maintenance Cost						
Exhaust manifold with pre-turbo catalyst	Mitigation/Investigation of mechanical stresses/cracking	0.81	0.81	0.91	0.96	0.98
Pre-Turbo DOC	Mitigation of aging, debris control	0.61	0.81	0.81	0.91	0.91
NO2/NOx maintainance control	Design of control system	0.6	0.6	0.79	0.85	0.85
New SCR formulation	Hydrothermal aging, pre-treatment methodology	0.61	0.61	0.8	0.9	0.9
Vaporizer system	Component durability, deposit control, metering control	0.5	0.5	0.6	0.8	0.85
Exhaust bypass controls	Engine transient response, manage hydrothermal aging	0.8	0.8	0.9	0.95	0.98
OEM Development Cost						
Packaging impact to vehicle	Baseline engine/aftertreatment space claim envelope	0.6	0.6	0.6	0.9	0.9
Estimated System Feasbility		0.65	0.68	0.77	0.90	0.91

Preliminary for Directional Use Only: This is a forward looking preliminary assessment of risk in the early stages prior to experimental demonstration. These assessments may change significantly as demonstration work progresses.

Commercial Assessment Summary

Aspect	Evaluation Criteria / Baseline	Current Feasibility	2 Yr. Potential	4 Yr. Potential	6 Yr. Potential	8 Yr. Potential
Initial Purchase Price						
System Cost	[illegible]aseline system = 1x	Rate wi[illegible]				[illegible] system cost
Operating Cost						
Active regen frequency (reduced passive regeneration)	Time between active regens over operating duty cycle	Rate with a feasibility percentage utilizing baseline system values and anticipated performance of final system				
Fluid Economy over [illegible]	[illegible] over cold FTP + warm FTP					
Fluid Economy over [illegible]	[illegible] over low temperature cycle					
Backpressure	Exhaust manifold pressure at rated temperature and flow					
Maintena[illegible]						
Exhaust[illegible]	[illegible] stresses/cracking					0.98
Pre-Turb[illegible]						0.91
NO2/NO[illegible]						0.85
New SC[illegible]	[illegible]ethodology					0.9
Vaporizer system	Component durability, deposit control, metering control	[illegible]	[illegible]	[illegible]	[illegible]	0.85
Exhaust b[illegible]	[illegible]age hydrothermal aging	0.8	0.8	0.9	0.95	0.98
OEM Develo[illegible]						
Packaging [illegible]	[illegible] space claim envelope	[illegible]	[illegible]	[illegible]	[illegible]	0.9
Estimated System Feasbility						0.91

Initial Cost

Planned 2017

Operating Cost

Maintenance Cost Via Risk Management

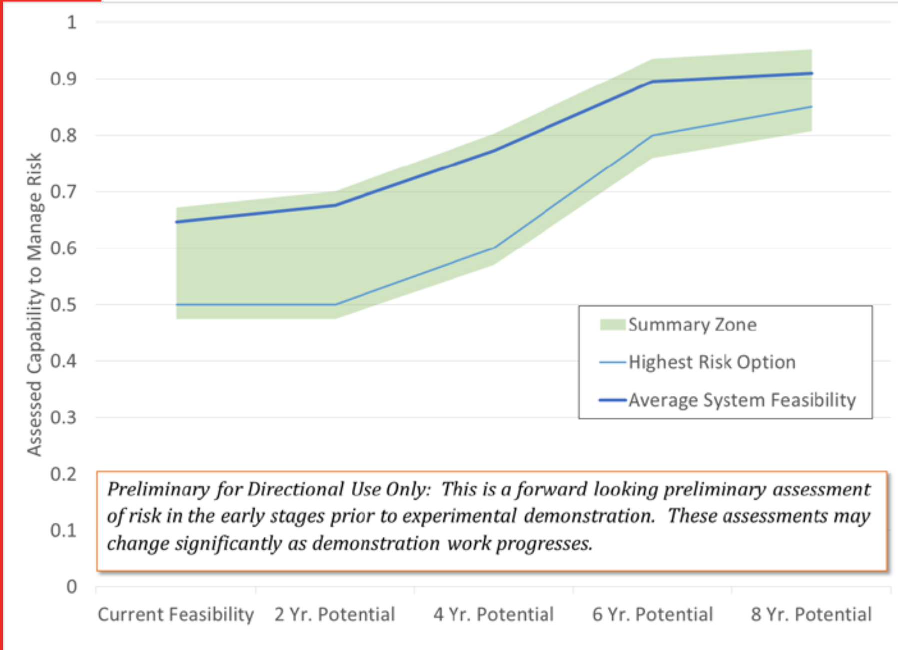
Percentage Readiness Assessed from 0 - 1

OEM Develop. Cost

Overall System Roll-Up

Preliminary for Directional Use Only: This is a forward looking preliminary assessment of risk in the early stages prior to experimental demonstration. These assessments may change significantly as demonstration work progresses.

