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

Dirk Bosteels, John May, Cécile Favre - AECC
Jon Andersson, Chris Such, Simon Fagg - Ricardo

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Association for Emissions Control by Catalyst AISBL

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

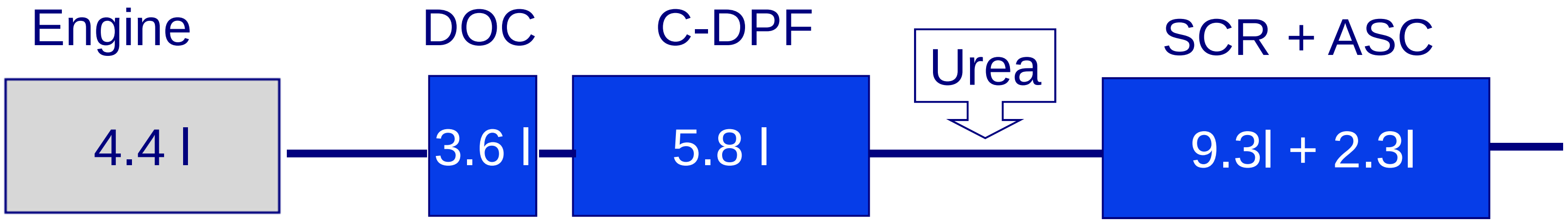
Test Engine

- 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)

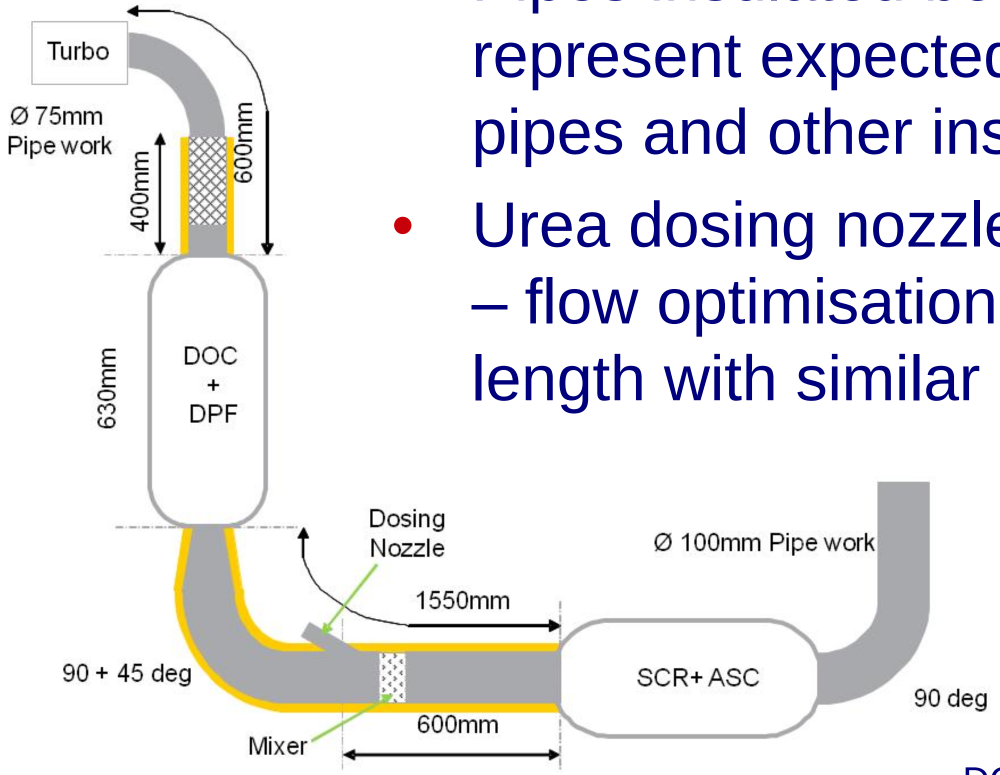
- Complete emissions control system supplied by AECC.
- Oxidation catalyst (DOC), catalysed particulate filter (C-DPF) and urea-SCR with ammonia slip catalyst (ASC).

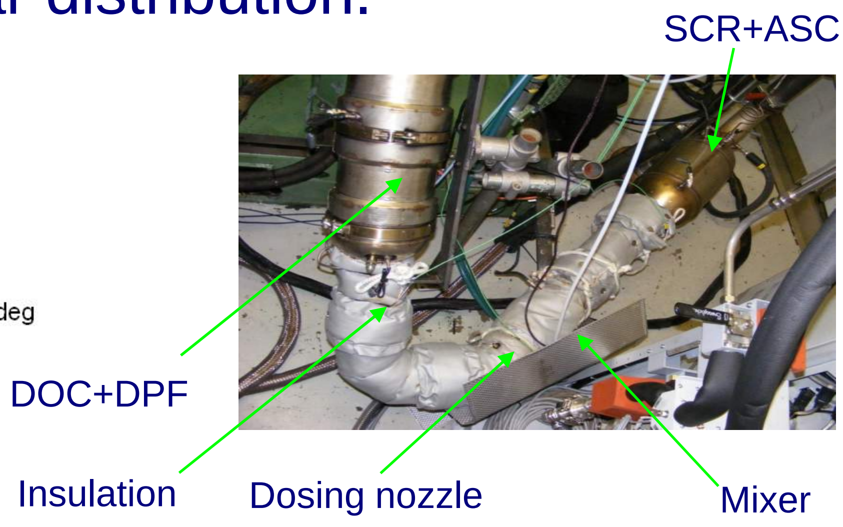


- System hydrothermally aged for 200hours at 600°C.
- Bosch advanced airless urea dosing system (DeNOx 2.2).
- NOx sensors at engine-out (input for dosing control) and downstream of the SCR system as monitor; not closed loop.
- Limited urea nozzle position optimization.

