CARB Low NO_X Demonstration Program Stage 3 Summary

SOUTHWEST RESEARCH INSTITUTE®

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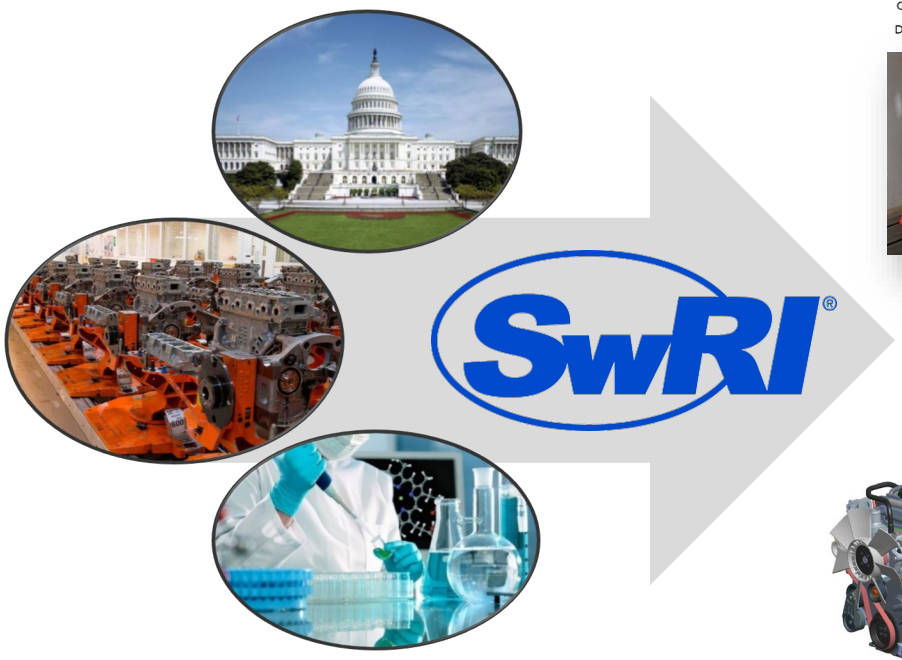
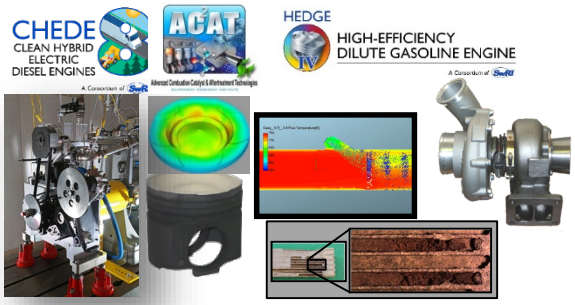
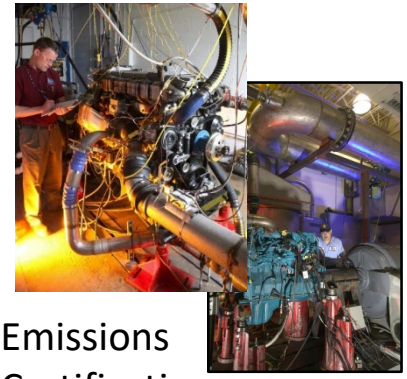
Southwest Research Institute

- One of the Largest Independent Not-for-Profit R&D Organizations in the U.S.
- Applied Research and Development
- Partnering With Industry, Government, and other R&D Labs
- Independent experts in the powertrain engineering, emissions measurements, and new technology development