Overall Risk Assessment Summary



- Overall risk is a function of weakest sub-system, however, alternatives may be found to mitigate
- Average feasibility gives way to roll-up typical combined system risks
- Summary zone used to describe most likely scenarios

Summary -

- Achieved ~90% NOx reduction target at SCR ~150°C on engine with gaseous NH_3 dosing and SLTNR SCR and DOC system; further improvements expected by optimizing SCR system;

- Developed ultra sonic reductant delivery technology using DEF to reduce droplet size and therefore minimize requirements of temperature and residence time; this will be tested on engine for demonstration

- Commercial viability will be assessed against identified technology risk factors with percentage of feasibility and confidence, to provide indication of potential for final system

Remaining Challenge

- Catalyst
  - Durability and Robustness of performance at all operation conditions
- Urea Vaporizer
  - System integration and control

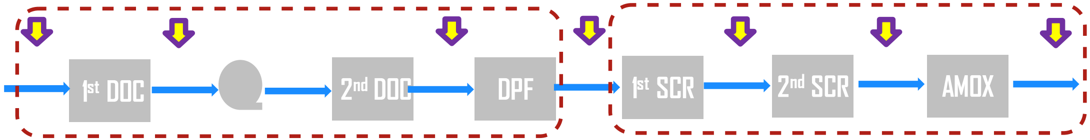
Future Work

- In SLTNR Scope and Timeline (by the end of 2017)
  - Complete final system on-engine demonstration
- Outside of SLTNR scope and timeline but needed toward a commercial viable product
  - NO2/NOx Control development : method to sense NO2/NOx for feedback control, identification of control levers and controller design
  - Low temperature SCR formulation improvement to mitigate performance degradation and tolerance to exhaust chemicals such as sulfur and HC.
  - Exhaust manifold design optimization with pre-turbo catalyst to reduce risk of mechanical/thermal stress/cracking
  - Pre-Turbo DOC design optimization to mitigate thermal aging, debris impact on turbo, system design to mitigate poor transient response
  - System integration to mitigate turbo slow transient response with pre-turbo catalyst
  - Packaging impact to vehicle and modify available space claim, estimate as step change

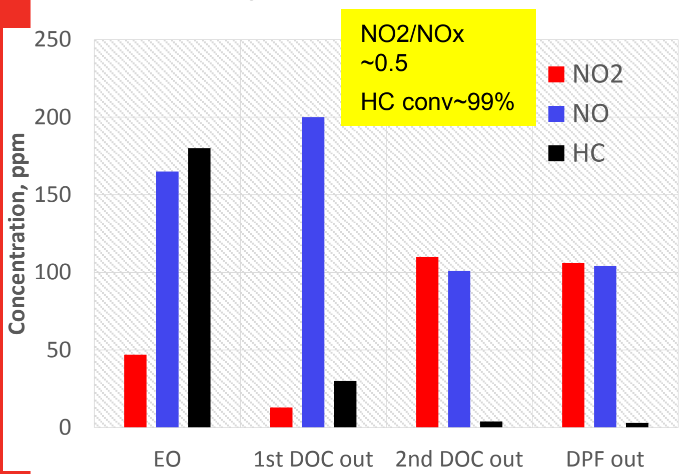
Technical Backup (Max 5 Slides)

Architecture #5(DOC GEN2+SCRGEN2)

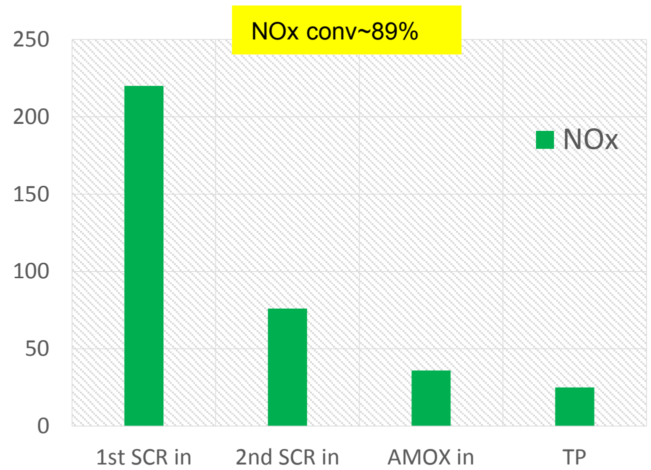
16 hour SS @1200 rpm, 85ft-lb, EGR=0.2, ANR ~1.0, SCR ~150C