Exhaust System Layout

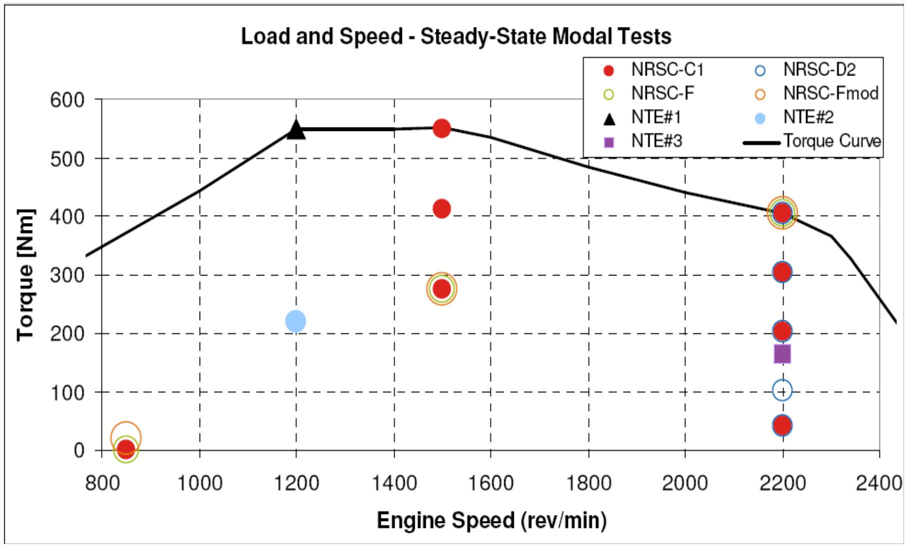
- Exhaust system lengths chosen to be representative of space available in typical industrial machine.
- Pipes insulated between ECS components to represent expected use of double skinned pipes and other insulation by OEMs.
- Urea dosing nozzle ~ 600mm upstream of SCR – flow optimisation could probably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

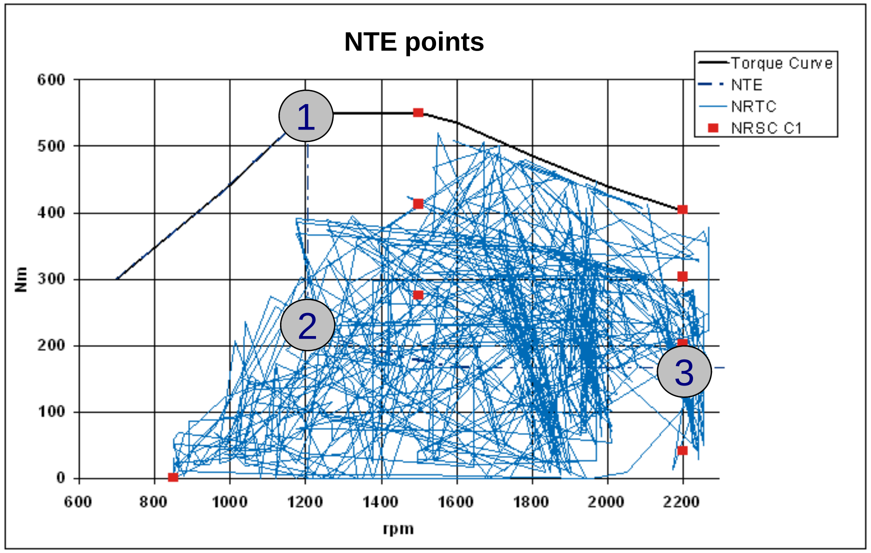




Test Cycles run

- 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.

