Heavy-Duty Certification Standards and Test Procedures Workgroup Meeting

Mobile Source Control Division California Air Resources Board
March 6, 2017
Outline

- Rulemaking Timeline
- Purpose of the Workgroup
- CARB Optional NOx Standards
- CARB HD Low NOx Research Activities
- Low Load Test Cycle
- Outside the Box Ideas
- Open Discussion/Questions
## Heavy-Duty Truck Rulemakings

### Scheduled Board Dates

<table>
<thead>
<tr>
<th>Rulemaking</th>
<th>Scheduled Board Hearing Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revisions to Periodic Smoke Inspection Program</td>
<td>September 2017</td>
</tr>
<tr>
<td>California Phase 2 GHG Standards</td>
<td>October 2017</td>
</tr>
<tr>
<td>Revisions to the Warranty Period and Recall Authority Requirements</td>
<td>December 2017</td>
</tr>
<tr>
<td>Revisions to the</td>
<td>2019</td>
</tr>
<tr>
<td>- NOx Standard and Test Procedures,</td>
<td></td>
</tr>
<tr>
<td>- In-Use Compliance Program, and</td>
<td></td>
</tr>
<tr>
<td>- Durability/Useful Life Requirements</td>
<td></td>
</tr>
<tr>
<td>Heavy-duty Inspection and Maintenance</td>
<td>2020</td>
</tr>
</tbody>
</table>
Purpose of Heavy-Duty Cert.
Standards and Test Procedures

Workgroup

- Provide stakeholders the opportunity to provide suggestions and comments
- Exchange data and ideas between CARB staff and stakeholders to make informed decisions
- Considerations
  - Potential supplemental test cycle
  - Low NOx technology
  - Emission measurement issues
  - Durability demonstration and useful life requirements
  - OBD implications
  - Other outside the box ideas
CARB Optional NOx Standards

• Adopted in 2013

• Optional NOx standards – three levels
  – 90%, 75%, and 50% below 2010 NOx standards
  – 0.02 g/bhp-hr, 0.05 g/bhp-hr, and 0.10 g/bhp-hr

• CARB Certified Engines:
  – 8.9L ISL G – CNG certified to 0.02 g/bhp-hr (90% below)
  – 6.7L ISB6.7 G – CNG certified to 0.1 g/bhp-hr (50% below)

• 8.9L ISL G Testing by UCR, CE-CERT
  – Meets the optional 0.02 g/bhp-hr NOx standard for both certification and non-certification cycles (Refuse, Neardock, Local, Regional, Bus)
    • (http://www.cert.ucr.edu/news/2017/2017-02-01.html)
  – Incentives being provided for deployment
CARB HD Low NOx Research Activities

– Stage 1 – Low NOx feasibility demonstration
  • CARB Funding: $1.6M
  • Contractor: SwRI
  • Additional support: MECA, Volvo, SwRI

– Stage 2 – Low load cycle (LLC) development/ LLC optimization
  • CARB funding: 1.05M
  • Contractor: SwRI

– Stage 3 – Low NOx Demonstration on an Alternative Non-Turbocompound (TC) Engine
  • Funding: CARB, AQMD, and others (total of $1.3M)
  • Contractor: SwRI
  • Additional support: MECA
Stage 1: Low NOx Program

- Started October 2013/ completed December 2016

- Optimization on FTP, RMC, WHTC, and CARB Idle
  - Target NOx on aged parts: 0.02 g/bhp-hr on the FTP and RMC

- Additional testing on 3 vocational cycles: NYBC, Cruise Creep, and OCTA bus cycle

- Two Engines:
  - CNG:  2012 Cummins ISX12 G (Stoichiometric), and
  - Diesel:  2014 Volvo MD13TC (Euro VI, with TC)

More information: https://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm
Stage 1: Natural Gas Engine

Engine and Aftertreatment (AT) Options

• Engine: 2012 Cummins ISX12 G, 11.9L, 320hp

• Engine upgraded to improve AFR control
  – Aftermarket prototype ECU from EControls
  – Proprietary injection and mixing hardware
  – Closed crankcase ventilation system

• AT Options: 4 packages of three way catalyst (TWC)

• Final downselected:
  – Close coupled TWC (9L) and underfloor TWC (20L)
  – Thermally aged to full useful life (FUL) – acceleration based on EPA Standard Bench Cycle for TWC
Stage 1: Natural Gas Engine
Final Aged Results – FTP, RMC, WHTC

