Heavy-duty Engine Standards

November 27, 2018
Outline

• Evolution of Heavy-Duty Engine Standards and Technologies
  • Past and Present
• Need for Emission Reductions
• Heavy-Duty Low NOx Plan
  • Heavy-Duty Low NOx Measures
  • Heavy-Duty Low NOx Demonstration Projects
• Questions
Evolution of Heavy-Duty Engine Standards and Technologies
Evolution of Heavy-Duty Engine Standards

- **NOx**
- **PMx10**

<table>
<thead>
<tr>
<th>Model Year</th>
<th>NOx</th>
<th>PMx10</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1990</td>
<td>6.0</td>
<td>5.0</td>
</tr>
<tr>
<td>1991</td>
<td>4.5</td>
<td>3.5</td>
</tr>
<tr>
<td>1994</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>1998</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2004</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2007</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>2010</td>
<td>0.1</td>
<td>0.01</td>
</tr>
</tbody>
</table>
1990-1994 Engine Optimization

- NOx standard from 6.0 to 5.0 g/bhp-hr in 1991

- PM standard from 0.6 to 0.25 g/bhp-hr in 1991 and
  - 0.1 g/bhp-hr in 1994

- Main Technologies/Strategies
  - Injection timing retard
  - Reduced intake manifold temperature
  - Electronic fuel injection
  - Increased fuel injection pressure
1998 Engine Optimization

• NOx standard from 5.0 to 4.0 g/bhp-hr in 1998

• Main Technologies/Strategies
  • Wide-spread use of electronic controls
  • Improved combustion chamber design
  • Increased fuel injection pressure
2004 Engine Optimization

• NOx standard reduced from 4.0 to about 2.0 g/bhp-hr (2.4 g/bhp-hr NOx+NMHC) in 2004

• Main Technologies
  • Cooled Exhaust Gas Recirculation (Cooled EGR)
  • Variable geometry turbocharger (VGT)
  • Common rail fuel injection
2007+ Aftertreatment Devices

- NOx reduced to 0.2 g/bhp-hr NOx and NMHC to 0.14 g/bhp-hr from combined NOx+NMHC standard of 2.4 g/bhp-hr
  - Phased-in on a percent-of-sales basis:
    - 50% in 2007-2009 and 100% in 2010
    - 2007-2009 engines were certified to a fleet average NOx of about 1.2 g/bhp-hr

- PM reduced from 0.1 to 0.01 g/bhp-hr

- Main Technologies: 2007-2009
  - Increased cooled EGR
  - Diesel Oxidation Catalysts (DOC)
  - Catalyzed Diesel Particulate Filter (DPF), and
  - Ultra Low Sulfur Diesel (ULSD)
    - 15 ppm Sulfur
Current Standard: 2010+ MY HD Engine Standard

- NOx = 0.20 g/bhp-hr and PM = 0.01 g/bhp-hr
- Main technologies
  - DOC
  - DPF
  - Urea-Selective Catalytic Reduction (Urea-SCR)
  - Ammonia Slip Catalyst (ASC)
  - Cooled EGR, VGT, high pressure injection, and other engine management strategies
  - ULSD
Otto-Cycle Engines

• Similar emission standards as diesel engines
  • Include gasoline, natural gas, and other fuels
  • From 1990 to 2008, >90% reduction in NOx standards; >80% reductions in HC
  • Current standards same as diesel engines

• Emission control technologies
  • Three-way catalysts
  • Cooled EGR
  • Engine improvements
    • Air-fuel ratio control, air handling, and combustion improvements
Continued Need for Emission Reductions
Air Quality Challenges

• Over 12 million Californians breathe unhealthy air

• Most areas expected to attain standards by 2026

• Key challenges:
  • South Coast ozone
  • San Joaquin Valley PM2.5
South Coast Emissions Inventory
Key Sources

• NOx benefits by 2031 with current program
  • Mobile source emissions reduced over 50 percent
  • Heavy-duty vehicle emissions reduced by nearly 70 percent

• Heavy-duty trucks and federal sources remain largest contributors

• Heavy-duty trucks emit 33 percent of statewide NOx, 509 tpd

• Need to reduce heavy-duty NOx by 90 percent
Updated 8-hour Air Quality Standard for Ozone – 70 ppb

Current Ozone Nonattainment Areas, 4/30/2018
(2008 Standard, 0.075 ppm)

Updated 8-hour Air Quality Standard for Ozone
(2015 Standard, 70 ppb)