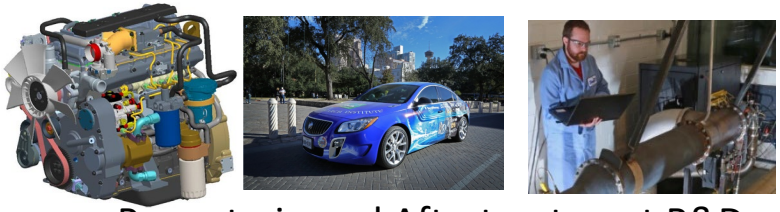




Advanced Research & Industry Consortium



Emissions Certification



Powertrain and Aftertreatment R&D

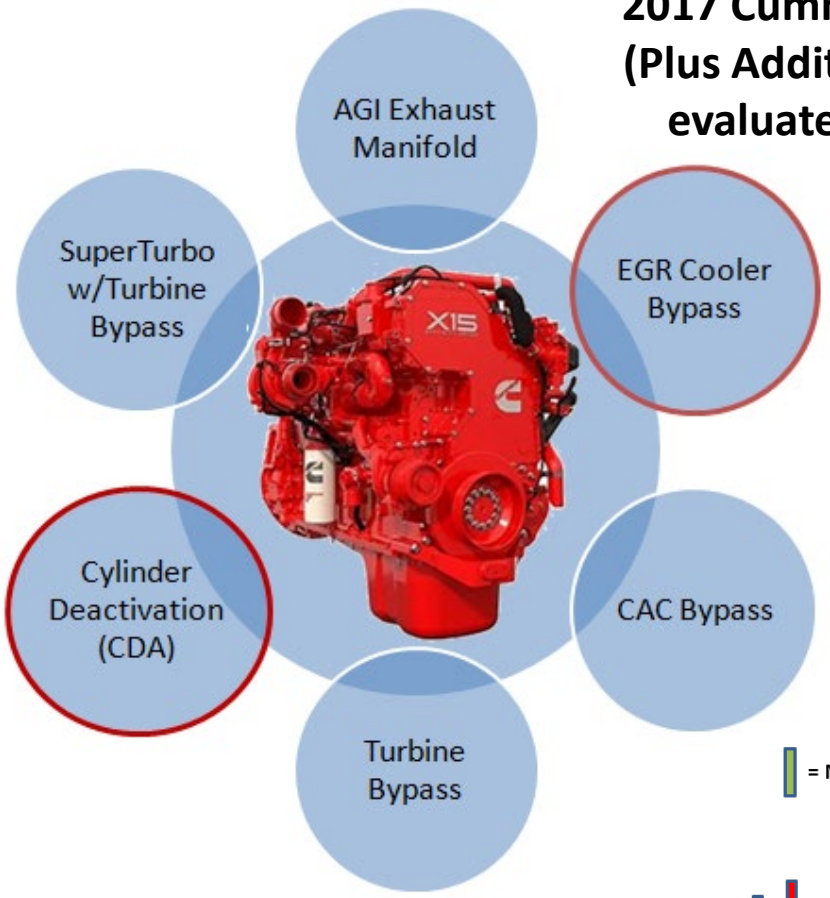
More than 40 years of Emissions R&D and Technology Demonstration

CARB Low NO_X Programs at SwRI

- ***Stage 1*** – *Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles (2014-2017)* - ***COMPLETE***
  - *Initial Technology Evaluation – Diesel and CNG*
  - *Primary focus on Regulatory Cycles*
- ***Stage 1b*** – *Repeat Aging and Evaluation of Stage 1 Hardware (2018-2019)* - ***COMPLETE***
  - *Answer questions from Stage 1 and provide robust parts for Stage 2*
- ***Stage 2*** – *Heavy-Duty Low Load Emission Control (2017-2019)* - ***COMPLETE***
  - *Expand previous technology evaluation to low-load and urban operating cycles*
- **Stage 3** – Further Evaluation and Development of Low NO_X Technologies on 2017 (non-Turbocompound) Engine Platform (2018-2020) – **In Progress**
  - Focus on both Low Load (Real world) and Regulatory cycles
  - ***Stage 3b – Engine Hardware Technology Effort organized by SwRI to augment Stage 3***
- Nonroad – Baseline Testing and Modeling (2019-2020) – ***In Progress***
- Nonroad Technology Demonstration (2020-2021) – ***Contracted***

