ARB Rulemaking and Research Efforts to Reduce Oxides of Nitrogen (NOx) Emissions from Heavy-Duty Vehicles

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California Needs Significant Reduction in NO\textsubscript{X}

- California needs significant reduction in NO\textsubscript{X} emissions from today’s level to meet the NAAQS for PM\textsubscript{2.5} and ozone by 2031
  - South Coast Air Basin needs 80% NO\textsubscript{X} reduction
  - San Joaquin Valley needs 50% NO\textsubscript{X} reduction

- Meeting the NAAQS provides significant health benefits
  - Fewer premature deaths, hospital admissions, and emergency room visits
Today’s Presentation Has Two Parts

- Part 1: Integrated efforts of Rulemaking and Research
  Efforts to reduce NO\textsubscript{X} emissions from heavy-duty vehicles

- Part 2: Final test results on a research project of
  “Evaluating technologies to lower NO\textsubscript{X} emissions from two heavy-duty engines”
Need for Low NO\textsubscript{X} from HD Engines

- Pre-2010 Fleet Turnover is necessary but insufficient
- Current 2010 HD engine NO\textsubscript{X} standards do not reach ozone NAAQS attainment
- Coordinated Federal action is needed on HD engines
- Projections based on 0.02g/bhphr performance in-use

Parallel Integrated Paths Forward

- Comprehensively improving NO$_X$ performance: More than ‘Just lowering the FTP’ standard
  - Better hardware and control strategies
  - In-use NO$_X$ performance across dutycycles
  - Durability and continued NO$_X$ control through useful life
  - Identification and remediation of high emitters
Low NOx Needed ‘In-Use’

- Need more than just ‘a lower FTP standard’
- ‘NO\(_x\) vs load factor’ is diverging at Low Load for currently marketed engines
- NO\(_x\) Inventory Fraction from Low Load (Green) projected to increase
Current Trucks Operating at Low Exhaust Temperatures

- ARB sponsoring in-use studies of vehicle activity
- Duty Cycle / Calibration interplay yielding significant time at low exhaust temperature
- Implications for SCR performance & NO\textsubscript{x} inventory

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Yoon et al. (2017, TRB presentation #P17-20763)
Under Emphasis of Low Load in Certification Cycles

- FTP and RMC-SET certification cycles represent the engine working under load

- Low Load: control needed when ‘not working hard’

- Need adequate characterization of low load operation on the timescale of system’s thermal behavior
Narrow Applicability of Existing In-use Compliance Program

- NTE Program useful for its intended examination of high sustained load operation

- NTE Program-allowed exclusions eliminate vast majority of typical vehicle operations
  - SCR-challenging operational temperatures specifically excluded
  - Intake Manifold Temperature allowances for EGR engines exempt large portions of reasonable operation

- New tools available: SCR, ULSD, advanced engine controls
Regulatory Durability & Useful Life Short Compared to HD Truck Usage

- Heavy Duty vehicles have long service lives
- Regulatory Useful-Life and Warranty periods account for a small fraction of HD vehicle live of operation

![Graph showing miles in thousands for different classes of HDV.]
Need to Identify and Remedy High Emitters

- Indications of in-use high emitters in fleet
  - Remote/plume sensing studies
  - Roadside pullover inspections
  - In-Use Surveillance dyno/PEMS testing program
  - High reported warranty claim rates

- HD does not have a multi-pollutant Inspection and Maintenance program (LD ‘Smog Check’ analog)
## Regulatory Development Plan

<table>
<thead>
<tr>
<th>Hearing</th>
<th>Action</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actions Taken</td>
<td>Optional Low NO\textsubscript{X} Standards:</td>
<td>Currently Certifying Engines</td>
</tr>
<tr>
<td></td>
<td>(50%, 75% &amp; 90% lower)</td>
<td></td>
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<tr>
<td></td>
<td>Innovative Technology Regulation</td>
<td>Undergoing final administrative steps</td>
</tr>
<tr>
<td>2017</td>
<td>Updates to Smoke Opacity Programs</td>
<td>2018</td>
</tr>
<tr>
<td></td>
<td>Warranty Updates</td>
<td>2018 and onwards</td>
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<tr>
<td></td>
<td>CA Heavy Duty Phase 2 GHG alignment</td>
<td>Paralleling federal program</td>
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<tr>
<td>2019</td>
<td>Low NO\textsubscript{x} Engine Performance Requirements</td>
<td></td>
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<tr>
<td></td>
<td>Low Load Certification Requirements</td>
<td>2023 and onwards</td>
</tr>
<tr>
<td></td>
<td>In-Use Compliance Program (currently NTE)</td>
<td></td>
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<tr>
<td></td>
<td>Warranty/Durability/ Useful Life Period Definitions</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>HD Inspection/Maintenance Program</td>
<td>Post 2020</td>
</tr>
</tbody>
</table>
Current Research Investments

Vehicle Activity by Vocation
Semi Tractor Trailers, Vocational Trucks, HD Hybrids

