SCR on Filter Based Aftertreatment for High Efficiency Engine Systems

BUILT FOR IT:

A UK based Energy Technologies Institute Funded Project
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*J.C. Martin – Johnson Matthey Catalyst

(*Co-authors) (**Presenter)
Outline

- Introduction
  - Global, collaborative project

- Results for NRTC and WHTC legislative cycles
  - System design impact
  - Summary of GHG Emissions

- Results for in-use vocational cycles
  - Work Based Windows Analysis

- Conclusion
Introduction

What is the ETI?

• Public-private partnership between global energy and engineering companies and the UK Government.

• Develop, demonstrate and de-risk new technologies for affordable and secure energy, and lower GHG emissions.

• Global consortium between Caterpillar, Johnson Matthey, and Loughborough University to develop aftertreatment for next gen HDD engines.
ETI Heavy Duty Vehicle (HDV) Programme Overview

**Why is HDV efficiency so important?**
- 2011: 8% of current UK CO₂ emissions are from HDVs
- 2050: Proportion is set to increase to approx 30% as other sectors reduce CO₂
  - Limited options for low-carbon fuel alternatives
  - Modelled scenarios consistently point to HDV efficiency as a cost-effective way to reduce emissions

**Objectives**
- Develop new vehicle concepts
- Develop new technologies to support concepts
- Produce demonstration vehicles that are 30% more efficient
- Develop supply chain to enable meaningful market deployment

**Enable substantial reduction in CO₂ emissions across sector**
Goal: Meet Both On Road and Off Highway Regulations

**Regulations On-Road:**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Test Cycle</th>
<th>CO</th>
<th>THC</th>
<th>NOₓ</th>
<th>PM</th>
<th>PN</th>
<th>NH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g/kWh</td>
<td></td>
<td></td>
<td>#/kWh</td>
<td>ppm</td>
<td></td>
</tr>
<tr>
<td>Euro V</td>
<td>ETC</td>
<td>4.0</td>
<td>0.55*</td>
<td>2</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Euro VI</td>
<td>WHSC</td>
<td>1.5</td>
<td>0.13</td>
<td>0.4</td>
<td>0.01</td>
<td>8.0 x 10^{11}</td>
<td>10</td>
</tr>
<tr>
<td><strong>Euro VI</strong></td>
<td><strong>WHTC</strong></td>
<td><strong>4.0</strong></td>
<td><strong>0.16</strong></td>
<td>0.46</td>
<td>0.01</td>
<td><strong>6.0 x 10^{11}</strong></td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>

*NMHC

**Regulations Off-Highway Engines 130 – 560 kWh:**

<table>
<thead>
<tr>
<th>Stage</th>
<th>CO</th>
<th>NOₓ</th>
<th>HC</th>
<th>PM</th>
<th>PN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/kWh</td>
<td></td>
<td></td>
<td>#/KWh</td>
<td></td>
</tr>
<tr>
<td>EU Stage IV</td>
<td>3.5</td>
<td>0.4</td>
<td>0.19</td>
<td>0.025</td>
<td>none</td>
</tr>
<tr>
<td><strong>EU Stage V</strong></td>
<td><strong>3.5</strong></td>
<td><strong>0.4</strong></td>
<td><strong>0.19</strong></td>
<td><strong>0.015</strong></td>
<td><strong>1 x 10^{12}</strong></td>
</tr>
</tbody>
</table>
Baseline Engine and Modifications

Baseline engine = 7 liter Cat® EU Stage IV compliant non-road engine.

Engine modifications made to improve BSFC:
- Remove EGR
- Adjust combustion timing
- Optimizing the air system
- 9 g/kWh Engine out NOx calibration
- 2 operating modes evaluated:
  - Conventional
  - Downsped

<table>
<thead>
<tr>
<th>Engine Calibration</th>
<th>Average NRTC Turbine Out Temperature (°C)</th>
<th>Typical Engine out NOx levels (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier 4 Final Baseline</td>
<td>304.7</td>
<td>~ 3.5</td>
</tr>
<tr>
<td>ETI Conventional</td>
<td>289.8</td>
<td>9.3</td>
</tr>
<tr>
<td>ETI Downsped</td>
<td>300.4</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Translating NRTC Test Points to Downsped Operating Mode

Speed vs. Torque data points from every second of NRTC cycle with an engine running conventional mode are translated into a power vs. time curve.