Stage 3 Low NO_X Hardware Configuration

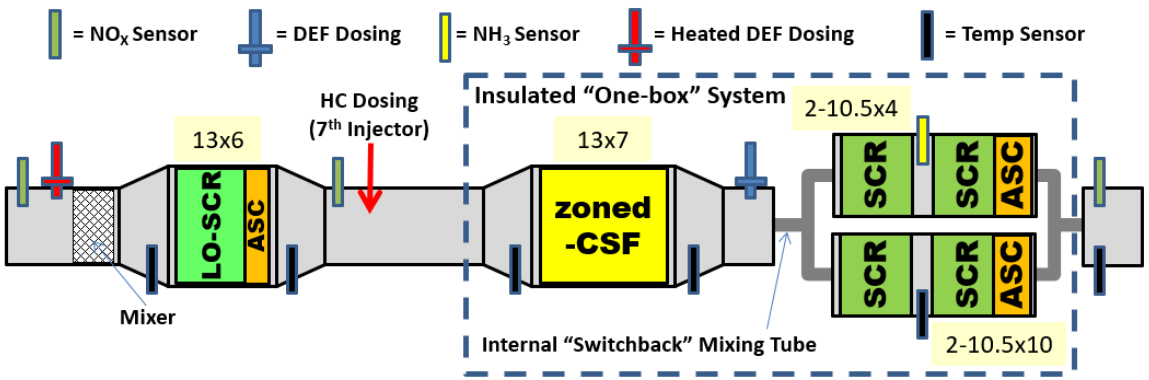
2017 Cummins X15 Engine (Plus Additional Hardware evaluated for Stage 3)



Targets:

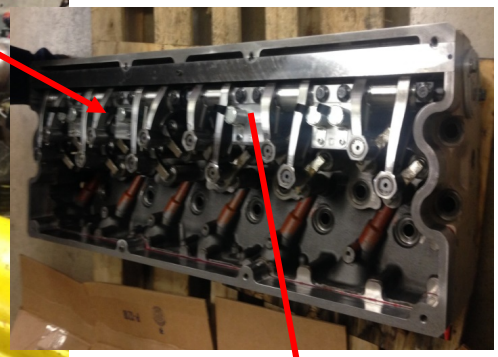
- **FTP/RMC NO_X 0.02 g/hp-hr**
- **Lowest feasible LLC and in-use NO_X**
- **No adverse GHG impact**

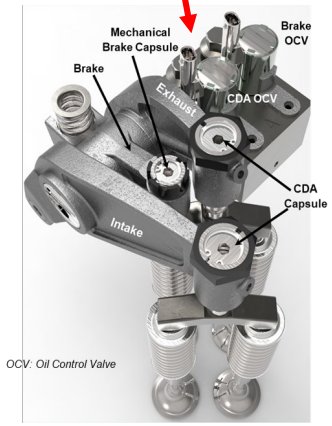
Advanced Low Aftertreatment (Dual SCR-Dual Dosing)