Map shows areas designated nonattainment by EPA as of 4/30/2018

Source: https://ozoneairqualitystandards.epa.gov/OAR_OAQPS/OzoneSliderApp/index.html#
Breakdown of NOx Emissions from Heavy-Duty Vehicles

‘til 2023:
• Pre-2010s dominate NOx
  → Ensuring Truck and Bus compliance

2023+:
• Deterioration-related emissions are largest
  → Need HD I/M and extended warranty
• Running, start and idling emissions also significant
  → Need lower standards, low-load cycle, improved in-use testing

Source: S. Pornazieri, AQPS, CARB
Evidence for Off-Cycle Emissions

NOx Emissions (g/bhp-hr) by Average Speed
Over Test Cycle or PEMS Session
0.2 g/bhp-hr Certified Engines

23 Trucks Tested by ARB, WVU, UCR CE-CERT
14 Driving Cycles
5 PEMS Routes

Potential off-cycle emissions

0.2 g/bhp-hr
Challenges to Meeting Low NOx Emissions

• Cold start conditions
  • Controlling NOx during warm up
  • Accelerating catalyst warm-up

• Controlling NOx at low-load operations

• Maintaining high efficiency NOx control during warm operation
  • High exhaust temperature
  • Space velocity management
  • Durability

• Must be accomplished with minimal fuel economy impact
Heavy-Duty Low-NOx Plan
CARB Optional NOx Standards

• Optional NOx standards: 2015+ MY Engines
  - 90%, 75%, and 50% below 2010 NOx standards
  - 0.02 g/bhp-hr, 0.05 g/bhp-hr, and 0.10 g/bhp-hr

• Engines certified to the optional NOx standards:
  - **0.02 g NOx/bhp-hr** (90% below current standard)
    - Cummins ISX12N - 11.9L CNG
    - Cummins ISL G - 8.9L CNG
    - Greenkraft V8 - 8.0L Gasoline, CNG, and LPG
    - Encore Tec 6.8L CNG
  - **0.05 g NOx/bhp-hr** (75% below current standard)
    - Encore Tec - 6.0L CNG
    - Roush CleanTech V10 - 6.8L LPG
    - Westport - 6.8L CNG
  - **0.10 g NOx/bhp-hr** (50% below current standard)
    - Roush CleanTech V10 - 6.8L CNG
    - Cummins ISB6.7 - 6.7L CNG
Establishing Low-NOx HD Engine Program

• Goals:
  • Develop HD Low-NOx engine standard
  • Develop Low-Load Cycle
  • Improve in-use compliance test
  • Extended warranty and useful life
  • Improved durability demonstration procedures
  • Simultaneous path to Low-NOx and Phase 2 GHG

• Timeframe:
  • CARB Board date: December 2019
  • Implementation schedule: 2023 – 2027

• More info at:
  https://www.arb.ca.gov/msprog/hdlownox/hdlownox.htm
Developing a Supplemental Low Load Certification Cycle

Background

• Current certification cycles (HD-FTP and RMC/SET) do not account for sustained low load operations

• HD-FTP is not of sufficient length to verify active thermal management of SCR systems

Objective

• Develop a new HD engine test cycle that:
  • Represents real-world urban tractor and vocational vehicle operations that are characterized by low engine loads
  • Is of sufficient length such that continuous active thermal management is required
  • Has an emission standard that balances the need for NOx emission reductions and any associated GHG emission impacts
Improving In-use Testing Program

• **Current in-use compliance requirements:** Not to Exceed (NTE) method
  • Applies only in certain conditions
  • Overlooks emissions behavior during the majority of In-Use operations
  • Significant number of engines pass ‘by default’ without any NTE events

• **Goal:** Leverage tools developed under NTE to apply an In-Use Emissions Standard to breadth of vehicle operation
  • Examining alternative Emissions Metrics and Windowing Methods
  • ~10% VMT projected to drive 50% of the NOx inventory: Need much wider coverage in Time and in Load
  • Both OEM and CARB run testing
Revising Useful Life Provisions

- **Proposed Amendments**

<table>
<thead>
<tr>
<th>VEHICLE / ENGINE CATEGORY</th>
<th>CURRENT USEFUL LIFE</th>
<th>LENGTHENED USEFUL LIFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 8 Heavy-Heavy GVWR &gt; 33,000 lbs.</td>
<td>435,000 mi 10 yrs / 22,000 hrs</td>
<td>~ 1-1.2 million mi 15 years / hours TBD</td>
</tr>
<tr>
<td>Class 6-7 Medium-Heavy 19,500 lbs. &lt; GVWR ≤ 33,000 lbs.</td>
<td>185,000 mi 10 yrs</td>
<td>~ 500,000 -550,000 mi 15 years</td>
</tr>
<tr>
<td>Class 4-5 Light-Heavy 14,000 lbs. &lt; GVWR ≤ 19,500 lbs.</td>
<td>110,000 mi 10 yrs</td>
<td>~ 250,000 –550,000 mi 15 years</td>
</tr>
</tbody>
</table>
Revising Warranty Period Requirements