In-Use Emissions
Plume Capture, Roadside Pullovers, PEMS & Lab Surveillance Testing

Strategy Evaluations
Near Zero pathways for HD, Low Load metrics & requirements, I/M methods & structure GHG credits/VSLs

High Emitter Remedies
Repair Durability, HD I/M Pilot

Technology Demonstrations
ZEV/near-ZEV Pilots & Incentive Funding, Low NOx Engines
Low NOₓ Demonstration Research Project

Objectives and Engines Selected

- Explore and demonstrate the feasibility of significant NOₓ reduction through heavy-duty engine and aftertreatment (AT) control strategies
- Target the emission rate of 0.02 g/bhp-hr NOx over the FTP cycle
- Continue to meet all applicable emissions standards including HC, CO, PM, and GHG

CNG – 2012 Cummins ISX12G
With cooled EGR and TWC

<table>
<thead>
<tr>
<th></th>
<th>Tailpipe NOx, g/hp-hr</th>
<th>FTP</th>
<th>RMC</th>
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<tbody>
<tr>
<td>Average</td>
<td>0.115</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>0.003</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>COV</td>
<td>2.7%</td>
<td>21.3%</td>
<td></td>
</tr>
<tr>
<td>SD % Std</td>
<td>1.5%</td>
<td>1.3%</td>
<td></td>
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</tbody>
</table>

Diesel - 2014 Volvo MD13
with cooled EGR, DPF, SCR, and Turbo-compound

<table>
<thead>
<tr>
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<th>Tailpipe NOx, g/hp-hr</th>
<th>FTP</th>
<th>RMC</th>
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<tbody>
<tr>
<td>Average</td>
<td>0.14</td>
<td>0.084</td>
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<tr>
<td>SD</td>
<td>0.012</td>
<td>0.0093</td>
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<tr>
<td>COV</td>
<td>8.5%</td>
<td>11%</td>
<td></td>
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<tr>
<td>SD % Std</td>
<td>5.9%</td>
<td>4.6%</td>
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Final Performance of CNG Engines with Final Aged Aftertreatment Systems

CNG – 2012 Cummins ISX12G
With cooled EGR and TWC

With Advanced Air/Fuel Ratio Control Strategies

ccTWC  ufTWC
Close-Coupled  Under-body

0.011 g/bhp-hr NOX

SwRI
Diesel Technology Screening Test Results

Multiple potential pathways to achieve $\text{NO}_x$ emissions below 0.02 g/bhp-hr
Technology Rankings for Preliminary Tests
(Incorporated Stakeholder Feedback)

- Based on Feb 2016 workshop and PAG member feedback
- Engine cell based evaluation in order until reaching a viable solution to 0.02 g/hp-hr at minimum fuel penalty / durability / cost / complexity

<table>
<thead>
<tr>
<th>System</th>
<th>Composite NOx Potential</th>
<th>Potential Composite FTP Penalty, %</th>
<th>Durability</th>
<th>Complexity</th>
<th>Cost</th>
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</thead>
<tbody>
<tr>
<td>PNA + HD1 + SCRF + SCR/ASC</td>
<td>0.02</td>
<td>0.9</td>
<td>8/13.3</td>
<td>10/10</td>
<td>4/9.8</td>
</tr>
<tr>
<td>NH3 + LO SCR + PNA + HDI + SCRF + SCR/ASC (HD1)</td>
<td>0.016</td>
<td>0.95</td>
<td>12/20.7</td>
<td>11/12.5</td>
<td>4/6.2</td>
</tr>
<tr>
<td>EHC/DOC + DEF + SCRF + SCR + SCR/ASC - (underevaluation)</td>
<td>0.01</td>
<td>1.05</td>
<td>7/9.4</td>
<td>7/9</td>
<td>4/6.2</td>
</tr>
<tr>
<td>MB + DOC + DEF + SCR + SCR + SCR/ASC</td>
<td>0.019</td>
<td>1.04</td>
<td>13/15.2</td>
<td>10/13.1</td>
<td>9/12.5</td>
</tr>
<tr>
<td>MB + DOC + DEF + SCR + SCR + SCR/ASC</td>
<td>0.018</td>
<td>1.04</td>
<td>9/10.7</td>
<td>8/10</td>
<td>8/7.7</td>
</tr>
<tr>
<td>DOC + MB + SCRF + SCR + SCR/ASC - (not evaluated)</td>
<td>1.04</td>
<td>1.04</td>
<td>9/10.7</td>
<td>8/10</td>
<td>7/7.7</td>
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</tbody>
</table>
Preliminary Test Results (FTP Composite NO$_x$) with Oven-Aged Aftertreatment Components

1. • 0.025 to 0.030 g/bhp-hr with 2kw HD1
   • 0.022 to 0.025 g/bhp-h with 6kw HD1