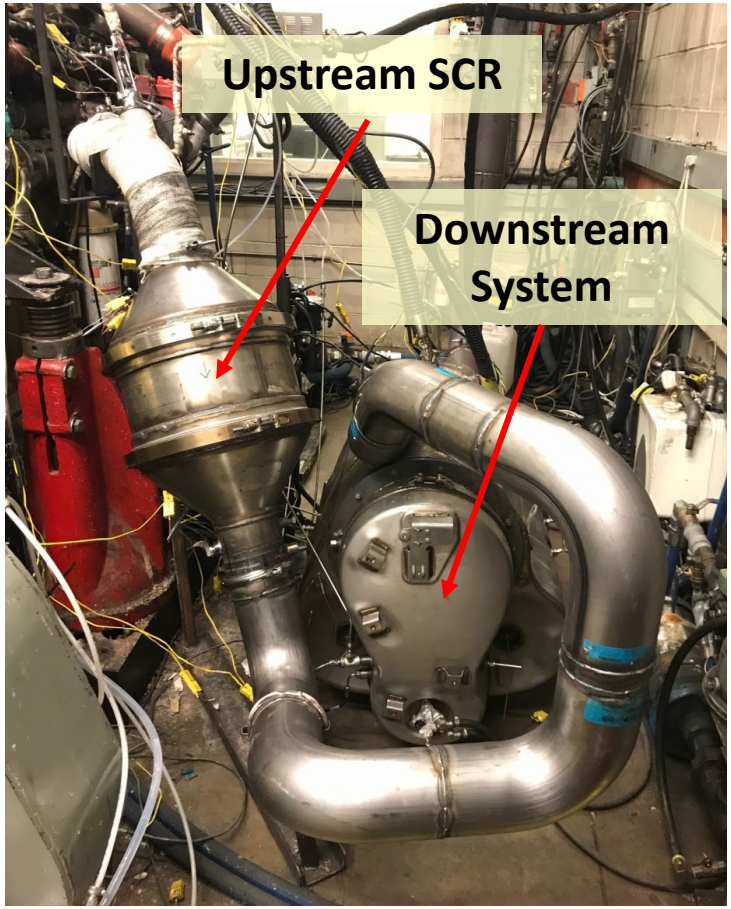
Stage 3 System - Actual Hardware

Cummins X15 Engine





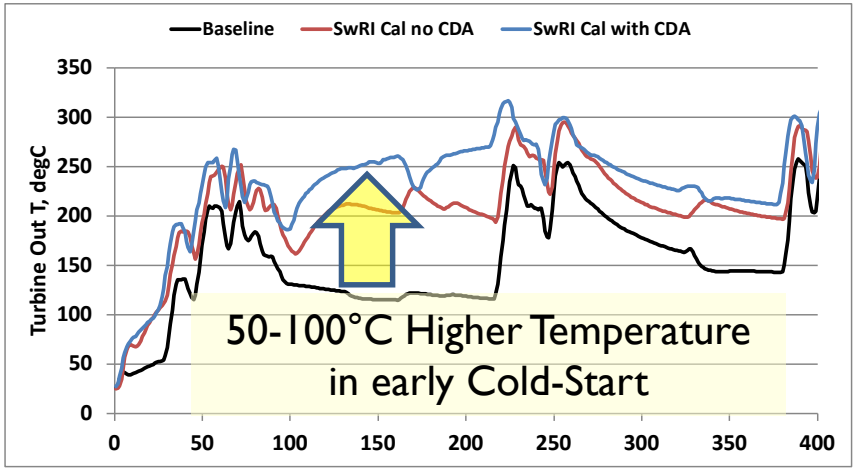
Low NO_X Aftertreatment System



Eaton Cylinder Deactivation (CDA) Hardware

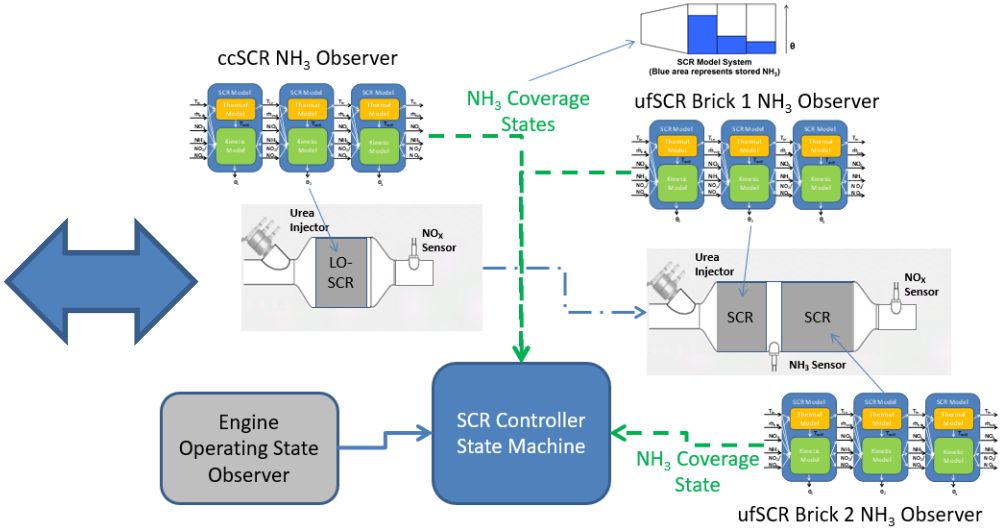
Stage 3 Engine and Aftertreatment Controls

Engine Controls



- Modified Engine Calibration and Hardware
- Increased Temperature and Reduced NO_X when Aftertreatment is Cold
- Minimal Impact in CO_2 over Cycles

Aftertreatment Controls



- Model-Based Aftertreatment Controls
  - Production Oriented
- High Precision
- Flexible for Wide Variety of Real-World Conditions