- **Proposed Amendments**

<table>
<thead>
<tr>
<th>VEHICLE / ENGINE CATEGORY</th>
<th>CURRENT WARRANTY</th>
<th>JUNE 2018 WARRANTY AMMENDMENTS*</th>
<th>LENGTHENED WARRANTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 8 Heavy-Heavy</td>
<td>100,000 mi</td>
<td>350,000 mi</td>
<td>≥435,000 mi</td>
</tr>
<tr>
<td>GVWR &gt; 33,000 lbs.</td>
<td>5 yrs / 3,000 hrs</td>
<td>5 yrs</td>
<td>5 years</td>
</tr>
<tr>
<td>Class 6-7 Medium-Heavy</td>
<td>100,000 mi</td>
<td>150,000 mi</td>
<td>≥185,000 mi</td>
</tr>
<tr>
<td>19,500 lbs. &lt; GVWR ≤ 33,000 lbs.</td>
<td>5 yrs / 3,000 hrs</td>
<td>5 yrs</td>
<td>5 years</td>
</tr>
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<td>14,000 lbs. &lt; GVWR ≤ 19,500 lbs.</td>
<td>5 yrs / 3,000 hrs</td>
<td>5 yrs</td>
<td></td>
</tr>
</tbody>
</table>

* Applies to 2022+ MY vehicles
Low NOx Demonstration Projects
Low NOx Demonstration Projects

• Stage 1 – Low NOx Feasibility Demonstration
  • Funding: $1.6M by CARB with support from MECA and Volvo
  • Final report at: https://www.arb.ca.gov/research/veh-emissions/low-nox/carb_2017-04-30_03-19503_finaledit.pdf

• Stage 1b – Re-aging of Stage 1 Aftertreatment Parts
  • Funding: $480,000 by SCAQMD with support from MECA

• Stage 2 – Low Load Duty Cycle (LLC) Development/ Low Load NOx Control
  • Funding: $1.05M by CARB

• Stage 3 – Low NOx Demonstration on an Alternative Non-Turbocompound (TC) Engine
  • Funding: $1.375M by CARB, SCAQMD and POLA with support from Cummins & MECA

• Stage 3b – Additional Low NOx Related Engine Hardware Development
  • Funding: $500K by EPA, CHEDE & MECA
Stage 1: Low NOx Program

Objectives

• Started October 2013

• Completion date: May 2017

• Optimization on regulatory cycles
  • Target NOx on aged parts: 0.02 g/bhp-hr on the FTP and RMC

• Includes a 12 L natural gas and 13 L diesel engine

• Solution must be technically feasible for production

• Solution must be consistent with path toward meeting future GHG standards CO₂, CH₄, N₂O

More information:
https://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm
Stage 1: Final Low NOx Configuration

• Diesel
  • Screened approximately 33 technology packages
  • Final low NOx configuration: **PNA+MB+DEF+SCRF+SCR+ASC**
  • Demonstrated on development parts: 0.012 g/bhp-hr NOx
  • Impact on GHG from baseline: 2% on FTP

• Natural Gas
  • Engine upgraded to improve air fuel ratio control
  • Aftertreatment options: 4 packages of three way catalysts (TWC)
  • Final down selected aftertreatment configuration:
    • Close-coupled TWC (9L) and underfloor TWC (20L)
Overall Stage 1 results

- **Diesel**
  - Final parts aged on engine thermally and chemically
  - Unexpected PNA canning failure during aging
  - PNA and SCRF were cleaned, recovered, and continued aging to the full useful life
  - Despite canning failure results were encouraging:
    - **Diesel NOx**: 0.034 g/bhp-hr on FTP and 0.038 g/bhp-hr on RMC

- **Natural Gas**
  - Final parts aged thermally to full useful life
  - **CNG NOx**: 0.010 g/bhp-hr on FTP and 0.001 g/bhp-hr on RMC
Low NOx Demonstration Projects – Stage 1b

• **Contract info**
  - Initiated in Feb 2018, to be completed by Jun 2018
  - Funding: $480,000 by SCAQMD with support from MECA
  - Contractor: SwRI

