Off-Road Engine Emissions: Bridging the Gap

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Cummins, Inc.
Customer Requirements

- Highly Sociable
- Electronic Integration
- Low Initial Cost
- Low Maintenance
- Fuel Efficient
- Reliable and Durable
- High Performance
Evolution of NA HD On-Highway Engines

- 1974 EPA (HC + NOx)
- 1988
- 1990
- 1994*
- 1998
- 2004
- 2007

**Particulate [g/(HP-hr)]**

- 0
- 0.1
- 0.25
- 0.6
- 1.0

**NOx [g/(HP-hr)]**

- 0
- 5
- 10
- 15

**Key Points:***
- **1978 Models**
  - Retard Timing
  - JWAC
  - Low Friction

- **1988 Models**
  - Retard Timing
  - Incr. Inj. Press.
  - Low temp JWAC
  - Higher Comp Ratio
  - Higher Boost

- **1991 Models**
  - Retard Timing
  - Incr. Boost, CAC
  - Incr. Inj. Press.
  - Electronic Inj. Control

- **1994**
  - Incr. Inj. Press.
  - Higher Comp Ratio

- **2004**
  - Incr. Boost

- **2007**
  - Incr. Inj. Press.

*500 ppm max. sulfur fuel available in 1994
Evolution of Mobile Off-Highway Engines

EPA 174-301 HP MOH Segment Shown

Tier I
- Retard Timing

Tier II
- High Boost, CAC
- Incr. Inj Pres
- Electronic Controls

Tier III

Tier I Models
- Retard Timing
- Incr. Inj Pressures

Particulate [g/(HP-hr)]

NOx [g/(HP-hr)]
World Emission Levels for HD Truck

1995

US
- EPA 94 Euro 1/2
- NOx>6.5 g/bhp/hr, PM>0.25 g/bhp/hr

Europe
- Group 0 Unregulated
- Group 1 NOx=3.5-6.5 g/bhp/hr, PM=0.1-0.25 g/bhp/hr
- Group 2 NOx=2.0-3.4 g/bhp/hr, PM=0.06-0.1 g/bhp/hr
- Group 3 NOx=1.0-1.9 g/bhp/hr, PM=0.05 g/bhp/hr
- Group 4 NOx<1.0 g/bhp/hr, PM<0.05 g/bhp/hr

2000

2010

2005

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Engine Manufacturer’s Product Dilemma

How to participate in worldwide diesel growth with an economic portfolio of products?
On-Highway Benchmark - North American Class 8 Truck

Legislated Vehicle Designs and Duty Cycle: Dimensions, Road Speed, GVW

60 MPH clean ram air, low fan usage

<500 ppm fuel sulfur since 1994

Standardized, modular components allow custom specification

300-600 HP typical

Market drivers: fuel economy, low cost of operation, availability, driver retention
Typical Off-Highway Application

NO Legislated Vehicle Designs and Duty Cycle: Dimensions, Road Speed, GVW

2000-3000 ppm fuel sulfur

0 MPH dirty cooling air, fan on all the time

Huge variety of standard machines w/ little customization

175-600 HP typical

Market drivers: Availability, productivity, ergonomics, packaging, noise

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Tier III Technology Considerations

Cost Sensitivity

Fuel Options

Emission Technology Options

2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

3.0 NOx* 302 - 751 HP QSL, QSM, QSX, QSK19

3.5 NOx* 49 - 99 HP B3.3, QSB

3.0 NOx* 100 - 173 HP QSB

3.0 NOx* 174 - 301 HP QSB, QSC

3.0 NOx* 302 - 751 HP QSL, QSM, QSX, QSK19

* Gr/BHP-HP NOx + NMHC

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Key Technologies
NOx and PM Reduction-2005

Starting Point: Advanced In-Cylinder Emission Control

NOx
- Cooled EGR
- Lean NOx
- Lean NOx + HC
- Plasma Assisted Lean NOX
- NOX Adsorber
- Microwave Preheating
- Selective Catalytic Reduction

Particulate
- Diesel Oxidation Catalyst
- Catalyzed Soot Filter
- Microwave Regenerated Soot Filter
**+**
- No extra fluid
- No Aftertreatment
- Common w. On-highway product
- Regulatory acceptance

**-**
- Increased heat rejection
- 500 ppm fuel required
**Urea SCR**

**+**

- Available technology
- No heat rejection impact
- Improved fuel economy
- Modular and scalable
- Sulfur tolerant

**-**

- Urea Infrastructure
- Regulatory acceptance?
- Tamperproofing
- Freezing
- Installation impact
- Unique off-road product

**UREA SCR Schematics**

- ECU
- Catalyst
- Urea metering
- Urea storage
By 2020, EPA estimates that non-road will contribute:
- 66% of mobile NOx
- 76% of mobile PM

Standards seem likely to harmonize around on-road technology, with recognition of the characteristics of the non-road markets.
Key Technologies
NOx and PM Reduction-2007

Starting Point: Advanced In-Cylinder Emission Control

- Cooled EGR
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- Plasma Assisted Lean NOx
- NOx Adsorber
- Microwave Preheating
- Selective Catalytic Reduction

NOx

+ +

Particulate

- Diesel Oxidation Catalyst
- Catalyzed Soot Filter
- Microwave Regenerated Soot Filter
Catalyzed Soot Filter

