Measured Emissions from a Dedicated NRMM Engine fitted with Particulate and NOx Emissions Controls

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Association for Emissions Control by Catalyst (AECC) AISBL

AECC members: European Emissions Control companies

Technology for exhaust emissions control on all new cars (OEM and Aftermarket) and an increasing number of commercial vehicles, non-road applications and motorcycles.
Content

- Engine and Emissions Control System, Test Cycles
- Urea Injection Calibration and Urea Consumption
- Sampling System and Preconditioning Protocols
- Measured Regulated and Unregulated Emissions
- Summary and Conclusions
Test Engine

- Industrial prototype engine developed for Stage IIIB, provided by OE manufacturer.
  - 4 cylinder, 4.4 litre engine, 93 kW at 2200 rpm.
  - High Pressure Common Rail (set at 160 MPa).
  - Variable Geometry Turbocharger.
  - Cooled EGR.
  - No emission control system supplied with the engine.

- Engine calibration.
  - Engineering company provided a slightly modified Stage IIIB engine calibration for engine-out emissions to be compatible with ECS on the NRTC.
  - Engine-out emissions: PM ~35 mg/kWh and NOx ~3.0 g/kWh.

- All calibration and test work used Carcal Reference 725A diesel fuel (max. 10ppm S), low ash 15w-40 engine lubricant and AdBlue® aqueous urea to ISO.
Emissions Control System (ECS)

- Complete emissions control system supplied by AECC.
- Oxidation catalyst (DOC), catalysed particulate filter (C-DPF) and urea-SCR with ammonia slip catalyst (ASC).
- System hydrothermally aged for 200 hours at 600°C.
- Bosch advanced airless urea dosing system (DeNOx 2.2).
- NOx sensors at engine-out (input for dosing control) and downstream of the SCR system as monitor; not closed loop.
- Limited urea nozzle position optimization.
Exhaust System Layout

- Exhaust system lengths chosen to be representative of space available in typical industrial machine.
- Pipes insulated between ECS components to represent expected use of double skinned pipes and other insulation by OEMs.
- Urea dosing nozzle ~ 600mm upstream of SCR – flow optimisation could probably reduce this length with similar distribution.
Test Cycles run

- **NRTC** - World Harmonised Non-Road Transient Cycle.
  - 20 minutes soak period and 10% cold weighting.
- **NRSC** - World Harmonised Non-Road Steady-State Cycle (ISO-8178 C1).
- **ISO-8178 D2 Cycle.**
- **ISO-8178 F and F-mod Cycles.**
- 3 selected Not-to-Exceed points (based on US practice).

Note: Urea Injection was not specifically calibrated for D2, F and F-mod cycles.
Urea Calibration and Consumption

• Urea Injection Calibrated for NRTC and NRSC C1.
  – Efficiency maps dependent on NH$_3$ loading, average brick temperature, exhaust flow rate.
  – Thermal model of ECS system calibrated in order to accurately predict SCR temperature within DCU.
• Urea consumption has been calculated over NRSC and NRTC by integrating the DeNOx dosing rate logged at 1Hz.
• Values correspond well to expected consumption given the NOx reduction over the cycles (2.5 - 3.0 g/kWh).

<table>
<thead>
<tr>
<th>Emissions Test</th>
<th>BSFC [g/kWh]</th>
<th>urea as % fuel (by volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRSC 8 mode</td>
<td>217</td>
<td>2.4</td>
</tr>
<tr>
<td>NRTC Cold</td>
<td>239</td>
<td>2.1</td>
</tr>
<tr>
<td>NRTC Hot</td>
<td>231</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Urea Injection Calibration for NRTC

- Urea dosing starts ~210s into cold NRTC (SCR T > 190°C).
- Dosing in hot NRTC interrupted when temperature falls.

**Cold NRTC**
- Urea dosing starts when SCR temperature > 190°C

**Hot NRTC**
- Urea dosing interrupted when SCR inlet temperature < 180°C
Preconditioning Procedures

• Test Order
  - Cold start tests were the first test every day followed by a soak period then the hot-start ‘partner’ test.
  - NRSC-C1 always preceded NRSC-D2, and NRSC-C1 always followed a dedicated intermediate preconditioning.
  - NRSC-F always followed a cold and hot start pair and always preceded Fmod and the three NTE tests.
  - Preconditioning run evening before each cold-start test.

• Preconditioning for day-to-day repeatability:
  - Operation at rated power with no dosing emptied stored ammonia and passively regenerated the DPF.
  - DPF loaded with soot by running at 1800 rpm, 120 Nm for ~50 minutes to achieve max. 0.1 g/litre DPF loading.
  - Finally, the urea dosing enabled for the last 7 minutes at the same operating condition to store 3.5 g of ammonia.
Exhaust System - Sampling Points

- Regulated gas + non-regulated gases (incl. NO₂) by FTIR.
- Particulate Mass (PM) via partial flow dilution system (MDLT).
- Temperatures (T) and pressure (P).
- Particle number measurements to HD PMP protocol.
- Dynamic Mobility Spectrometer for particle size analysis.