<table>
<thead>
<tr>
<th>Engine</th>
<th>Pollutant</th>
<th>Unit</th>
<th>FTP</th>
<th>RMC-SET</th>
<th>WHTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>NOx</td>
<td>g/bhp-hr</td>
<td>0.115</td>
<td>0.012</td>
<td>0.308</td>
</tr>
<tr>
<td></td>
<td>CH₄</td>
<td>ppm</td>
<td>0.96</td>
<td>1.20</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>ppm</td>
<td>542</td>
<td>454</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>NH₃</td>
<td>ppm</td>
<td>76</td>
<td>162</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engine</th>
<th>Pollutant</th>
<th>Unit</th>
<th>FTP</th>
<th>RMC-SET</th>
<th>WHTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low NOₓ</td>
<td>NOx</td>
<td>g/bhp-hr</td>
<td>0.01  (91%)*</td>
<td>0.001 (92%)</td>
<td>0.011 (96%)</td>
</tr>
<tr>
<td></td>
<td>CH₄</td>
<td>ppm</td>
<td>0.15  (84%)</td>
<td>0.93 (23%)</td>
<td>0.10 (94%)</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>ppm</td>
<td>547   (-0.9%)</td>
<td>445 (2.0%)</td>
<td>513 (-0.6%)</td>
</tr>
<tr>
<td></td>
<td>NH₃</td>
<td>ppm</td>
<td>52    (32%)</td>
<td>37 (77%)</td>
<td>44 (56%)</td>
</tr>
</tbody>
</table>

Note: *(%) Percent reduction from baseline
CARB Idle NOx is essentially zero.
# Stage 1: Natural Gas Engine

## Final Aged Results – Vocational Cycles

<table>
<thead>
<tr>
<th>Engine</th>
<th>Pollutant</th>
<th>Unit</th>
<th>NYBC</th>
<th>Cruise Creep</th>
<th>OCTA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>NO(_x)</td>
<td>g/hp-hr</td>
<td>0.9</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>CH(_4)</td>
<td>g/hp-hr</td>
<td>1.9</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>CO(_2)</td>
<td>ppm</td>
<td>672</td>
<td>612</td>
<td>553</td>
</tr>
<tr>
<td></td>
<td>NH(_3)</td>
<td>ppm</td>
<td>12</td>
<td>124</td>
<td>92</td>
</tr>
<tr>
<td><strong>Low NO(_x)</strong></td>
<td>NO(_x)</td>
<td>g/hp-hr</td>
<td>0.002</td>
<td>0.002</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>CH(_4)</td>
<td>g/hp-hr</td>
<td>0.5</td>
<td>1.0</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>CO(_2)</td>
<td>ppm</td>
<td>661</td>
<td>897</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>NH(_3)</td>
<td>ppm</td>
<td>25</td>
<td>85</td>
<td>47</td>
</tr>
</tbody>
</table>
Stage 1: Diesel – AT System

AT Options

- Engine: 2014 Volvo MD13TC (Euro VI, with TC)

Traditional Approach

- Burner
- EHC
- Fuel Dosing
- DEF
- NH₃ injection
- Heated Dosing

Advanced Approach

- Burner
- EHC
- Fuel Dosing
- DOC
- PNA
- DEF
- Compact Mixing
- NH₃ injection
- Heated Dosing
- SCR
- ASC
- Blank
Screened approximately 33 technology packages
Ranked them based on fuel penalty, cost, durability, and complexity
Top four ranking packages tested on engine dynamometer with development aged parts

Demonstrated well below 0.02 g/bhp-hr NOx
  - PNA+MB+DEF+SCRF+SCR+ASC
  - 0.012 g/bhp-hr NOx

Impact on GHG from baseline including engine calibration
  - 2% on FTP – (0.5% engine cal, 0.5% SCRF regen, 1% mini-burner)
  - < 0.5% on RMC-SET – due to increased frequency of SCRF regen only
Stage 1: Diesel – AT System

Aging

• Final parts aged on engine thermally and chemically

• Issues during aging
  – PNA canning failure (detected @ 710 hours)
  – Mat material in front of SCRF (and some in channels)
  – Large buildup of coke/soot on PNA front

• PNA and SCRF were cleaned and recovered in a manner that did not further disturb aging
### Stage 1: Diesel – AT System

Final Aged Parts – FTP and RMC

<table>
<thead>
<tr>
<th></th>
<th>NOx (g/bhp-hr)</th>
<th>FTP</th>
<th>RMC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cold</td>
<td>Hot</td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
<td>Tail Pipe</td>
<td>0.71</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>NOx Conv. (%)</td>
<td>75.0</td>
<td>98.4</td>
</tr>
<tr>
<td><strong>Development Aged Parts</strong></td>
<td>Tail Pipe</td>
<td>0.027</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>NOx Conv. (%)</td>
<td>97.8</td>
<td>99.7</td>
</tr>
<tr>
<td><strong>Final “Engine” Aged</strong></td>
<td>Tail Pipe</td>
<td>0.114</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>NOx Conv. (%)</td>
<td>95.8</td>
<td>99.3</td>
</tr>
</tbody>
</table>