• **Issues:**
  - **Regeneration**
    - **Level**
    - **Frequency**
    - **Speed/Load/Duty Cycle Dependence**
  - **Wide applicability will require active regeneration**
  - **Once initiated, regeneration must be controlled**
    - **Soot loading**
    - **Reduction in engine airflow during regeneration can lead to excessive temperatures and catastrophic failure**

![Graph showing engine duty cycle requirement](image)
• Many duty cycles are very light
• Exhaust temperatures are low
• CSF regeneration a big issue
  – Winter conditions

• Ultralow sulfur fuel will be a requirement for many applications
• Active regeneration may be required for broad applicability
DPF/NO\textsubscript{x} Adsorber System

Note: Sensors from lower circuit have been omitted for clarity.
Effect of Fuel Sulfur on NO$_x$ Adsorber Performance

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Time (Hours)

NO$_x$ Conversion (%)

Phillips Ultralow Sulfur ~5 ppm
Low Sulfur ~ 400 ppm
Urea SCR System

- High range NO\textsubscript{x} sensor with O\textsubscript{2}
- Low range NO\textsubscript{x} sensor

- Externally heated lines and metering pump
- Urea Tank
- Heat source (e.g., electric)

- Variable Position valve
- ΔP sensor
- MAF
- DPF
- Pre
- SCR
- DOC

- Quality sensor
- Temperature sensor

- Cummins, Inc.

- Heat source (e.g., electric)
The Tier III Gap

Today
Tier II

2005 Tier III
Cooled EGR
Urea SCR
Infrastructure Regulatory

2010?
Tier IV?
Automotive Technology
Adsorber or Urea SCR
Soot Filter
ULSF Single Fuel
Bridging the Gap!

• Tier III in 2005 will require focus on the key underlying issues:
  – Fuel sulfur
  – Urea
• Rationalization w/ on-highway seems inevitable
• Tier III will only be an interim technology
• Significant air burden gains w/ advanced aftertreatment are possible...given time and development
• System solutions needed to keep US Manufacturers competitive!

Clean, Safe, and Efficient Business Solutions for End-Users!
Backup
EPA MOH Emission Standards

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Model Year


Oxides of Nitrogen (g/bhp-hr)

15

Unregulated level

82% reduction of NOx

54%

35%

40%

Tier I

Tier II

Tier III

? ?
## Projected Emissions Requirements

<table>
<thead>
<tr>
<th></th>
<th>US EPA</th>
<th>European</th>
<th>Industrial</th>
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<tr>
<td></td>
<td>98</td>
<td>2002</td>
<td>‘07 NPRM</td>
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<tr>
<td>NOx (gm/hp-hr)</td>
<td>4.0</td>
<td>2.0</td>
<td>0.2</td>
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<tr>
<td>PM (gm/hp-hr)</td>
<td>0.05-0.10</td>
<td>0.05-0.10</td>
<td>0.01</td>
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End-User Cost Comparison
US Heavy Duty

Estimated On-Highway NOx (g/bhp-hr)

Estimated Annual Customer Cost Increase (%)

Assumptions for Base HD Vehicle:
NOx = 8.0 g/bhp-hr
100,000 miles/year
6 miles/gal fuel consumption
$1.40 Gal Diesel Fuel Cost
4 Yr. SL Depreciation (25% RV)
Future Solutions Demand System Integration!

Clean, Safe, and Efficient Business Solutions for End-Users!
Peak Torque PM - ISM370

OICA Mode 2 - 518°C (964°F) catalyst inlet temperature

PM (g/bhp hr)

Non-Sulfate   Sulfate + H2O

Fuel Sulfur (ppm)

0.000
0.005
0.010
0.015
0.020
0.025
0.030

3  30  150  350  3  30  150  350
World Energy Consumption

- World energy usage increases by 78%
- Usage in Industrialized Countries increases by 44%
- Usage in EE/FSU remains relatively constant
- Usage in Developing Countries increases by 219%

Source: Energy Information Administration International Energy Outlook 1999
NOx Adsorber/Particulate Filter
Conflicting Regeneration Requirements

- **HIGH:** Temperatures, NO2 Concentration, O2 Partial Pressure
- **MODERATE:** Space Velocities

- **LOW:** NO2 Concentrations, O2 Partial Pressures, Space Velocities

**Primary Exhaust Flow**

**Secondary Flow During Regeneration**
Catalyzed Soot Filter

• Required to meet 2007 EPA and beyond emission levels
• Self-regenerates above certain exhaust temperatures (~300 C)
• Can be very efficient (~90+%)

Fundamental Research
System Development

Soot Filter System Design
MOH Tier III Customer Cost Analysis - PRELIMINARY
(@ 3.0g/bhp-hr NOx)

Application

Annual Incremental Cost vs. Tier I

Cooled EGR
SCR (w/ 8g engine)
Mobile Off-Highway Market is very Diverse
Trends in Off-Highway Equipment

Noise Treatment
Emphasis on operator vision
High Power density
Trends in Off-Highway Equipment

Compact Machines
Emphasis on operator vision
and productivity
Low Noise
Innovative Packaging
World Emission Levels for Mobile Off Highway

1995

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