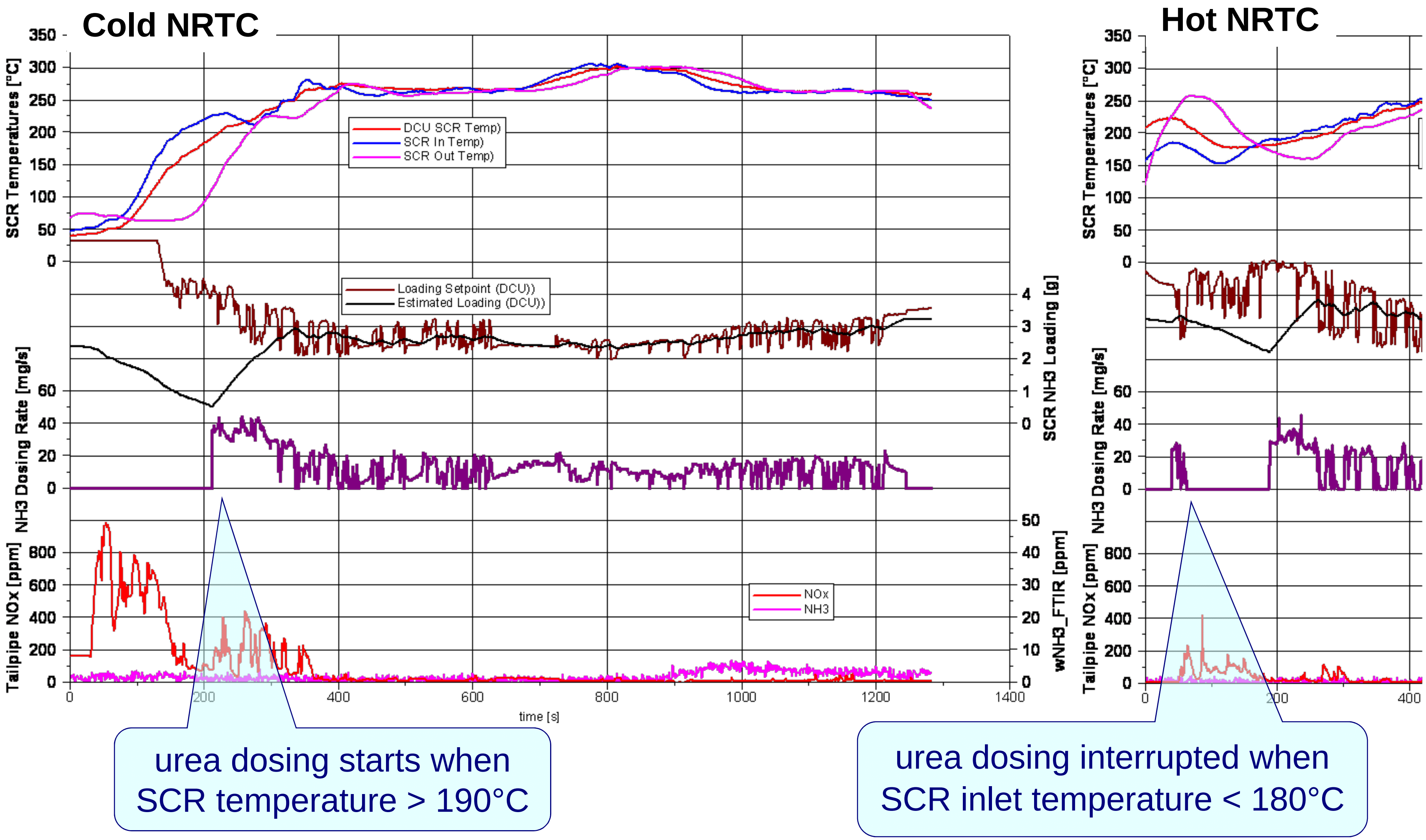
Urea Calibration and Consumption

- 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).

Emissions Test	BSFC [g/kWh]	urea as % fuel (by volume)
NRSC 8 mode	217	2.4
NRTC Cold	239	2.1
NRTC Hot	231	2.2