- WHTC results were similar to the FTP results
Stage 1: Diesel – AT System

GHG Impacts

<table>
<thead>
<tr>
<th></th>
<th>BSCO2, g/hp-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cold</td>
</tr>
<tr>
<td>Baseline Engine</td>
<td>574.2</td>
</tr>
<tr>
<td>Final ULN Config</td>
<td>604.4</td>
</tr>
<tr>
<td>% change</td>
<td>5.3%</td>
</tr>
</tbody>
</table>

- Mini-burner air: 0.4% | 0.2% | 0.2% |
- Increased SCR Regeneration: 0.3% | 0.3% |

Total FTP CO2 Impact: 2.5% | 1.6%

- Tailpipe NH3 < 2 ppm cycle average
- Tailpipe N2O = 0.10 g/hp-hr
Stage 1: Diesel – AT System
Final Aged Parts – CARB Idle and Cruise Creep

### Carb Idle

<table>
<thead>
<tr>
<th></th>
<th>Low Idle (550 rpm)</th>
<th>PTO Idle (1100 rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EO NOx (g/hr)</td>
<td>TP NOx (g/hr)</td>
</tr>
<tr>
<td>Baseline</td>
<td>46.1</td>
<td>11.7</td>
</tr>
<tr>
<td>with relight</td>
<td>10.6</td>
<td>0.2</td>
</tr>
<tr>
<td>without relight</td>
<td>7.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### Cruise Creep x 10

<table>
<thead>
<tr>
<th></th>
<th>EO NOx (g/hr)</th>
<th>TP NOx (g/hr)</th>
<th>% Conv.</th>
<th>Fuel Rate kg/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>71.8</td>
<td>13.3</td>
<td>81.0</td>
<td>2.75</td>
</tr>
<tr>
<td>with relight</td>
<td>41.3</td>
<td>7.45</td>
<td>82.0</td>
<td>2.76</td>
</tr>
<tr>
<td>without relight</td>
<td>41.1</td>
<td>12.8</td>
<td>69.0</td>
<td>2.63</td>
</tr>
</tbody>
</table>

- Tests run both with and without burner re-light to show impact of thermal management on NOx and fuel consumption
## Stage 1: Diesel – AT System

### Final Aged Parts - NYBC and OCTA

<table>
<thead>
<tr>
<th></th>
<th>EO NOx (g/bhp-hr)</th>
<th>TP NOx (g/bhp-hr)</th>
<th>% Conv.</th>
<th>Fuel Rate kg/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NYBCx4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>6.10</td>
<td>2.30</td>
<td>62.0</td>
<td>5.29</td>
</tr>
<tr>
<td>with relight</td>
<td>3.90</td>
<td>0.38</td>
<td>90.0</td>
<td>5.30</td>
</tr>
<tr>
<td>without relight</td>
<td>3.60</td>
<td>0.78</td>
<td>78.0</td>
<td>5.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>TP NOx (g/bhp-hr)</th>
<th>% Conv.</th>
<th>CO2 (g/bhp-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OCTA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>3.8</td>
<td>99.4</td>
<td>529</td>
</tr>
<tr>
<td>with relight</td>
<td>2.7</td>
<td>99.8</td>
<td>534</td>
</tr>
<tr>
<td>without relight</td>
<td>2.7</td>
<td>99.6</td>
<td>543</td>
</tr>
</tbody>
</table>

- Tests run both with and without burner re-light to show impact of thermal management on NOx and fuel consumption
Stage 2: LLC Development/Optimization on Low Load Profiles

- Follow-on project to Stage 1
  - Initiated in January 2017,
  - Completion by June 2018
  - ARB funding: $1 M
  - Contractor: SwRI
    - NREL as subcontractor for LLC development

- Engine/AT system from Stage 1
  - **Stage 1b** contract being considered—aging of new AT parts for use in Stage 2

- Program tasks/objectives:
  - Develop low load duty cycle profiles and LLC
  - Optimize emission control over these low load profiles and the LLC and determine impacts on GHG
  - Evaluate accuracy of broadcast torque at low loads
  - Evaluate other testing metrics for determining in-use emissions at low loads
Stage 2: LLC Development

Tasks

• Define Low load profiles:
  – Average power at 10% or less, with max ~ 15%

• Typical types of low load profiles:
  – Operation where SCR is “cooled off” below operating temperature and then need to warm up to operating temperature
  – Operation where SCR is initially warm but cooled below effective operating temperature
  – Operation that is in thermal equilibrium with a light load profile (i.e., sustained light load control)

• Develop a single cycle (LLC) representing low load operations
Stage 3: Low NOx Demonstration Alternative Engine Platform (Non-TC)