• **Objectives**
  - Re-age Stage 1 aftertreatment parts, due to failure experienced during the original aging process that resulted in suspected hardware damage

• **Status**
  - Completed aging process
  - Currently performing final tests over FTP and RMC
Low NOx Demonstration Projects – Stage 2

- **Contract info**
  - Initiated in Jan 2017, to be completed in Dec 2018
  - Funding: $1.05M by CARB
  - Contractor: SwRI (with NREL as subcontractor)

- **Objectives**
  - Develop low load profiles and combine them into a Low Load Cycle (LLC) that could be used for certification
  - Re-calibrate Stage 1 engine/AT system to achieve ultra-low NOx levels under low load operation
  - Examine different “load” metrics for improvement of in-use testing
    - Characterize accuracy of broadcast ECM torque and fueling rate
    - Develop proper metrics for evaluating low load operation
Low NOx Demonstration Projects – Stage 2

• **Status**

  **Low Load Cycle Development**
  • Several candidate cycles developed
  • Baseline testing currently being performed
  • Final LLC to be released shortly

  **Low Load Recalibration**
  • Awaiting completion of Low Load Cycle development and baseline testing
  • Calibration over low loads to begin shortly
  • Work on both engine-based and AT-based (mini-burner) approaches

  **Low Load Metric Testing**
  • Three candidate Class 8 engines from three different manufacturers
  • Test Variables: broadcast torque, fuel rate, NOx sensor data (NOx and O₂), exhaust flow
  • Data analysis currently in progress

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![Candidate Low Load Cycle](image-url)
Low NOx Demonstration Projects – Stage 3

- **Contract info**
  - Initiated in Jun 2017, to be completed in Jun 2019
  - Funding: $1.325M by CARB and SCAQMD
  - Additional support from Cummins (2017 MY X15 engine) and MECA (AT parts and final aging)
  - Contractor: SwRI

- **Objectives**
  - Optimization on FTP, RMC, and CARB Idle
    - Target NOx emission rate: 0.02 g/bhp-hr on FTP and RMC
    - Optimization on low load profiles developed from Stage 2

- **Status**
  - Baseline testing on regulatory cycles completed
Low NOx Demonstration Projects – Stage 3b

- **Contract info**
  - Initiated in Dec 2017
  - Funding: $500K by EPA, CHEDE and MECA
  - Contractor: SwRI

- **Objectives**
  - Explore additional engine hardware options on Stage 3 engine to help reduce GHG impact and simplify AT system configuration
  - Options to be considered include: cylinder deactivation, turbine bypass, EGR cooler bypass, charge air cooler (CAC) bypass, insulated exhaust manifold

- **Status**
  - Cylinder deactivation and EGR cooler bypass testing in progress
  - Insulated exhaust manifold and turbine bypass testing completed
Questions?
Contacts

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Further Information

CARB Website
https://ww2.arb.ca.gov/

Heavy-Duty Low NOx Program
https://www.arb.ca.gov/msprog/hdlownox/hdlownox.htm

Optional Reduced NOx Emission Standards for On-Road Heavy-duty Engines
https://www.arb.ca.gov/msprog/onroad/optionnox/optionnox.htm

Technology and Fuels Assessments
https://www.arb.ca.gov/msprog/tech/tech.htm

On-Road Heavy-Duty Vehicle Program
https://www.arb.ca.gov/msprog/onroadhd/onroadhd.htm
Backup Slides
Evolution of Heavy-Duty Engine Standards and Technology

- **<1990**: Injection timing retard, some charge air cooling
- **1991**: Same as 1990 plus electronic fuel injection, increased injection pressure, reduced intake manifold temperature
- **1994**: Continued improvement of previous technologies
- **1998**: Same as 1991–94 plus advances in combustion chamber design, electronic controls, Electronic unit injectors (1500-1700 bar)
- **2004**: Same as 1998 plus cooled EGR, VGT, common rail fuel inj. (1800–2000 bar)
- **2007**: Same as 2004 plus high EGR, DOC, DPF, ULSD
- **2010**: Same as 2007 plus Urea–SCR

**Emission Standard (g/bhp-hr)**

- **NOx**
- **PMx10**

Model Year:
- 1990
- 1991
- 1994
- 1998
- 2004
- 2007
- 2010
Example of Compliant 2010 HDDE

Heavy-Duty Engine Certification

- Engine (versus vehicle) certification due to many engine/transmission/chassis combinations

- Engine dynamometer testing
  - g/bhp-hr (versus g/mi for vehicles)
  - Transient FTP and SET Tests
  - Not-to Exceed Test (NTE)