CARB Low NO\textsubscript{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

More than 40 years of Emissions R&D and Technology Demonstration
CARB Low NO\textsubscript{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\textsubscript{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 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

Upstream SCR

Downstream System

Eaton Cylinder Deactivation (CDA) Hardware
Stage 3 Engine and Aftertreatment Controls

**Engine Controls**

- Modified Engine Calibration and Hardware
- Increased Temperature and Reduced NO\textsubscript{X} when Aftertreatment is Cold
- Minimal Impact in CO\textsubscript{2} over Cycles

**Aftertreatment Controls**

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

![Graph showing temperature differences](image-url)
Aftertreatment Aging Methods

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

- Development Aged parts
  - Thermal aging only
  - 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
- Tailpipe NO\textsubscript{X} Reduced \~ 85% on FTP/RMC, 20X less NO\textsubscript{X} on LLC (urban, low load)
- Low NO\textsubscript{X} Engine is GHG / CO\textsubscript{2} Neutral compared to Baseline Engine
  - \~1 % increase in CO\textsubscript{2} on LLC where base engine has poor NO\textsubscript{X} control (low load / fuel consumption)
- Idle Emissions: 0.1 to 0.3 g/hr (CARB Idle Test)
Aftertreatment NO\textsubscript{X} Efficiency

- Shift in conversion from 0-hr to 1000-hr:
  - FTP /RMC \sim 0.35\%, LLC \sim 1.6 \%
- Margin available to target (for degradation) at 0-hr
  - FTP / RMC \sim 0.2\%, LLC \sim 1\%
- Further NO\textsubscript{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\textsubscript{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\textsubscript{X} engine below proposed thresholds on this field route

<table>
<thead>
<tr>
<th>Bin</th>
<th>Proposed Thresholds</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/hp-hr</td>
<td>g/hr</td>
<td>g/hp-hr</td>
<td>g/hr</td>
</tr>
<tr>
<td>Idle (&lt; 6%)</td>
<td>7.5</td>
<td>0.8</td>
<td>0.049</td>
<td>0.054</td>
</tr>
<tr>
<td>Low (6%-20%)</td>
<td>0.075</td>
<td>0.025</td>
<td>0.049</td>
<td>0.054</td>
</tr>
<tr>
<td>Mid-High (&gt; 20%)</td>
<td>0.03</td>
<td>0.026</td>
<td>0.049</td>
<td>0.054</td>
</tr>
<tr>
<td>Total Cycle</td>
<td>0.024</td>
<td>0.023</td>
<td>0.049</td>
<td>0.054</td>
</tr>
</tbody>
</table>

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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