Technology Development for High Efficiency Clean Diesel Engines and a Pathway to 50% Thermal Efficiency

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August 5, 2009
Evolution of Heavy Duty Diesel Engine Efficiency

Class 8 Line Haul Application: Highway Cruise Condition

Brake Thermal Efficiency (%)

- **DoE Vehicle Technologies**
  - 55% BTE Engine Assessment
  - 50% BTE Engine Demonstration

- **HECC DoE Co-Sponsored Program**
  - (DE-PS26-04NT42099-01)

- **Waste Heat Recovery DoE Co-Sponsored Program**
  - (DE-FC26-05NT42419)
ISX Technology Roadmap for Efficiency Improvement

Black – Enabling Technology for HECC Program Phase 3

- Variable Valve Actuation
- Fuel System
  - High Injection Pressure
  - Piston Bowl/Nozzle
  - Multiple injections
- Advanced LTC
  - Enhanced PCCI
  - Mixed Mode Combustion
- Variable Intake Swirl
- EGR Loop
  - Lower Pressure Drop
  - Alternative Cooling
- Turbo Technology
  - Electrically Assisted
  - 2-Stage
- Controls
  - Charge Air Manager
  - MAF
  - Closed Loop Combustion
- Electrically Driven Components
- Aftertreatment
  - DOC
  - DPF
  - SCR
  - Sensors

Phase 3: 2008 - 2009
Achieving a Wide Range of Engine Out NOx Capability

In-Cylinder NOx Control

EGR+DOC+DPF

- EGR System + Combustion System + Air Handling
- Program Baseline
- Advanced Fuel Injection System + EGR System + Controls
- Air Handling + Sensors + Calibration
- Low \( \Delta P \), High Flow Rate EGR + VVA

EGR+DOC+DPF + SCR

- SCR NOx Conversion Efficiency: 79%-84%
- Engine Out PM Level: 85%-88%
- >89%

2007 Engine + SCR

- BSNOx [g/hp-hr]
- BSDPM [g/hp-hr]

\[ \Delta = 0.03 \]

% Change in Fuel Consumption Relative To Baseline

-0% to -12%

* Robustness remains an issue for In-Cylinder NOx Control
Fuel Consumption Comparison of the In-Cylinder vs SCR NOx Control Engine Architectures

In-Cylinder NOx Control
EGR+DOC+DPF

EGR+DOC+DPF

2007 Engine
+ SCR

DPF+SCR

Program Baseline

Non – HECC Engine
(2007 Production Engine)

14% Improvement in BTE

7.5% Improvement in BTE

BSN0x [g/hp-hr]

BSN0x [g/hp-hr]

Δ=0.03

SCR NOx Conversion Efficiency

SCR NOx Conversion Efficiency

79%-84%

85%-88%

>89%

% Change in Fuel Consumption Relative To Baseline

0%

-3%

-6%

-9%

-12%

Engine Out PM Level Assuming DPF

Non – HECC Engine
(2007 Production Engine)

7.5% Improvement in BTE

79%-84%
Evolution of High Efficiency SCR
Does Not Include DEF Usage

Reduction in Fuel Consumption Compared to 2007 Engine (%)

Percent Improvement in SCR NOx Conversion Efficiency Relative to 2010 SCR System Capability

Transient Drive Cycle Results

Represent Changes in Aftertreatment Hardware Including Feedback Controls for Urea Dosing
Evolution of High Efficiency SCR

Does Not Include DEF Usage

Percent Improvement in SCR NOx Conversion Efficiency Relative to 2010 SCR System Capability

Acceptable Payback Period For Class 6, 7, and 8 Vehicles

Reduction in Fuel Consumption Compared to 2007 Engine (%)

Represent Changes in Engine Architecture Including Thermal Management Strategies

Transient Drive Cycle Results

2% 4% 6% 8% 10% 12%

2% 4% 6% 8% 10%
**Potential Fuel Consumption Benefit of Higher SCR NOx Conversion Efficiency**

- **Fuel Consumption**
- **Fuel and DEF Consumption***
- **Engine Out NOx**

![Graph showing fuel consumption and conversion efficiency](image)

- ANR=1
- **~10% Fuel Consumption Reduction**
- **2007 EO NOx – Non SCR**

* Assumes DEF cost = diesel fuel cost/2
Potential Fuel Consumption Benefit of Higher SCR NOx Conversion Efficiency

* Assumes DEF cost = diesel fuel cost/2
**Technical Barriers with Possible Solutions**

**In-Cylinder NOx Control**
- Vehicle heat rejection
  - Low temperature radiator configuration (multiple options considered)
- Power density limitations
  - Increased vehicle heat rejection capability
  - Cylinder pressure capability
- Robustness
  - Reduce charge flow and fuel flow variation
    - Control algorithms
    - Sensor technology
    - EGR cylinder to cylinder distribution
- Transient response
  - 2-stage turbo
  - Electrically assisted boost
  - CAC bypass

**High NOx Conversion Efficiency SCR**
- >97% conversion efficiency over relevant drive cycles
  - Conversion of urea to ammonia (eliminate urea derived deposits)
  - NOx selectivity of the ammonia slip catalyst
- System pressure drop
- Packaging
  - Unique arrangements defined
  - Reduce catalyst size via zone coating
  - New substrate material for smaller size
- Fuel efficient thermal management for transient emissions (FTP)
  - Turbomachinery
  - Injection strategy
  - EGR cooler by-pass
  - Compressor by-pass
Improved Customer Value

- Must significantly reduce the aftertreatment cost
  - Aggressive target should be a 50% reduction in price

- Diesel particulate filter size reduction with lower $\Delta P$ and combined SCR functionality
  - As SCR NOx conversion efficiency increases, PM emissions reduced drastically
  - DPF operating in passive regeneration mode

- Eliminate ammonia slip catalyst

- Greater than 50% reduction in precious metal loading of DOC

- Key is system integration with novel control strategies
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Evolution of Heavy Duty Diesel Engine Efficiency

- 1985
- 1990
- 1995
- 2000
- 2005
- 2010
- 2015
- 2020
Nearly a 10% performance improvement is possible – though with high additional cost and system complexity.

Future development must focus on the most promising and realistic potentials energy recovery sources -

**Cost Reduction is a Key Area of Emphasis for the Cummins 2nd Generation ORC WHR System**
Engine Fuel Energy Balance to Meet 50% BTE

Fuel Energy 100%

- Indicated Power 51.7%
  - Gas Exchange 2.2%
  - Friction 0.9%
  - Accessories 1.1%
- Brake Power 50.1%
- Exhaust 27.2%
  - Exhaust Source (ORC) 1.7%
- Heat Transfer 21.1%
  - EGR Source (ORC) 0.8%