Urea Injection Calibration for NRTC

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



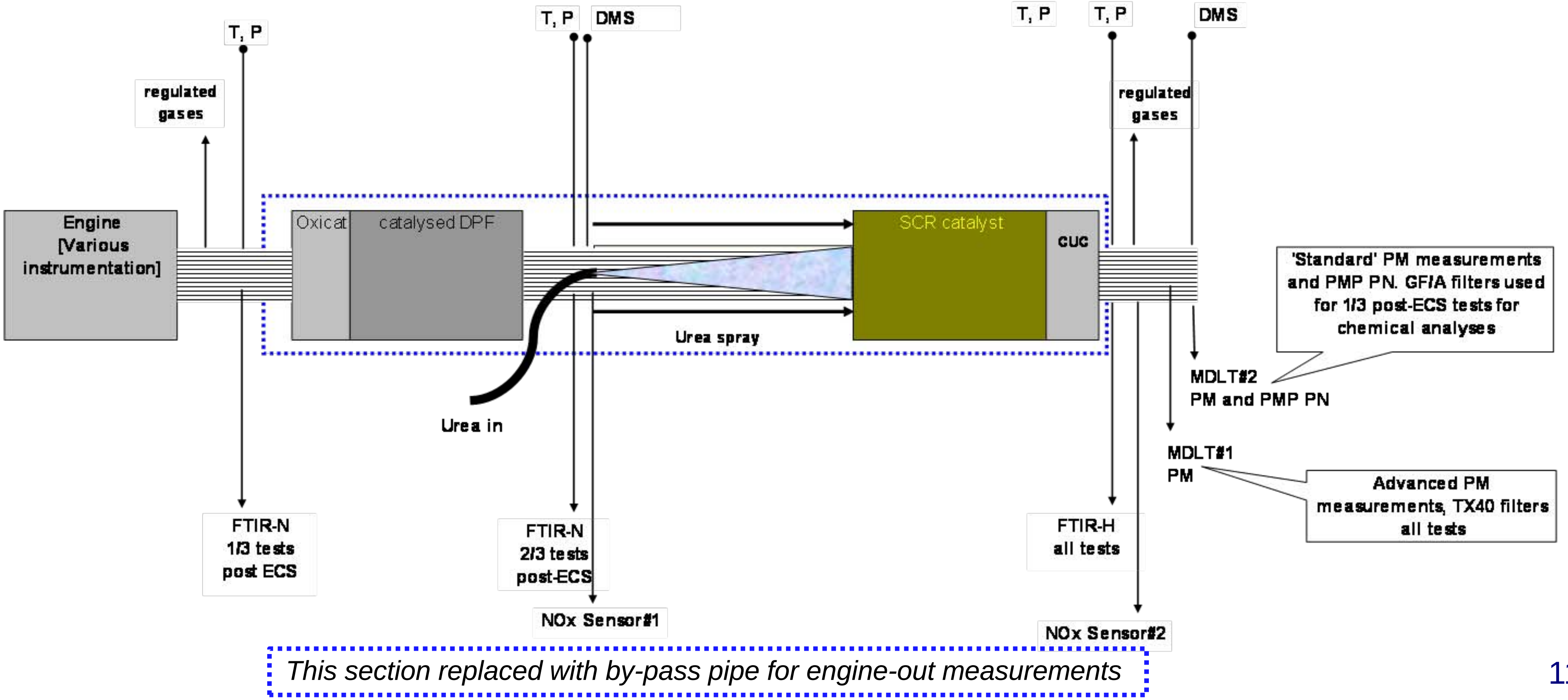
Preconditioning Procedures

- 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.

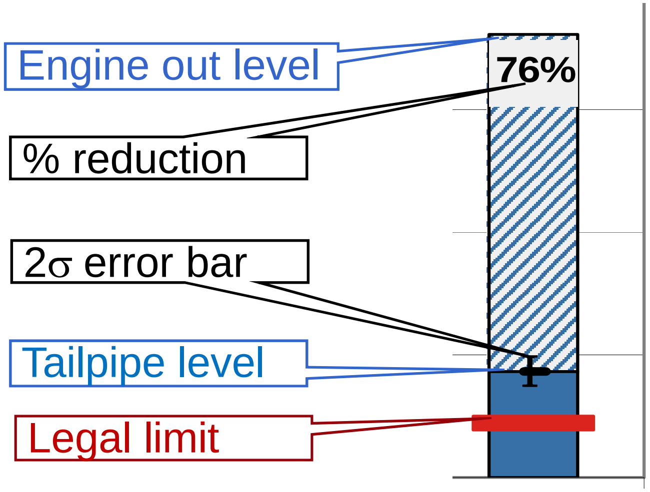
Exhaust System - Sampling Points

- Regulated gas + non-regulated gases (incl. NO_2) 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.