• Follow-on project to Stages 1 and 2
  – Contract currently under processing
  – Kick off in summer of 2017
  – Co-funded by ARB, AQMD, and others: $1.325M Total
  – MECA support: AT system and final aging
  – Engine platform without TC (likely 2017 model year)
  – AT system can be different than that demonstrated in Stages 1 and 2

• Optimization on
  – FTP, RMC, and CARB Idle
    • Target NOx emission rate: 0.02 g/bhp-hr on FTP and RMC
  – Low load profiles from Stage 2 development
Low Load Test Cycle Development

- **Activity Data**
  - NREL Fleet DNA Database
    - 500 vehicles
    - 20 vocations
  - CARB program with UCR
    - 90 – 2010 and newer model heavy-duty vehicles
    - 19 vocational/regional groups
    - Includes ECU broadcast data

- Industry data?
- Industry thoughts on approach, need for low load cycle?
Other Outside the Box Ideas

• Geofencing
  – One low NOx national standard, and
  – Secondary calibration that is switched on when vehicle operates under extended low load operations within a geofenced area
  – Pros: minimizes overall penalty in GHG emissions
  – Cons: In-use enforcement issues – determining compliance, tampering, etc.

• Crediting vehicle technologies that provide NOx reductions? (e.g., stop-start, improved transmissions, hybrids, etc.)
  – Power train testing
  – Modeling (GEM)

• Other Concepts?
Questions? Comments?
Backup slides
Vocational Cycles

New York Bus Cycle (NYBC) x 4 Cycle

Cruise Creep x 10 Cycle

Orange County Transit Authority Bus Cycle (OCTA)
Stage 1: Diesel – AT System

Screening Test Results

Multiple potential pathways to achieve NOx emissions below 0.02 g/bhp-hr
Stage 1: Diesel – AT System

Final Technology Rankings from Screening

<table>
<thead>
<tr>
<th>System</th>
<th>Composite NO\textsubscript{x} Potential</th>
<th>Potential Composite FTP Penalty, %</th>
<th>Durability</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PNA + HD1 + SCR + SCR/ASC</td>
<td>0.02</td>
<td>0.9</td>
<td>8/13.3</td>
<td>10/10</td>
</tr>
<tr>
<td>NH3 + LO SCR + PNA + HDI + SCR + SCR/ASC (HD1)</td>
<td>0.016</td>
<td>0.95</td>
<td>12/20.7</td>
<td>11/56</td>
</tr>
<tr>
<td>EHC/DOC + DEF + SCR + SCR + SCR/ASC - (under evaluation)</td>
<td>///</td>
<td>1.05</td>
<td>7/9.4</td>
<td>7/9</td>
</tr>
<tr>
<td>PNA + MB + DEF + SCR + SCR/ASC</td>
<td>0.01</td>
<td>1.04</td>
<td>13/15.2</td>
<td>10/13.1</td>
</tr>
<tr>
<td>MB + DOC + DEF + SCR + SCR + SCR/ASC</td>
<td>0.019</td>
<td>1.04</td>
<td>9/10.7</td>
<td>8/10</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>
</tr>
<tr>
<td>DOC + MB + SCR + SCR + SCR/ASC - (not evaluated)</td>
<td>///</td>
<td>1.04</td>
<td>9/10.7</td>
<td>8/10</td>
</tr>
<tr>
<td>MB + DOC + DPF + SCR + SCR/ASC</td>
<td>0.025</td>
<td>0.62</td>
<td>6/6.4</td>
<td>5/7</td>
</tr>
<tr>
<td>EHC/DOC + DPF + HD1 + SCR + SCR/ASC (not evaluated)</td>
<td>///</td>
<td>0.98</td>
<td>5/8.6</td>
<td>6/9</td>
</tr>
<tr>
<td>PNA + HD1 + SCR + SCR/ASC</td>
<td>0.029</td>
<td>0.9</td>
<td>8/13.3</td>
<td>5/13</td>
</tr>
<tr>
<td>PNA + NH3 + DEF + SCR + SCR/ASC</td>
<td>0.031</td>
<td>0.72</td>
<td>8/13.4</td>
<td>8/13</td>
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<tr>
<td>NH3 + LO SCR + DOC + DPF + HD1 + SCR + SCR/ASC + SCR/ASC</td>
<td>///</td>
<td>0.65</td>
<td>4/15.2</td>
<td>3/16</td>
</tr>
<tr>
<td>DOC + DPF + EHC + HD1 + SCR + SCR/ASC</td>
<td>0.033</td>
<td>1.2</td>
<td>2/7.2</td>
<td>2/7</td>
</tr>
</tbody>
</table>

- Scoring Based on Program Advisory Group forum