Engine Technologies for Nonroad Tier 3 and Tier 4

2007 NvMA/MSHA/NIOSH DPM Workshop
June 6, 2007
Elko, NV

Michael C. Block
Emisstar LLC
Presentation Overview

• Emisstar – “Who We Are & What We Do”
• EPA Emissions Standards
• Diesel Combustion ‘101’
• Tier 3 Technologies
• Tier 4 Technologies
Emisstar LLC

“Mobile Emissions Technology, Policy, and Implementation”

- Formed in April 2005
- Focus on mobile sources diesel emissions remediation
- Over 60 years collective experience
  - Air quality science & engineering
  - Engineering & project management,
  - Business development, & strategic planning
  - Diesel engine and emissions control technology
- 3 Offices in United States – NY, TX, NH

www.emisstar.com
### EPA Nonroad Regs – Tiers 1-3

<table>
<thead>
<tr>
<th>Engine Power</th>
<th>Tier</th>
<th>Year</th>
<th>CO (g/kWh)</th>
<th>HC</th>
<th>NMHC+NOx (g/kWh)</th>
<th>NOx (g/kWh)</th>
<th>PM (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW &lt; 8 (hp &lt; 11)</td>
<td>Tier 1</td>
<td>2000</td>
<td>8.0 (6.0)</td>
<td>-</td>
<td>10.5 (7.8)</td>
<td>-</td>
<td>1.0 (0.75)</td>
</tr>
<tr>
<td>8 ≤ kW &lt; 19 (11 ≤ hp &lt; 25)</td>
<td>Tier 2</td>
<td>2005</td>
<td>8.0 (6.0)</td>
<td>-</td>
<td>7.5 (5.6)</td>
<td>-</td>
<td>0.8 (0.6)</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>2000</td>
<td>6.6 (4.9)</td>
<td>-</td>
<td>9.5 (7.1)</td>
<td>-</td>
<td>0.8 (0.6)</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2005</td>
<td>6.6 (4.9)</td>
<td>-</td>
<td>7.5 (5.6)</td>
<td>-</td>
<td>0.8 (0.6)</td>
</tr>
<tr>
<td>19 ≤ kW &lt; 37 (25 ≤ hp &lt; 50)</td>
<td>Tier 1</td>
<td>1999</td>
<td>5.5 (4.1)</td>
<td>-</td>
<td>9.5 (7.1)</td>
<td>-</td>
<td>0.8 (0.6)</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2004</td>
<td>5.5 (4.1)</td>
<td>-</td>
<td>7.5 (5.6)</td>
<td>-</td>
<td>0.6 (0.45)</td>
</tr>
<tr>
<td>37 ≤ kW &lt; 75 (50 ≤ hp &lt; 100)</td>
<td>Tier 1</td>
<td>1998</td>
<td>-</td>
<td>-</td>
<td>9.2 (6.9)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2004</td>
<td>5.0 (3.7)</td>
<td>-</td>
<td>7.5 (5.6)</td>
<td>-</td>
<td>0.4 (0.3)</td>
</tr>
<tr>
<td>75 ≤ kW &lt; 130 (100 ≤ hp &lt; 175)</td>
<td>Tier 1</td>
<td>2001</td>
<td>5.0 (3.7)</td>
<td>-</td>
<td>4.7 (3.5)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>1997</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.2 (6.9)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2003</td>
<td>5.0 (3.7)</td>
<td>-</td>
<td>6.6 (4.9)</td>
<td>-</td>
<td>0.3 (0.22)</td>
</tr>
<tr>
<td></td>
<td>Tier 3</td>
<td>2007</td>
<td>5.0 (3.7)</td>
<td>-</td>
<td>4.0 (3.0)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>130 ≤ kW &lt; 225 (175 ≤ hp &lt; 300)</td>
<td>Tier 1</td>
<td>1996</td>
<td>11.4 (8.5)</td>
<td>1.3 (1.0)</td>
<td>9.2 (6.9)</td>
<td>0.54 (0.4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2003</td>
<td>3.5 (2.6)</td>
<td>-</td>
<td>6.6 (4.9)</td>
<td>-</td>
<td>0.2 (0.15)</td>
</tr>
<tr>
<td>225 ≤ kW &lt; 450 (300 ≤ hp &lt; 600)</td>
<td>Tier 1</td>
<td>1996</td>
<td>11.4 (8.5)</td>
<td>1.3 (1.0)</td>
<td>9.2 (6.9)</td>
<td>0.54 (0.4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2001</td>
<td>3.5 (2.6)</td>
<td>-</td>
<td>6.4 (4.8)</td>
<td>-</td>
<td>0.2 (0.15)</td>
</tr>
<tr>
<td>450 ≤ kW &lt; 560 (600 ≤ hp &lt; 750)</td>
<td>Tier 1</td>
<td>2002</td>
<td>3.5 (2.6)</td>
<td>-</td>
<td>6.4 (4.8)</td>
<td>-</td>
<td>0.2 (0.15)</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2006</td>
<td>3.5 (2.6)</td>
<td>-</td>
<td>4.0 (3.0)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>kW ≥ 560 (hp ≥ 750)</td>
<td>Tier 1</td>
<td>2000</td>
<td>11.4 (8.5)</td>
<td>1.3 (1.0)</td>
<td>9.2 (6.9)</td>
<td>0.54 (0.4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2006</td>
<td>3.5 (2.6)</td>
<td>-</td>
<td>6.4 (4.8)</td>
<td>-</td>
<td>0.2 (0.15)</td>
</tr>
</tbody>
</table>