This section replaced with by-pass pipe for engine-out measurements.
Regulated Emissions Measurement

- Triplicate tests were carried out for tailpipe emissions on each of the test cycles.
  - Results have been averaged for these tests and standard deviation calculated.

- Simultaneous sampling of emissions:
  - PM & PN: engine-out Horiba MDLT via bypass. post ECS Horiba MDLT.

- All tailpipe data is shown with $2\sigma$ error bars.
HC and CO Emissions

- Engine-out emissions are below limit for most cycles.
NOx Emissions

- NOx conversion is high (85-95%) over most test cycles, limits are readily met with the exception of NRSC F & Fmod which are close to the limits.
- NOx conversion efficiency highly dependent on test cycle temperature.
Profile of Nitrogen Species through ECS - Weighted NRTC and NRSC C1

NO to NO\textsubscript{2} conversion across the DOC+DPF

NO\textsubscript{x} reduction ~93%.

NO\textsubscript{2} well below engine-out levels at tailpipe

NO\textsubscript{x} reduction ~91%
PM Emissions

- PM reduction across DPF meets limits with considerable margin over all cycles.
Particle Number Results (PMP)

- Cold and hot transient cycle tailpipe PN results well below $10^{11}$/kWh.
- Steady state cycles (NRSC variants) all at PN levels $\sim 10^{11}$/kWh or below.
- NTE points PN emissions all $>10^{11}$/kWh and NTE #2 $>10^{12}$/kWh.
- Engine-out PN from all cycles ranged from $\sim 6 \times 10^{13}$ to $\sim 3 \times 10^{14}$/kWh.

- Tailpipe PN range $\sim 10^{10}$ to $<1.8 \times 10^{12}$
- Engine-out PN range $\sim 10^{13}$ to $>10^{14}$
Further Optimisation Potential

• Thermal Management.
  - Further improvement of SCR efficiency over the cold phase of the NRTC is expected to offer a further small benefit in overall weighted NRTC emissions.

• System design.
  - Component volumes and integration would be optimised for a production application.

• System optimisation.
  - Including urea dosing and distribution.

• Engine calibration.
Summary and Conclusions

- A state-of-the-art engine system comprising a low emissions industrial engine designed for Stage IIIB and an Emissions Control System produced substantial reductions in all regulated pollutants over a range of test cycles.
- The engine system was not fully optimised; there was no thermal management to assist with warm-up from cold starts.
- Stage IV emissions limits were met with engineering margin.
- NOx conversion efficiencies were 95% and 92% over the NRTC and NRSC C1 cycles respectively, resulting in tailpipe NOx levels of 169 and 216 mg/kWh.
- Tailpipe NO\textsubscript{2} levels were 50% or less of engine-out.
- PM conversion efficiencies were 96% and 97% over the NRTC and NRSC C1 cycles respectively, resulting in tailpipe PM levels of 1 to 2 mg/kWh (partial flow method).
- ECS efficiency for PMP Particle Numbers was >99.8% for all transient and steady state cycles.
<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>HC</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage IV Limits (mg/kWh, 56-130 kW)</td>
<td>5000</td>
<td>190</td>
<td>400</td>
<td>25</td>
</tr>
<tr>
<td>Weighted NRTC</td>
<td>13.28</td>
<td>6.76</td>
<td>168.89</td>
<td>1.70</td>
</tr>
<tr>
<td>C1 cycle</td>
<td>1.22</td>
<td>3.60</td>
<td>216.36</td>
<td>1.32</td>
</tr>
<tr>
<td>D2 cycle</td>
<td>nd</td>
<td>3.32</td>
<td>205.14</td>
<td>1.50</td>
</tr>
<tr>
<td>F cycle</td>
<td>6.05</td>
<td>8.92</td>
<td>373.31</td>
<td>2.02</td>
</tr>
<tr>
<td>NTE #1</td>
<td>nd</td>
<td>1.21</td>
<td>155.32</td>
<td>1.06</td>
</tr>
<tr>
<td>NTE #2</td>
<td>nd</td>
<td>1.96</td>
<td>134.5</td>
<td>3.19</td>
</tr>
<tr>
<td>NTE #3</td>
<td>nd</td>
<td>2.70</td>
<td>106.99</td>
<td>1.93</td>
</tr>
</tbody>
</table>

![Graph showing emissions data](image)
Thank you... OE engine manufacturer Yara International, urea supplier Ricardo UK and the AECC Members... and you for your attention.