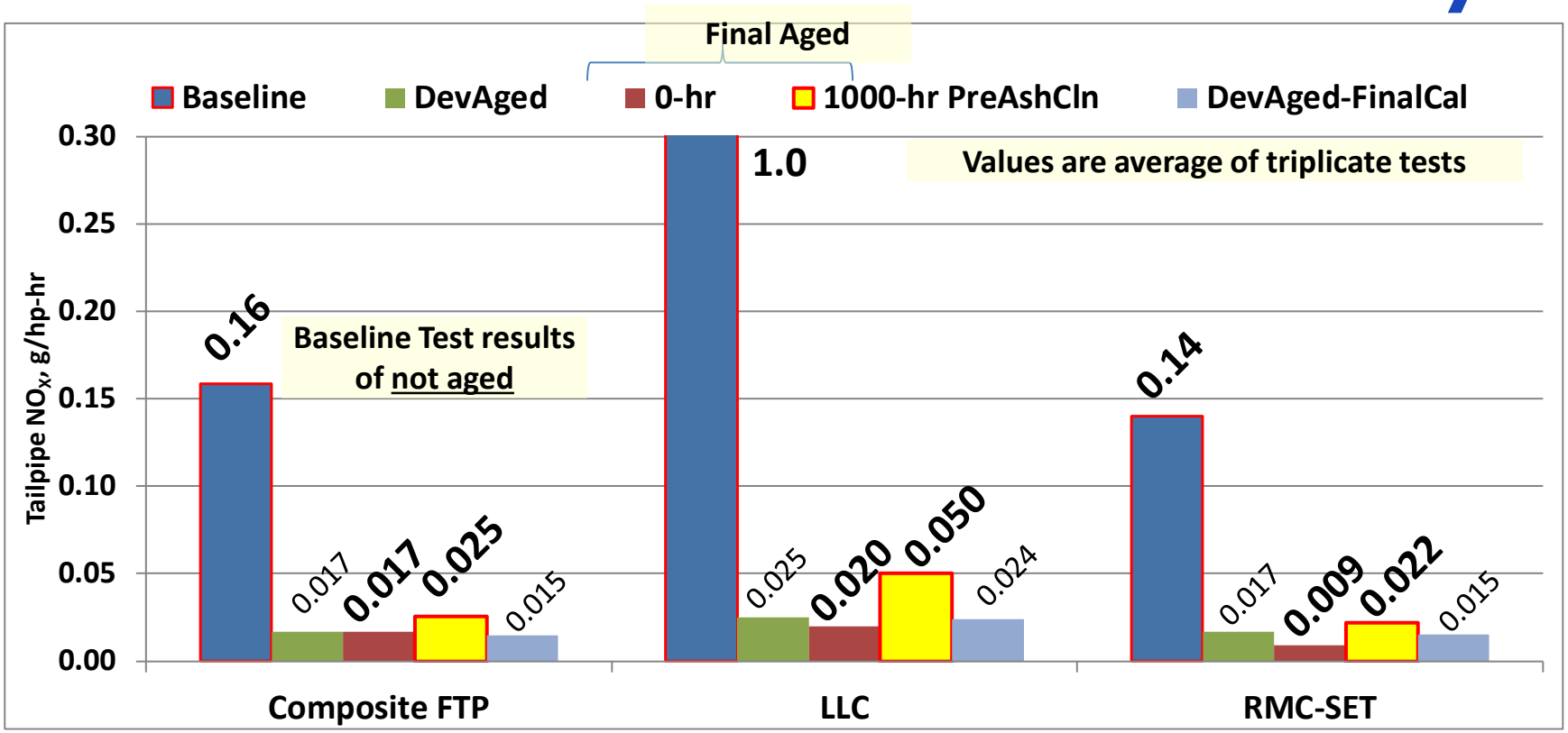
Aftertreatment Aging Methods

- Two types of Aging for the program parts <u>both based on 435,000 miles FUL</u>

- Development Aged parts
  - <u>Thermal aging only</u>
  - Used for calibration and controls development work