† Not adopted, engines must meet Tier 2 PM standard.

On-hwy ’04:
- 2.4 NOx
- 0.1 PM
## EPA Nonroad Regs – Tier 4

### Tier 4 Emission Standards—Engines Up To 560 kW, g/kWh (g/bhp-hr)

<table>
<thead>
<tr>
<th>Engine Power</th>
<th>Year</th>
<th>CO</th>
<th>NMHC</th>
<th>NMHC+NOₓ</th>
<th>NOₓ</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW &lt; 8 (hp &lt; 11)</td>
<td>2008</td>
<td>8.0 (6.0)</td>
<td>-</td>
<td>7.5 (5.6)</td>
<td>-</td>
<td>0.4ᵃ (0.3)</td>
</tr>
<tr>
<td>8 ≤ kW &lt; 19 (11 ≤ hp &lt; 25)</td>
<td>2008</td>
<td>6.6 (4.9)</td>
<td>-</td>
<td>7.5 (5.6)</td>
<td>-</td>
<td>0.4 (0.3)</td>
</tr>
<tr>
<td>19 ≤ kW &lt; 37 (25 ≤ hp &lt; 50)</td>
<td>2008</td>
<td>5.5 (4.1)</td>
<td>-</td>
<td>7.5 (5.6)</td>
<td>-</td>
<td>0.3 (0.22)</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>5.5 (4.1)</td>
<td>-</td>
<td>4.7 (3.5)</td>
<td>-</td>
<td>0.03 (0.022)</td>
</tr>
<tr>
<td>37 ≤ kW &lt; 56 (50 ≤ hp &lt; 75)</td>
<td>2008</td>
<td>5.0 (3.7)</td>
<td>-</td>
<td>4.7 (3.5)</td>
<td>-</td>
<td>0.3ᵇ (0.22)</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>5.0 (3.7)</td>
<td>-</td>
<td>4.7 (3.5)</td>
<td>-</td>
<td>0.03 (0.022)</td>
</tr>
<tr>
<td>56 ≤ kW &lt; 130 (75 ≤ hp &lt; 175)</td>
<td>2012-2014</td>
<td>5.0 (3.7)</td>
<td>0.19 (0.14)</td>
<td>-</td>
<td>0.4 (0.30)</td>
<td>0.02 (0.015)</td>
</tr>
<tr>
<td>130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)</td>
<td>2011-2014ᵇ</td>
<td>3.5 (2.6)</td>
<td>0.19 (0.14)</td>
<td>-</td>
<td>0.4 (0.30)</td>
<td>0.02 (0.015)</td>
</tr>
</tbody>
</table>

ᵃ - hand-startable, air-cooled, DI engines may be certified to Tier 2 standards through 2009 and to an optional PM standard of 0.6 g/kWh starting in 2010
ᵇ - 0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012
ᶜ - PM/CO: full compliance from 2012; NOₓ/HC: Option 1 (if banked Tier 2 credits used)—50% engines must comply in 2012-2013; Option 2 (if no Tier 2 credits claimed)—25% engines must comply in 2012-2014, with full compliance from 2014.12.31
ᵈ - PM/CO: full compliance from 2011; NOₓ/HC: 50% engines must comply in 2011-2013