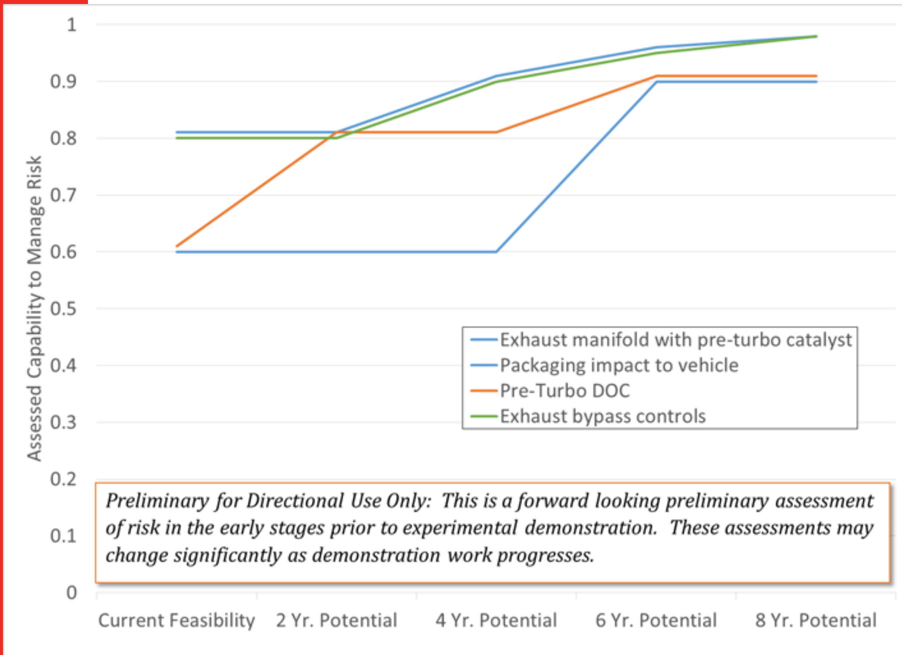
DOC System Performance



SCR System Performance

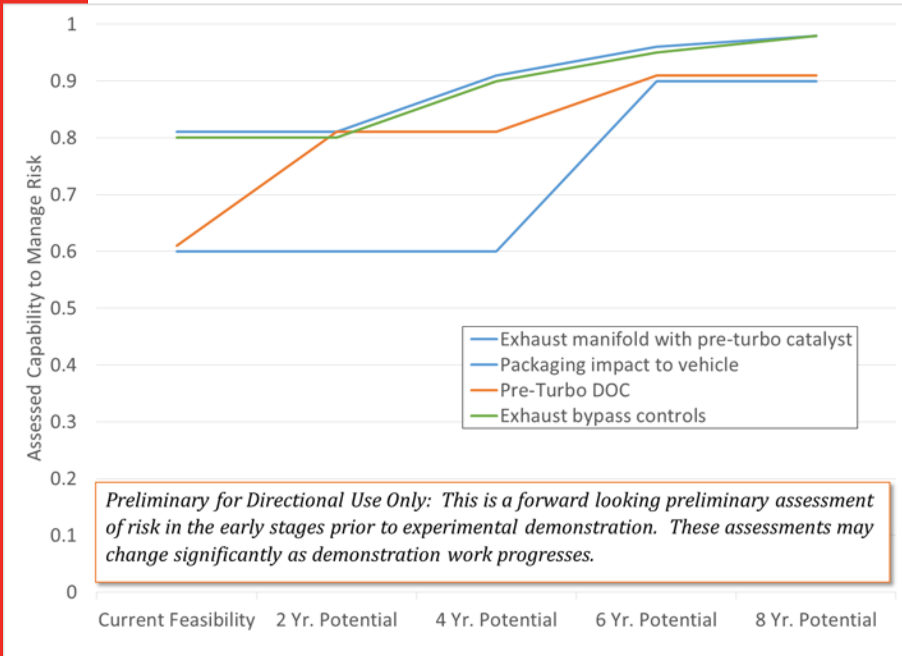


Lower Risk Aspects Graphical Summary



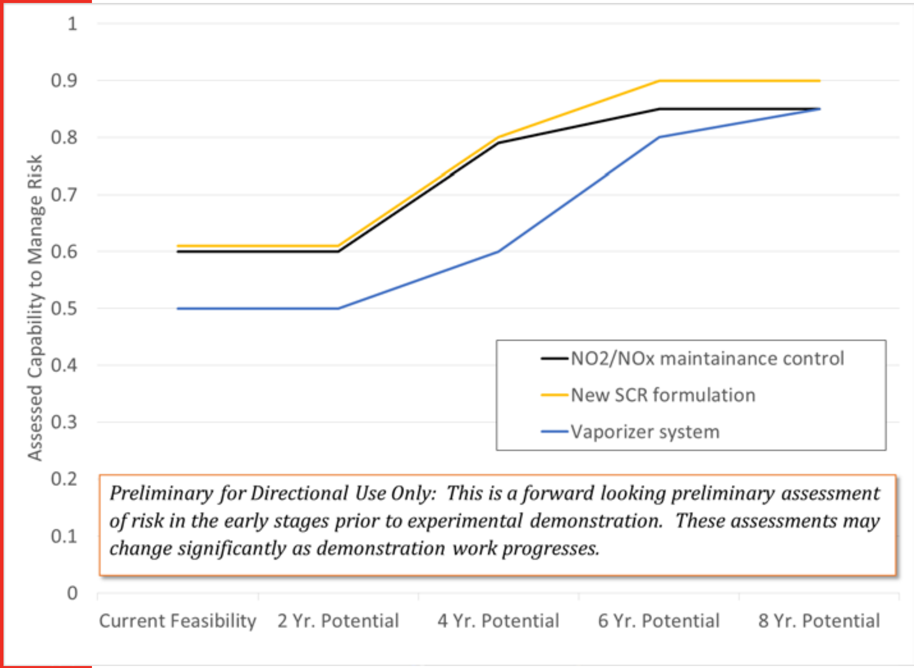
- Exhaust manifold with pre-turbo catalyst
  - Design work to reduce risk of mechanical/thermal stress/cracking
- Packaging impact to vehicle
  - Will take time to work with vehicle manufacturers and modify available space claim, estimate as step change

Lower Risk Aspects Graphical Summary



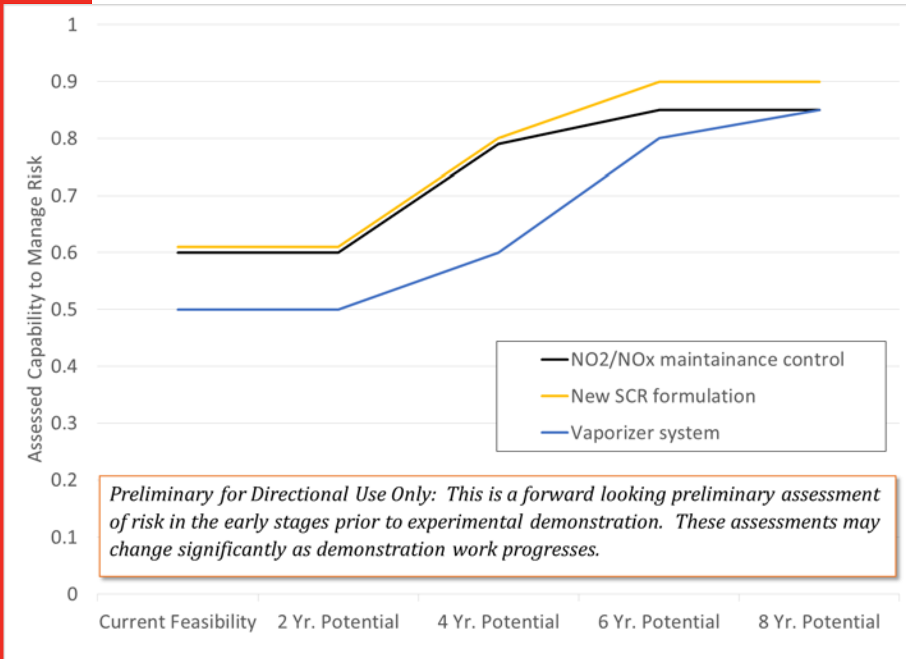
- Pre-Turbo DOC
  - Mitigation of thermal aging, mitigation of debris into turbo, system design to mitigate poor transient response
- Exhaust bypass controls
  - Requirements need to be well defined and created, but have experience with similar systems with exhaust valves and turbocharger bypasses previously

Higher Risk Aspects Graphical Summary



- NO_2/NO_x Control
  - Reduce variability of DOC, method to sense NO_2/NO_x for feedback control, identification of control levers and controller design
- New SCR formulation
  - Catalyst design to mitigate hydrothermal aging; pre-treatment methods to mitigate ammonia nitrite formation without negative impact on NO_x conversion

Higher Risk Aspects Graphical Summary



- Vaporizer System
  - Robust design for variety of environmental conditions; system design to mitigate deposit formation, robust metering control of DEF and integration into ECM controls