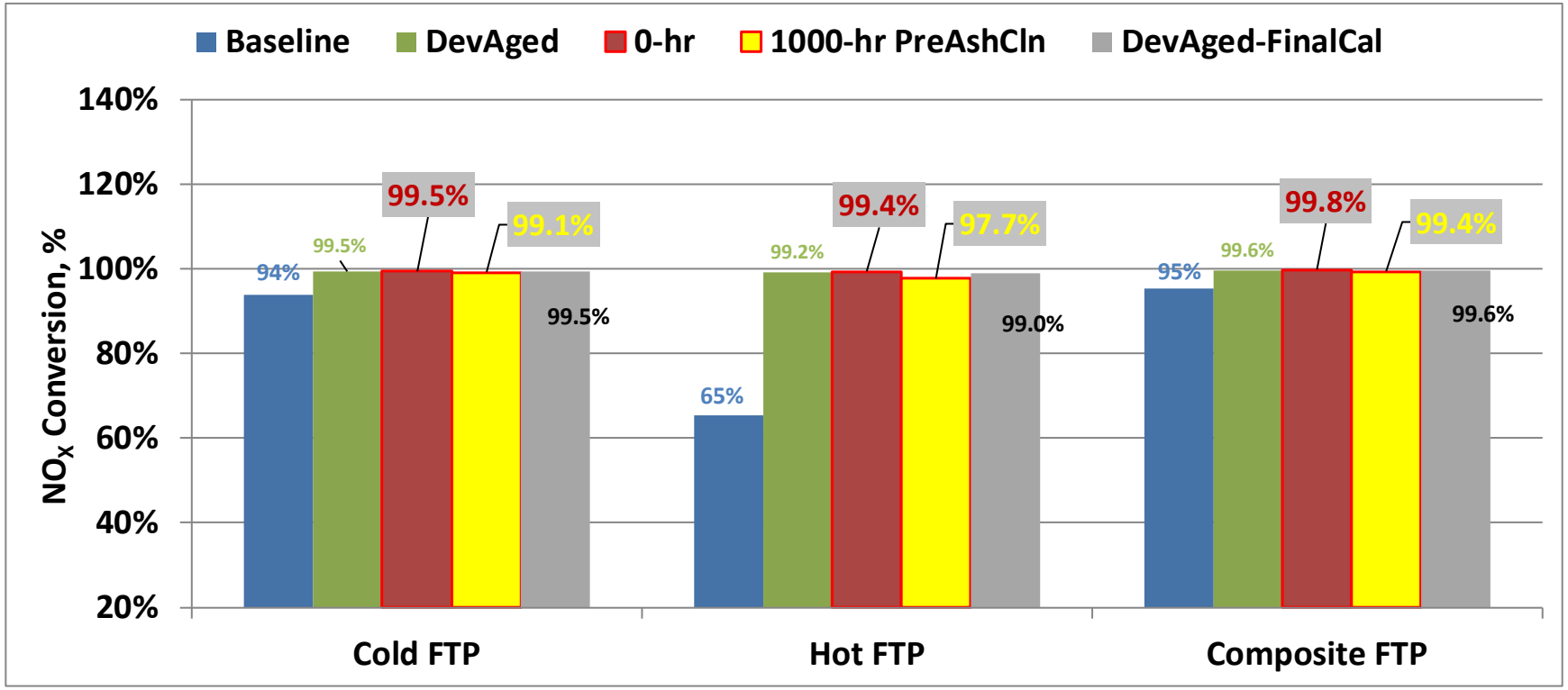
- Final Aged parts
  - Thermal, Chemical, Physical aging – representative of real world
    - Regeneration exotherms, Oil Poisons, Sulfur, Ash…
  - Accelerated aging method developed by SwRI (10X over field)
  - ***Used for final demonstration***

Emission Performance Test Summary



- Tailpipe NO_X Reduced ~ 85% on FTP/RMC, <u>20X less NO_X on LLC (urban, low load)</u>
- Low NO_X Engine is GHG / CO_2 Neutral compared to Baseline Engine
  - ~1 % increase in CO_2 on LLC where base engine has poor NO_X control (low load / fuel consumption)
- Idle Emissions: 0.1 to 0.3 g/hr (CARB Idle Test)

Aftertreatment NO_X Efficiency



- Shift in conversion from 0-hr to 1000-hr:

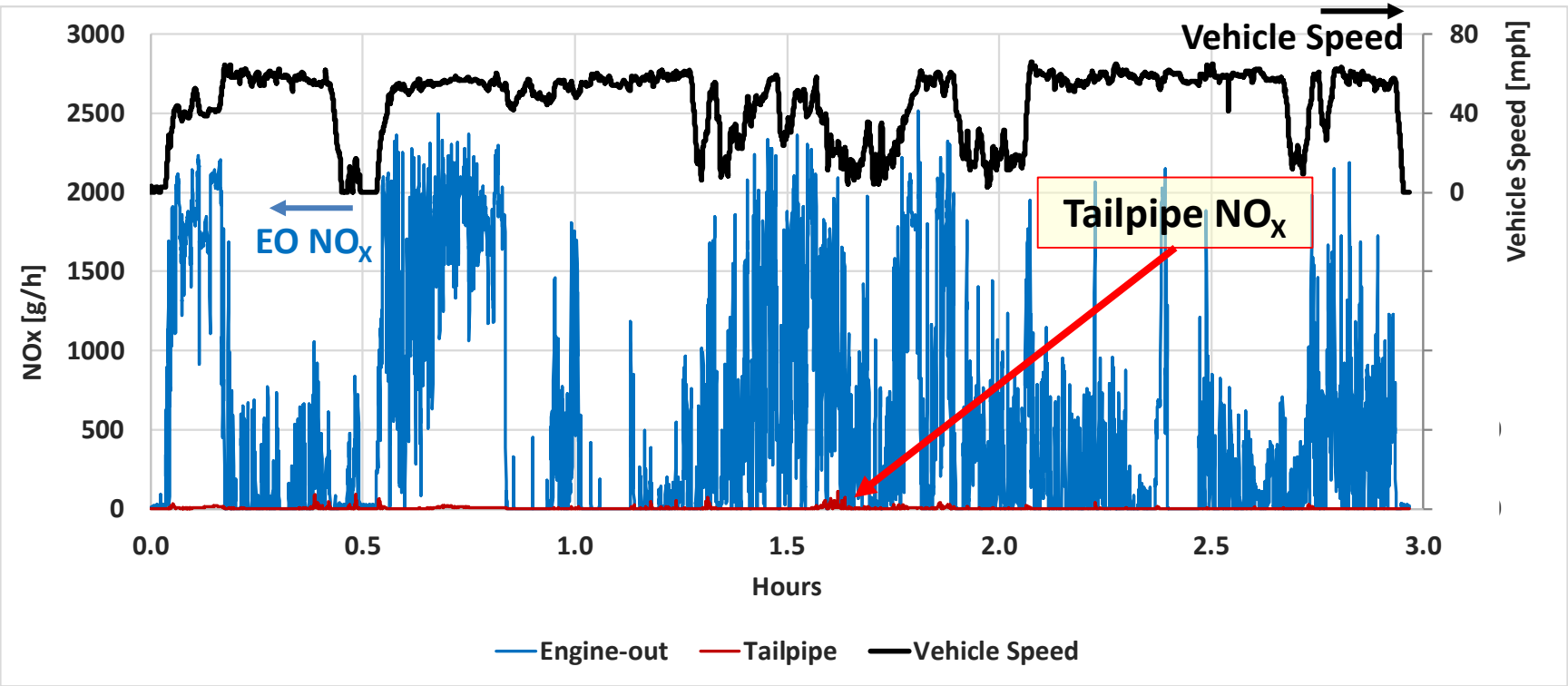
  FTP /RMC ~ 0.35%, LLC ~ 1.6 %
- Margin available to target (for degradation) at 0-hr

  FTP / RMC ~ 0.2%, LLC ~ 1%
- Further NO_X improvement possible if system can be made more robust to degradation