**On-Hwy:** 0.2 NOₓ, 0.01 PM
## EPA On-Hwy Regulations

### 2004 -- 2010 Diesel Engines Emission Standard (g/bhp-hr)

<table>
<thead>
<tr>
<th>Model Year</th>
<th>NOx</th>
<th>NOx + nmHC**</th>
<th>nmHC**</th>
<th>PM</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 - 2006</td>
<td>N/A</td>
<td>2.4</td>
<td>N/A</td>
<td>0.10</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OR</td>
<td>2.5 provided that nmHC&lt;=0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007 - 2009</td>
<td>&gt;= 50% of engines: 0.2</td>
<td>&lt;= 50% of engines: 2006 NOx + nmHC standard</td>
<td>0.14</td>
<td>0.01</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>OR</td>
<td>Single averaged NOx FEL with 20% discount applied*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010 +</td>
<td>0.2</td>
<td>N/A</td>
<td>0.14</td>
<td>0.01</td>
<td>15.5</td>
</tr>
</tbody>
</table>

* Per EPA regulations, averaged NOx standard is approximately 1.2 g/bhp-hr  
** nmHC = nonmethane hydrocarbons
EPA Nonroad Fuel Regs

- **500 ppm**
  - June 2007 (unregulated prior, ≈ 2,500 ppm)
  - Nonroad
  - Locomotive
  - Marine
- **15 ppm** (ULSD)
  - June 2010 for nonroad
  - June 2012 for locomotive and marine
The Diesel Engine – “the good”

![Graph showing thermal efficiency vs. load for different types of engines](image-url)
The Diesel Engine – “the bad”

Particulate number
The Diesel Engine

Intake
Air only

Compression
Compressed air
Fuel injected near TDC

Power/Work/Expansion

Exhaust
Piston & Combustion Chamber
The Diesel Engine
The Diesel Engine

Combustion “Rules of Thumb”:

• Longer ignition delay – more time for the air in the combustion chamber to mix with the injected fuel.
• Results in hotter flame, once combustion starts.
• Hotter flame = higher temperatures and pressures.
• Result: more complete combustion, PM goes down, but NOx goes up.
• Converse – decrease amount of pre-mix time
  • Process runs cooler and at lower pressures.
  • Combustion less complete & cooler – PM goes up; NOx goes down. (thermodynamic NOx/PM tradeoff)

Fuel type and composition, and on-engine strategies, all do one thing - they affect the time of ignition delay, which affects combustion temperatures and pressures, which influences the amount of NOx and PM formation in the exhaust.
Tier 3 Technologies

• Airflow optimization
• FIE type & control
• EGR
• DOC
Airflow Optimization

- Combustion chamber design
- Injector location
- Reduced crevice volumes
- Increased compression ratio
- VVT (variable valve timing)
- Turbocharger matching/advanced developments
  - Electric assist
  - Variable geometry
  - Compounding (two small better than one large)
Combustion Chamber Design

- Straight-sided off-center
- Reentrant, central

Air motion optimization
FIE

• Serve three primary functions:
  • Deliver fuel to the engine,
  • Determine *when* in the combustion cycle the fuel will be injected – injection timing.
  • Determine the *amount* of fuel injected during the engine cycle – injection metering.
Critical relationships between injection & emissions:

- **Pilot-injection**
  - A “pre” injection of a small quantity of fuel, *before* the primary, injection event.
  - Keeps the extent of pre-mixed combustion lower.
  - Lowers combustion chamber temperatures and pressures.
  - Reduces NOx.

- **Post-injection**
  - A second injection *after* the primary injection event
  - Increases exhaust temperatures to promote diesel particulate filter regeneration.

- **Multiple injections**
  - Injection strategy consisting of a number of injections per combustion cycle
  - Optimizes engine performance (power and low emissions) over different operating regimes.

- **“Boot” or “rate shaping” injection**
  - Fuel injection rate starts out low and increases as the injection proceeds.
  - Boot injection is single injection event as opposed to multiple injections.