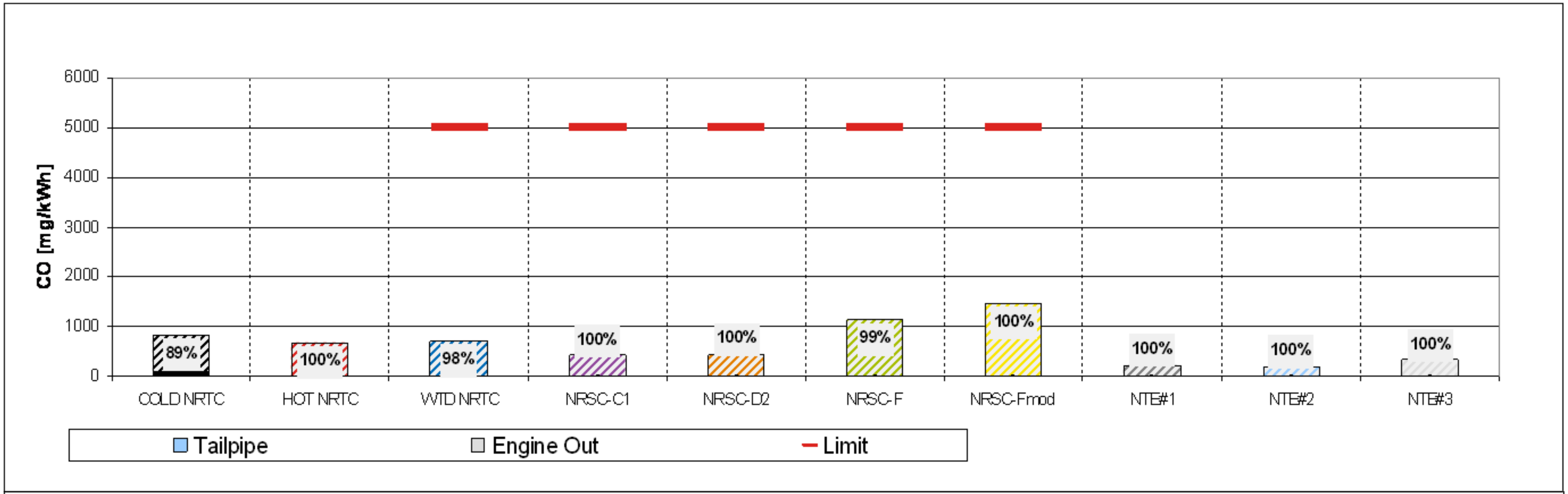
Regulated Emissions Measurement

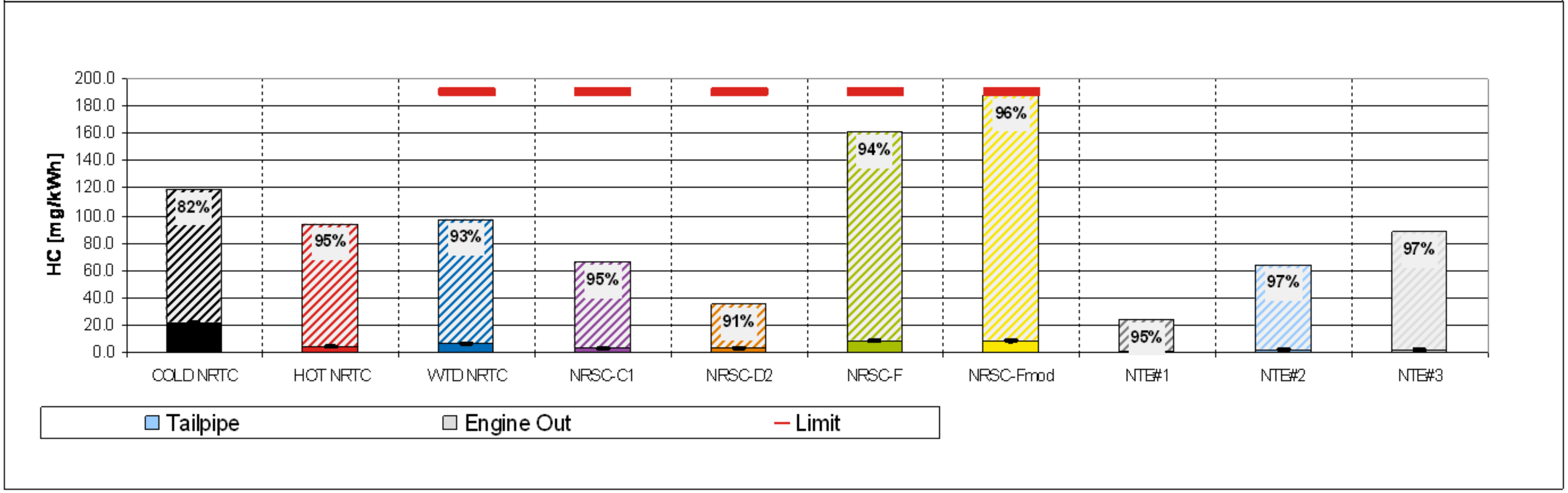
- Triplicate tests were carried out for tailpipe emissions on each of the test cycles.
  - Results have been averaged for these tests and standard deviation calculated.
- Simultaneous sampling of emissions:
  - Gaseous: engine-out raw sample.
    post ECS raw sample.
  - PM & PN: engine-out Horiba MDLT via bypass.
    post ECS Horiba MDLT.
- All tailpipe data is shown with 2σ error bars.



HC and CO Emissions

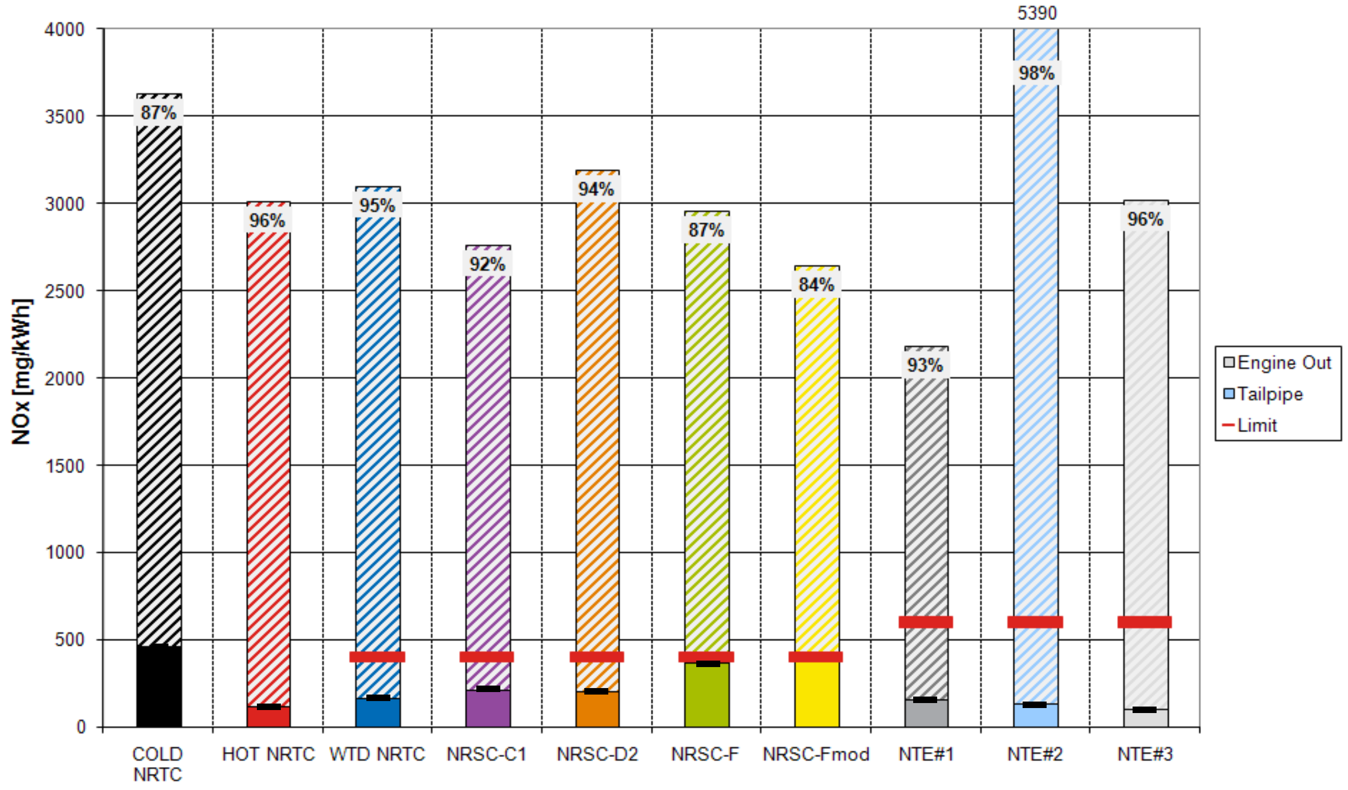
- Engine-out emissions are below limit for most cycles.