2. • 0.022 to 0.025 g/bhp-h with 1kw HD2 and 3” zeolite LO-SCR

3. • Not evaluated due to insufficient heat potential for 0.02 or below

4. • 0.022 to 0.025 with 3” zeolite LO-SCR and 3.5kW HD1
   • 0.012 g/hp-hr with 10kw mini-burner

Selected for the final demonstration
Aftertreatment Aging

- Used an 2009 Cummins ISX diesel engine
- 4 hour cycle (DAAAC modified)
- Ran for 847 hours, equivalent to
  - 100% FUL thermal aging
  - 23% FUL chemical aging
- Unexpected PNA canning failure at 710 hours
  - Resulted in large buildup of coke/soot on PNA front, matting material in front of SCRF (and some in channels)
Final Performance of Low NO$_x$ Engines with Final Aged Aftertreatment Systems

### Diesel (2014)

<table>
<thead>
<tr>
<th>Catalyst Aging</th>
<th>Composite FTP NO$_x$ (g/bhp-hr)</th>
<th>RMC NO$_x$ (g/bhp-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degreened</td>
<td>0.008</td>
<td>0.010</td>
</tr>
<tr>
<td>Development Thermal Aging Only</td>
<td>0.012</td>
<td>0.015</td>
</tr>
<tr>
<td>100% FUL Thermal Aging &amp; 23% FUL Chemical Aging</td>
<td>0.034</td>
<td>0.038</td>
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</table>

### BSCO$_2$, g/hp-hr

<table>
<thead>
<tr>
<th></th>
<th>Cold</th>
<th>Hot</th>
<th>Composite</th>
<th>RMC</th>
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<tbody>
<tr>
<td>Baseline Engine</td>
<td>574.2</td>
<td>542.6</td>
<td>547.4</td>
<td>457.7</td>
</tr>
<tr>
<td>Final ULN Config</td>
<td>604.4</td>
<td>548.8</td>
<td>558.2</td>
<td>463.6</td>
</tr>
<tr>
<td>% change</td>
<td>5.3%</td>
<td>1.1%</td>
<td>2.0%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Mini-burner air</td>
<td>0.4%</td>
<td>0.2%</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>Increased SCRF Regeneration</td>
<td>0.3%</td>
<td>0.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total FTP CO$_2$ Impact</td>
<td>2.5%</td>
<td>1.6%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diesel - 2014 Volvo MD13 with cooled EGR, DPF, SCR, and Turbo-compound with Advanced Cold-Start Strategies
Final Performance of Low NOₓ Engines with Final Aged Aftertreatment Systems

- Presented multiple technology pathways to lower NOₓ emissions significantly from CNG and diesel engines
  - Suggest demonstrate the technology pathways with different engine platforms such as a diesel engine without turbo-compound
- Demonstrated large reduction of NOₓ emissions from the engines with the advanced engine and aftertreatment control strategies
  - Continue optimization of emission improvements over vocational cycles
  - Need further investigation of the performance of the final configurations over low-load operating conditions (A contract is in place with SwRI)
- Found unexpected incidents during diesel catalyst aging, which possibly led to the higher NOₓ emissions than expected from the final diesel configuration
  - Need further investigation of catalyst aging over the full useful-life
Conclusions

- Meeting the challenge of further NO\textsubscript{X} control from heavy duty vehicles is necessary to meet California’s health-based NAAQS obligations

- CARB is moving forward with parallel efforts to lower new engine emissions and see that those emissions remain low in-use, during warranty, and through useful life

- Technology demonstration efforts are showing large NO\textsubscript{X} reductions are possible with technology available today
  - Certified 0.02g/bhp-hr CNG engine is on the market
  - Diesel work shows good potential for similar NO\textsubscript{X} performance
  - A follow-up research work is in place
For More Information

- Low NO\textsubscript{X} project portal: https://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm
- Heavy-duty vehicle rulemaking portal: https://www.arb.ca.gov/msprog/hdlownox/hdlownox.htm
- SAE papers from the low NO\textsubscript{X} demonstration project:
  - Sharp, C., Webb, C., Neely, G., Carter, M. et al., "Achieving Ultra Low NO\textsubscript{X} Emissions Levels with a 2017 Heavy-Duty On-
    doi:10.4271/2017-01-0954.
    Highway TC Diesel Engine – Comparison of Advanced Technology Approaches. SAE World Congress Experience. April 4-6, 2017, Detroit, Michigan. Manuscript was accepted for an SAE paper publication.
    Highway TC Diesel Engine and an Advanced Technology Emissions System – NO\textsubscript{X} Management. SAE World Congress Experience. April 4-6, 2017, Detroit, Michigan. Manuscript was accepted for an SAE paper publication.
  - Smith, I.; Webb, C.; Sharp, C.; Yoon, S.; Carter, M. (2017) (2017). Achieving 0.02 g/bhp-hr NO\textsubscript{X} Emissions from a Heavy-
    Duty Stoichiometric Natural Gas Engine Equipped with Three-way Catalyst. SAE World Congress Experience. April 4-6, 2017, Detroit, Michigan. Manuscript was accepted for an SAE paper publication.