*Goal: Using advanced FIE, design injection strategy to minimize both NOx and PM while not affecting, or affecting as little as possible, engine power and fuel economy.*
FIE

Multiple & rate shaping injection strategies
FIE

2 requirements – High injection pressures (34,000 psi+); On demand

PLN
EUI
Common Rail

![Diagram of FIE systems]

![Graph showing pressure vs. engine speed]

EMISSTAR
- **Dilution of the intake air with inert gases**, leading to a decrease of oxygen concentration in the combustion process.
- **Heat absorption** by the EGR stream, primarily due to the heat absorbing capacity of CO₂ (thermal effect), as well as through the dissociation of CO₂ (chemical effect), leading to a reduction in combustion pressures and temperatures.
Simplified EGR System

EGR

Turbocharger

Turbo Intercooler & EGR Intercooler (not shown)

Diesel Engine

EGR valve

Aftertreatment or muffler
DOCs – Operating Principle (SOF)

Hydrocarbons + O₂ = CO₂ + H₂O
CO + ½ O₂ = CO₂
DOCs – HC (gaseous) & CO

\[
\text{Hydrocarbons} + O_2 = CO_2 + H_2O
\]

\[
CO + \frac{1}{2} O_2 = CO_2
\]
DOCs – Sulfate (SO$_4$) ‘Make’

\[
2\text{SO}_2 + \text{O}_2 = 2\text{SO}_3 \\
\text{SO}_3 + \text{H}_2\text{O} = \text{H}_2\text{SO}_4
\]

• Sulfur dioxide (from sulfur in diesel fuel) oxidizes in the DOC to form sulfur trioxide.

• Water resident in the exhaust combines with sulfur trioxide to form sulfuric acid.

• When discharged from the tailpipe, exhaust containing sulfuric acid precipitates under cooling to form sulfate PM.

• Sulfate PM is part of total PM, and is “counted” in the PM content of the exhaust.
# DOCs – At a Glance

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Moderate total PM reduction performance (20-30%) – benefit if applied in high vehicle volumes.</td>
<td>1. Low PM reduction efficiency – drawback if applied in low vehicle volumes.</td>
</tr>
<tr>
<td>2. Comparatively low cost.</td>
<td>2. Ineffective in reducing elemental carbon (i.e. “soot”).</td>
</tr>
<tr>
<td>4. Tolerant of sulfur content in diesel fuel (not “poisoned”).</td>
<td>4. Easy installation – but occasionally requires revised brackets to accommodate additional weight over muffler.</td>
</tr>
<tr>
<td>5. May provide high PM reduction on older engines, especially 2-cycle engines (both have higher SOF concentrations in diesel exhaust).</td>
<td>5. Potential for sulfate make.</td>
</tr>
</tbody>
</table>
Will Use Enhanced Tier 3 Technologies, + 

- HCCI/Dual Mode
- DPF
- CCV
- SOF Control – in cylinder & lube oil
- SCR
- LNT
HCCI – operating principle

- “Homogeneous Charge Compression Ignition”
- a.k.a., “premixed combustion”
- Even fuel dispersion into combustion chamber.
- Eliminates fuel rich zones that promote PM formation.
- “Global combustion throughout the chamber.”
- How?
  - VVT
  - Engine management
  - Other techniques
HCCI – issues

- Start of combustion
  - Injection of fuel into the engine precipitates heterogeneous combustion.
  - Promotes high PM emissions.
- High load operation
  - Inherently unstable.
  - Dual Mode operation shows promise.

*Unknown candidate technology for Tier 4.*
DPFs – Operating Principle

Soot Entrapment

Exhaust enters (PM, HC, CO)

Cell Plugs

Regen: O\(_2\), NO\(_2\) & HEAT!

Trapped Soot (PM)

Exhaust exits (CO\(_2\), H\(_2\)O)

Ceramics + catalytic coating
DPF Regeneration

Excess $O_2 + NO_2$

+ the following five “energy source” alternatives:

• Engine exhaust heat (‘EGT’)
  ECS, Nett, DHL, Engelhard, JMI, Donaldson

• Shore power/plug-in – ECS, Cleaire

• On-board electrical – Rypos

• Fuel burner – Huss, CleanAIR, Airmeex

• Catalytic combustion of fuel – Arvin, Emitec
ADPF – Shore-Power Electrical Regeneration
ADPF – Onboard Electrical Regeneration

RYPOS ADPF™

Source: Rypos
ADPF – Fuel Burner

Source: Huss
ADPF – Catalytic Combustion of Fuel

Source: DieselNet
## DPFs – At A Glance

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Very high total PM reduction performance (90%).</td>
<td>1. High cost.</td>
</tr>
<tr>
<td>2. Comparatively easy installation – not as straightforward as the DOC,</td>
<td>2. Requires ULSD.</td>
</tr>
<tr>
<td>but not as complex as other PM control technologies.</td>
<td>3. Requires threshold exhaust temperature to ensure regeneration.</td>
</tr>
<tr>
<td>3. Regeneration should be unnoticed by the vehicle operator (some active</td>
<td>4. Requires periodic (usually yearly) removal and cleaning to remove unregenerated ash deposits.</td>
</tr>
</tbody>
</table>
| systems require operator intervention).                                  | 5. Weight/”mounting”.
|                                                                         | 6. NO$_2$ (precious metal catalyzed systems).                                              |
CCV – Closed Crankcase Ventilation

- Crankcase emissions are created as a by-product of the diesel combustion process.