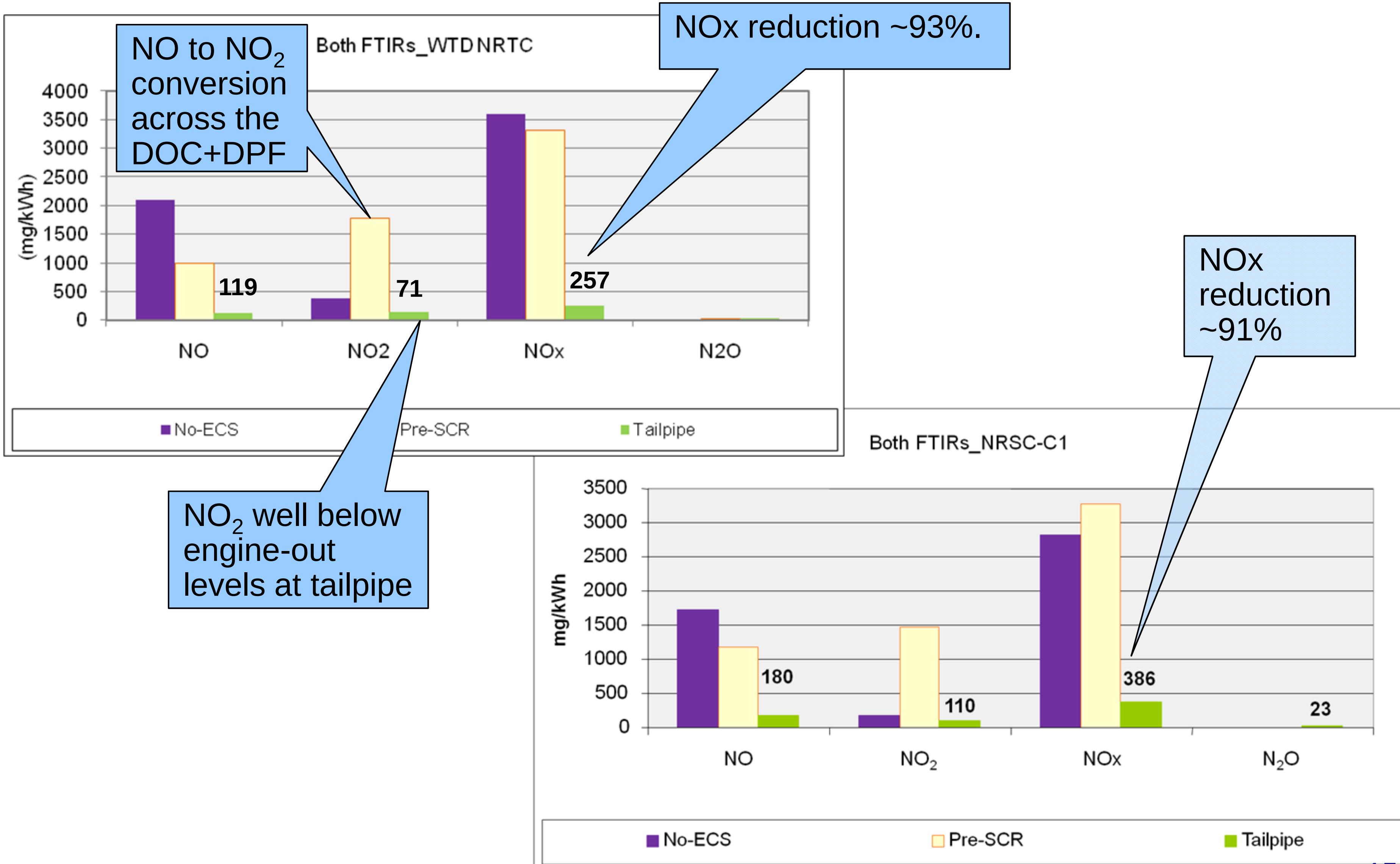


NOx Emissions

- 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.