The power vs. time data points are then converted back to speed vs. torque data points for the engine in Downsped Mode.
Aftertreatment System Installation

- Modified Cat® C7.1 engine installed in JM HDD Test Cell
- Aftertreatment initially installed in a "straight" line from DOC to tailpipe
- Insulated pipe used between turbo out and DOC to reduce heat losses of catalyst system
- All catalysts provided by Johnson Matthey (JM)
- Aged catalysts (650°C/100h)
NRTC Results on Linear System Layout

Aged at 650°C for 100 hours prior to evaluation

- NO$_2$/NOx > 25%
- ANR = 1.2

Linear System Engine Test results (Weighted)

<table>
<thead>
<tr>
<th>Engine Mode</th>
<th>Turbo Outlet Average Cycle T (°C)</th>
<th>NOx Conv. (%)</th>
<th>Tailpipe (TP) NOx (g/kWh)</th>
<th>Tailpipe (TP) N$_2$O (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>290</td>
<td>96.7</td>
<td>0.29</td>
<td>0.26</td>
</tr>
<tr>
<td>Downsped</td>
<td>300</td>
<td>98.3</td>
<td>0.15</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Compact System Layout with Urea Hydrolysis Catalyst (UHC)

- Turbo Out
- DOC 8.7 dm³
- UHC 1.9 dm³
- ASC 7.2 dm³
- Tailpipe
- Cu-SCR 18.5 dm³
- Cu-SCRF® 22.2 dm³

UHC
DEF injector
UHC
ASC
SCRF
SCR
DOC
Turbo out/ System Inlet
Exhaust Pipe

Linear (red) vs. compact design (blue) NRTC Temperature Profile

- Compact layout and insulation blanked resulted in SCRF inlet temp increase across the NRTC
NRTC Results for Conventional Mode Using Compact Design

At low temperatures the urea hydrolysis catalyst improves the NOx reduction.

<table>
<thead>
<tr>
<th>Layout</th>
<th>Conventional mode NOx [g/kWh]</th>
<th>Max.TP NH₃ (ppm)*</th>
<th>PN #/kWh</th>
<th>N₂O (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>0.94</td>
<td>4.3</td>
<td>9.0e9</td>
<td>0.26</td>
</tr>
<tr>
<td>Compact Design</td>
<td>0.60</td>
<td>3.3</td>
<td>2.2e9</td>
<td>0.32</td>
</tr>
</tbody>
</table>

*Model Predictive Controls used in compact design to maximize use of available NH₃, and minimize slip.

Regulation: NOx < 0.4, NH₃ < 10, PN < 1e12
NRTC Results for Downsped Mode Using Compact Design

Aftertreatment Controls Calibration Unchanged between Engine Operating Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Layout</th>
<th>NOx [g/kWh]</th>
<th>Weighted</th>
<th>% NOx</th>
<th>Max.TP NH₃ (ppm)*</th>
<th>PN #/kWh</th>
<th>N₂O (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>Linear</td>
<td>0.29</td>
<td>96.8</td>
<td>4.3</td>
<td>9.0e9</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>Compact</td>
<td>0.11</td>
<td>98.8</td>
<td>3.3</td>
<td>2.2e9</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Downsped</td>
<td>Compact</td>
<td>0.08</td>
<td>99.0</td>
<td>2.9</td>
<td>2.2e9</td>
<td>0.22</td>
<td></td>
</tr>
</tbody>
</table>

Regulation: NOx < 0.4, NH₃ < 10, PN < 1e12

Compact Design Conventional (blue) vs. Downsped (green)
Operating Mode Warm NRTC Temperature and Cumulative

Compact Design SCRF® inlet Temps similar, Downsped 20°C advantage for final 400s
GHG Emissions over NRTC Using Downsped Mode

- About 10% of total GHG was N₂O made by the SCR system
- Increased NOx conversion over ETI engine did not increase N₂O
- 20% Lower GHG obtained using new SCR system on downsped engine

N₂O = 298* CO₂
Additional Cycles for Simulated In Use Work Analysis

✓ Remainder of presentation to focus on 3 of these applications:

- **Backhoe**
- **On-road Truck (WHITC)**
- **Braunschweig (bus)**
- **Wheel Loader**
- **Articulated Truck**
- **Ag (tractor)**

➢ **Wide variety of cycles represent the range of uses of HDD engines on mobile applications.**
### Comparison Between Regulatory and Vocational Cycles

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Compact Design SCRF® Inlet Average T (°C)</th>
<th>Percentage of time under 250°C</th>
<th>Cycle Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRTC</td>
<td>291</td>
<td>&lt; 45%</td>
<td>20</td>
</tr>
<tr>
<td>On road truck (WHTC)</td>
<td>229</td>
<td>~ 80%</td>
<td>30</td>
</tr>
<tr>
<td>Bus</td>
<td>207</td>
<td>100%</td>
<td>29</td>
</tr>
<tr>
<td>Articulated Truck</td>
<td>384</td>
<td>0%</td>
<td>25</td>
</tr>
</tbody>
</table>

The average SCRF® inlet temperatures for WHTC and Bus cycles represent a real challenge for NOx conversion.

WHTC Performance using Compact Design

- Colder exhaust of WHTC vs. NRTC, increases challenge to AT performance
- >97% NOx conversion

<table>
<thead>
<tr>
<th>Mode</th>
<th>NOx [g/kWh]</th>
<th>Max.TP NH₃(ppm)</th>
<th>PN #/kWh</th>
<th>N₂O (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EO</td>
<td>Weighted % NOx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>9.5</td>
<td>0.26</td>
<td>97.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Downsped*</td>
<td>8.8</td>
<td>0.24</td>
<td>97.2</td>
<td>9.4*</td>
</tr>
</tbody>
</table>

SCRF Inlet temperatures
- WHTC
- NRTC

**Note:**

- * indicates optimized conditions.
Simulated In Use Testing Using Compact Design

- Local transit bus done in Braunschweig, Germany
- Cat® 725 Articulated Truck in Peterlee, UK

Procedure:
- Run engine in test cell following simulated vocational cycle
- Follow cold start procedure of NRTC for first test of the day using vocational cycle (“Cold Cycle”)
- Repeat the vocational cycle immediately after completing the cold cycle (“Warm Cycle”) – no soak time
- Continue repeating vocational cycle until change in NOx tailpipe levels < 5% between two contiguous runs (“Nth Cycle”)
- Replicate Nth cycle to fill out 8 hours of operation data
- Generate a set of “work based windows” for analysis based on this combined data set
Bus Cycle: Cumulative TP NOx Improves With Repetition; Conventional (Dashed Lines) < Downsped (Solid Lines)

Vocational Cycle       Operating Mode     NOx [g/kWh]               Relevant Regulation for Conformity factor
                      Cold     1st Warm Average Warm 90th percentile*
Bus                    Conventional 1.60   0.03   0.01   0.014   0.46
                      Downsped   2.36   0.46   0.38   0.39
Articulated Truck     Conventional 1.06   0.25   0.30   0.35   0.40
                      Downsped   1.08   0.25   0.29   0.25

*90% of all Work Based Windows have TP NOx < this value

- Coldest (Bus) and Hottest (Articulated Truck) Cycles pass WBW type NOx requirements
- All other vocational cycles evaluated passed WBW type NOx requirement
Summary and Conclusions

- An SCR on Filter (SCRF®) based aftertreatment system was evaluated using a high efficiency engine operating in either conventional or downsped mode.
- EU Stage V and Euro VI regulations for NOx, PN, and NH₃ slip were met over each operating mode.
- In-use compliance was demonstrated using WBW type analysis over relatively hot (Articulated Truck) and cold (Bus) vocational cycles over each operating mode.
- The downsped mode reduces GHG emissions due mainly to lower BSFC while simultaneously holding N₂O formation constant over the AT system despite increased NOx conversion.
- >97% NOx conversions for most applications were similar over both operating modes, despite downsped mode exhaust being colder. Conversions over the downsped bus cycle were lower than conventional mode due to increased %cycle time spent below 200°C (50% vs. 70%), where urea dosing was limited.
- A versatile Cu SCRF® based aftertreatment system has been developed to provide high NOx conversion and PN reduction to meet future emission regulations on advanced engine technologies.
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