- A certain percentage of engine exhaust gases pass by the piston rings and valve seals and find their way into the crankcase (oil sump and oil pan assembly) of the engine.

- Typically, these products vent into the atmosphere

- US EPA regulation will require that these “blow-by” gases be vented *not* into the atmosphere, but recirculated back into the engine for subsequent “re-combustion.”

- To effectively and safely perform this “recirculation” operation requires a vapor separator, filtering and recirculating device, generically known as *closed crankcase ventilation* or **CCV**.
CCV

Filter cleans crankcase ventilation port and returns clean gas to air intake.

Source: Donaldson
CCV
SOF Control

- In-cylinder
  - Piston ring design
  - 4 valve heads
  - Valve stem oil control (seals, guides)
- Lubricating Oil – ‘SAPS’ (Sulfated Ash, Phosphorous, and Sulfur)
  - Designed for US2007 on-highway truck
  - Applicable to nonroad/miming applications
  - Backwards compatible (existing engines)

SOF = ‘Soluble Organic Fraction’
SCR – NOx Reduction

![Diagram of SCR system]

- Engine
- Pre-Oxidation Catalyst
- Mixing
- SCR Catalyst
- Exhaust Gas
- Control Unit
- Urea Injection
- Oxidation Catalyst
- Hydrolysis Catalyst
- Urea Tank
- Pump

Ammonia reactions:

- \(6NO + 4NH_3 = 5N_2 + 6H_2O\)
- \(4NO + 4NH_3 + O_2 = 4N_2 + 6H_2O\)
- \(6NO_2 + 8NH_3 = 7N_2 + 12H_2O\)
- \(2NO_2 + 4NH_3 + O_2 = 3N_2 + 6H_2O\)
- \(NO + NO_2 + 2NH_3 = 2N_2 + 3H_2O\)
SCR – Issues

- **Urea replenishment:**
  - Extra maintenance and operational cost.
  - Bake into procedure.
  - Disincentive.

- **Emission compliance:**
  - Normal operation w/o urea
  - No NOx reduction will be realized.
  - No financial incentive to replenish.

- **Stability of urea solution:**
  - 32.5% urea solutions crystallize at –11°C (12°F).
  - Urea may decompose while exposed to increased temperatures during storage or in vehicle tanks.

- **Transient performance:**
  - Generally poorer NOx reductions under real-world conditions.
  - Potential for ammonia slip.

- **Low temperature performance:**
  - Low or no NOx conversion occurs at low temperatures, typically < 250 – 300°C.

- **High cost & complexity:**
  - Urea injection and control components
  - Does not change with the engine size.
  - From a cost perspective, SCR systems more suitable for large diesel engines.
Case Study – Truck SCR + DPF (Mack)
LNT – theoretical operation

- Adsorption & storage of NOx → lean operating conditions

\[
\begin{align*}
NO + \frac{1}{2}O_2 &= NO_2 \\
BaO + NO_2 + \frac{1}{2}O_2 &= Ba(NO_3)_2
\end{align*}
\]

- Release to N\(_2\) → rich operating conditions

\[
\begin{align*}
Ba(NO_3)_2 &= BaO + 2NO + 1\frac{1}{2}O_2 \\
Ba(NO_3)_2 &= BaO + 2NO_2 + \frac{1}{2}O_2 \\
NO + CO &= \frac{1}{2}N_2 + CO_2
\end{align*}
\]
LNT – Issues

- Sulfur poisoning
  - Desulfation – 600 – 700°C, rich operation
  - Sulfur traps – add on in exhaust

- Durability – thermal cycling, R/L
- Very complex & costly
- Integrated engine management
- Packaging
- Fuel penalty
- Secondary emissions – H₂S & N₂O
Michael C. Block, Principal
Office: (603) 487-3235
Mobile: (603) 520-4147
michael.block@emisstar.com

www.emisstar.com