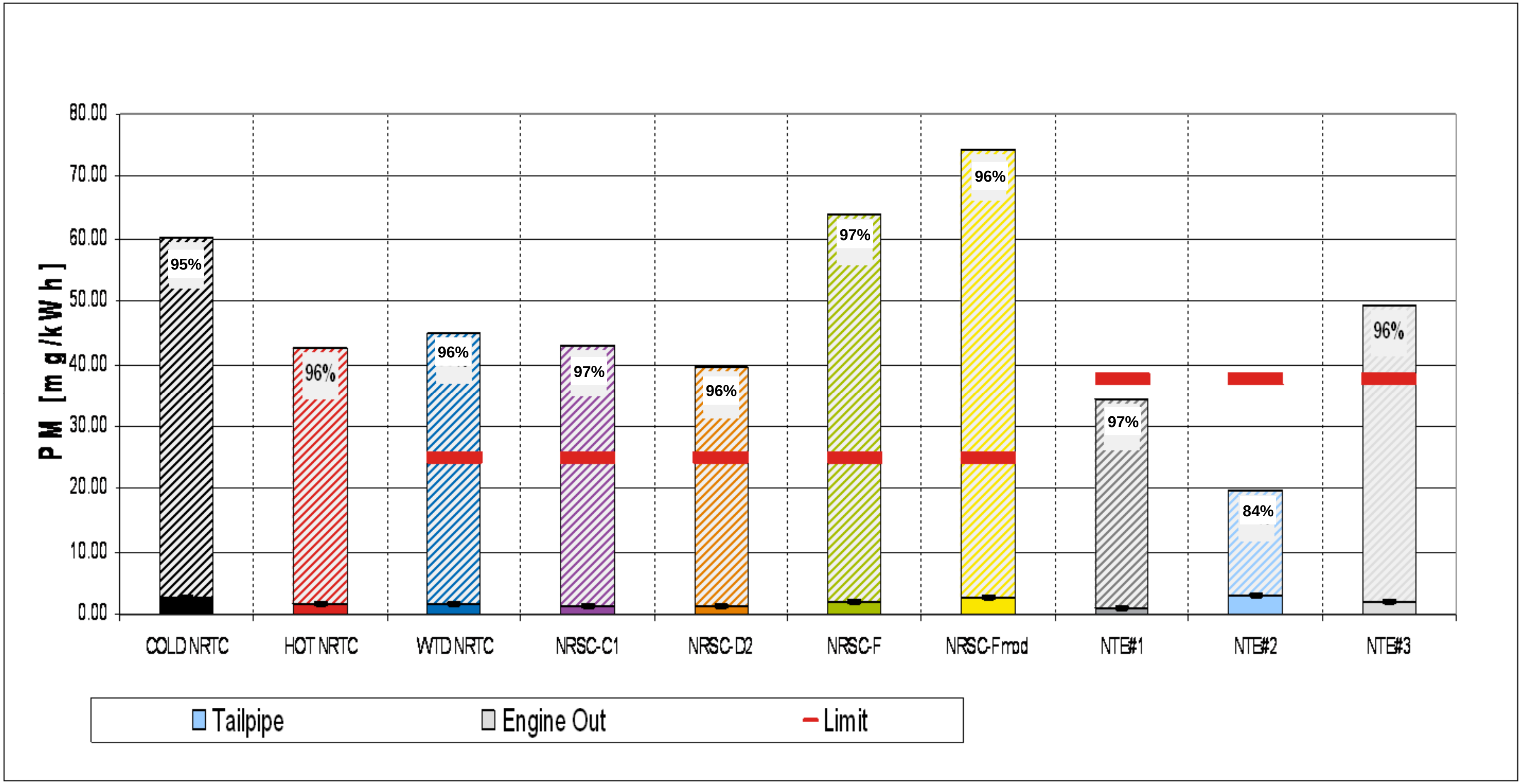


Profile of Nitrogen Species through ECS - Weighted NRTC and NRSC C1



PM Emissions

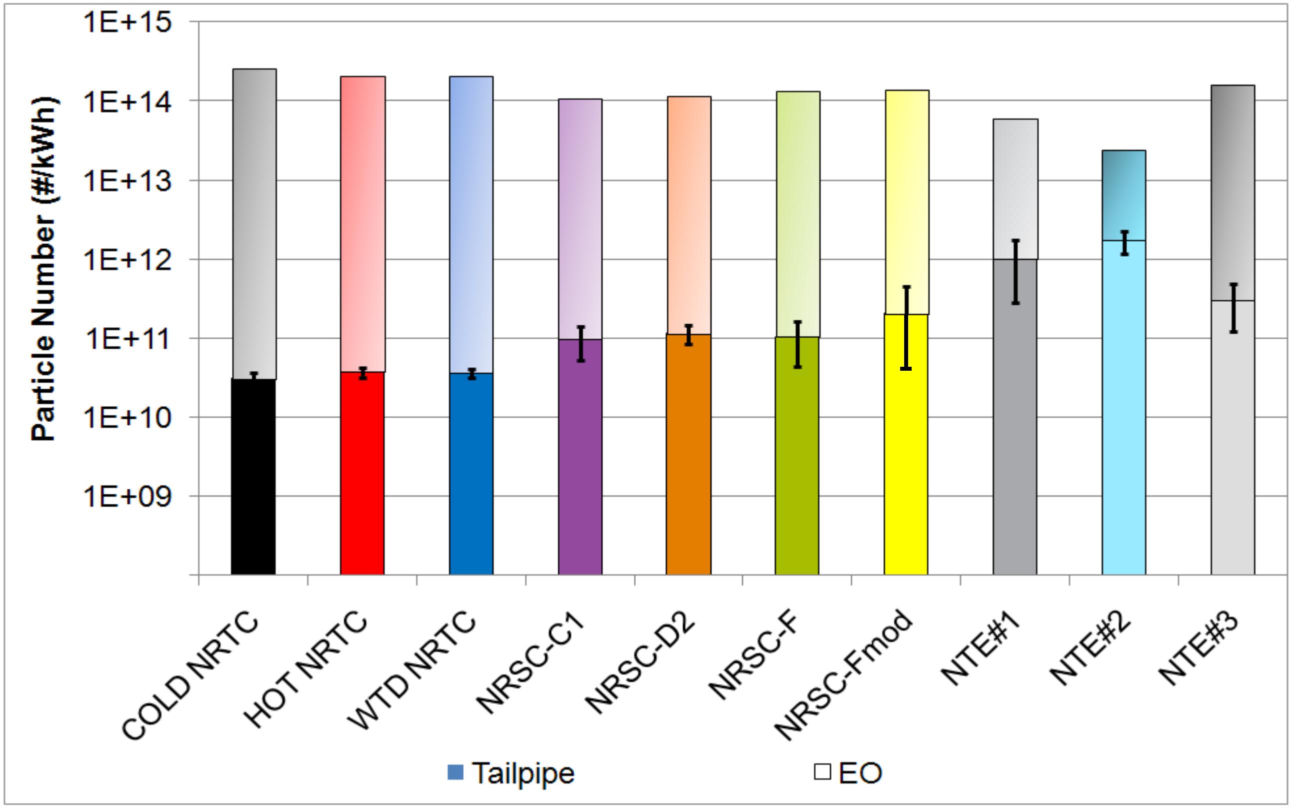
- PM reduction across DPF meets limits with considerable margin over all cycles.