Further Improvement on Long Term NO_X Performance - Opportunities

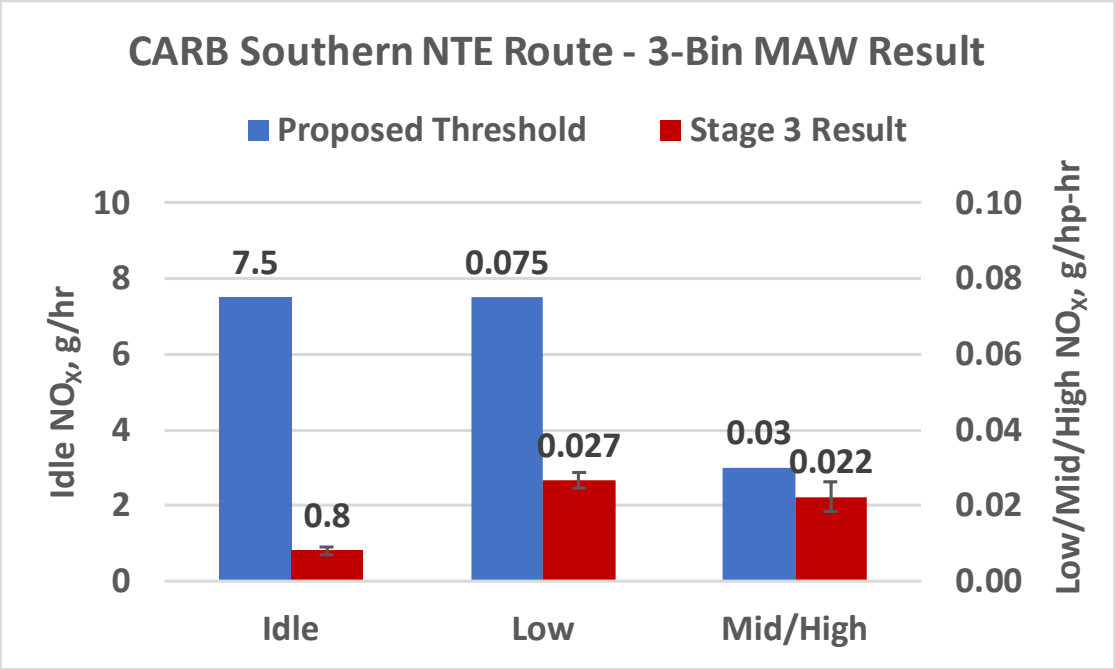
- Move to traditional DOC + DPF architecture
  - More robust and likely slightly better CO_2
- Further improvement in downstream mixing
- Small Increase in downstream catalyst volume for high load points
- Catalyst Formulation
  - More low temperature poisoning resistance
  - Better long-term high temperature selectivity of NH_3 oxidation
- Further Controls Improvement - Catalyst Aging Model
- Target = Reduce Aging Impact by Half

Field Cycle Result – Low NO_X Engine Emission Performance



- **Representative in-use route – 99.4% NO_X reduction**
  - **Engine-out = 4 g/hp-hr, Tailpipe = 0.023 g/hp-hr**
- Route provided by EMA based on actual in-use testing by WVU
- Translated to engine-cycle for lab usage
- CARB Southern NTE Route – traditionally a difficult route for current 2010+ trucks

Field Cycle Result Summary
Low NO_X Engine 3-Bin MAW In-Use Analysis



- Using New In-Use 3-bin methodology proposed in CARB ISOR for 2024+
- Stage 3 Low NO_X engine below proposed thresholds on this field route

Bin	*Proposed Thresholds*	Run 1		Run 2		Run 3	
		g/hp-hr	g/hr	g/hp-hr	g/hr	g/hp-hr	g/hr
Idle (< 6%)	*7.5*	0.049	**0.8**	0.054	**0.9**	0.042	**0.7**
Low (6%-20%)	*0.075*	**0.025**	1.6	**0.029**	1.8	**0.026**	1.6
Mid-High (> 20%)	*0.03*	**0.026**	5.1	**0.023**	5.0	**0.018**	3.9
Total Cycle		0.024		0.023		0.021	

Results with Development Aged Parts

Stage 3 Program Acknowledgements

- California Air Resources Board (CARB)
- U.S. Environmental Protection Agency (EPA)
- South Coast Air Quality Management District (SCAQMD)
- Manufacturers of Emission Controls Association (MECA)
  - and MECA member companies who supplied aftertreatment hardware
- Cummins Inc.
- Eaton Corporation

- members of the stakeholder Program Advisory Group

- contributions to this effort from the Truck and Engine Manufacturer's Association (EMA) and the SwRI CHEDE-VII industry consortium

Questions ?

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