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 ~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 ~6×10^{13} to ~3×10^{14}/kWh.

- Tailpipe PN range ~10^{10} to <1.8×10^{12}
- Engine-out PN range ~10^{13} to >10^{14}



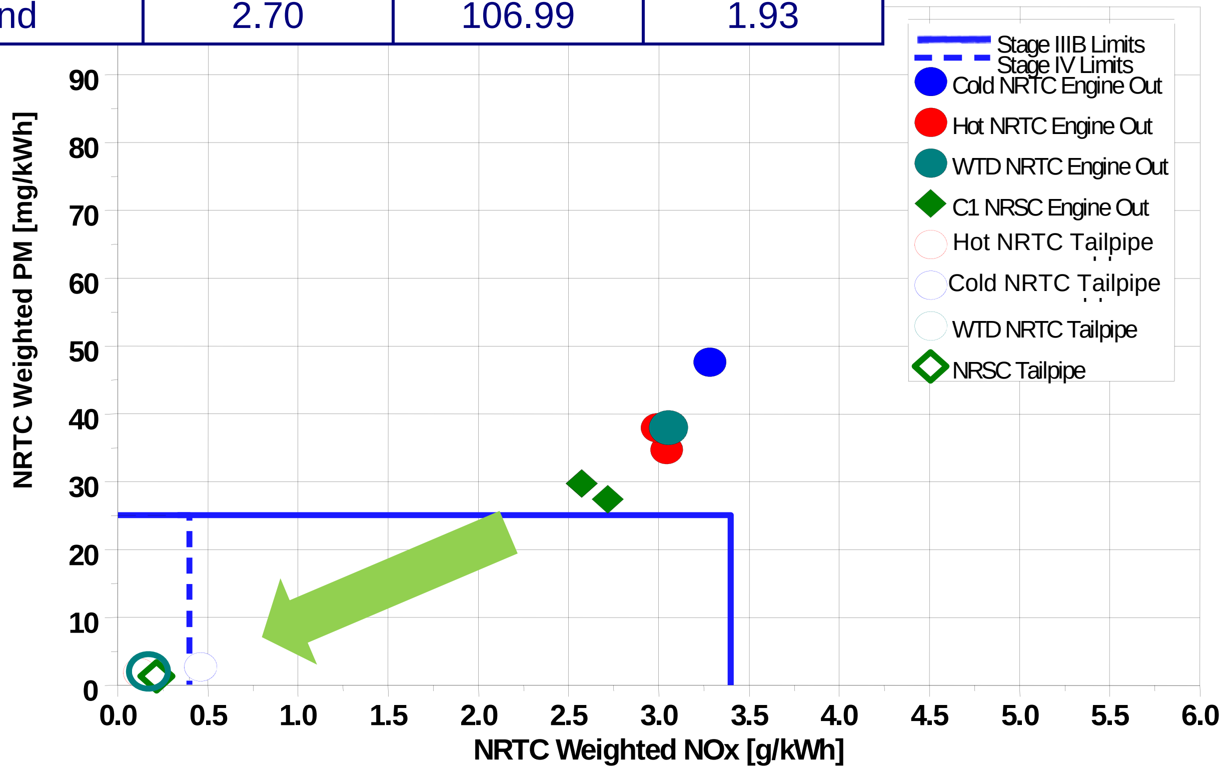
Further Optimisation Potential

- 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_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.

(mg/kWh)	CO	HC	NOx	PM
Stage IV Limits (mg/kWh, 56-130 kW)	5000	190	400	25
Weighted NRTC	13.28	6.76	168.89	1.70
C1 cycle	1.22	3.60	216.36	1.32
D2 cycle	nd	3.32	205.14	1.50
F cycle	6.05	8.92	373.31	2.02
NTE #1	nd	1.21	155.32	1.06
NTE #2	nd	1.96	134.5	3.19
NTE #3	nd	2.70	106.99	1.93



Thank you...

OE engine manufacturer

Yara International, urea supplier

Ricardo UK and the AECC Members

... and you for your attention.