

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

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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

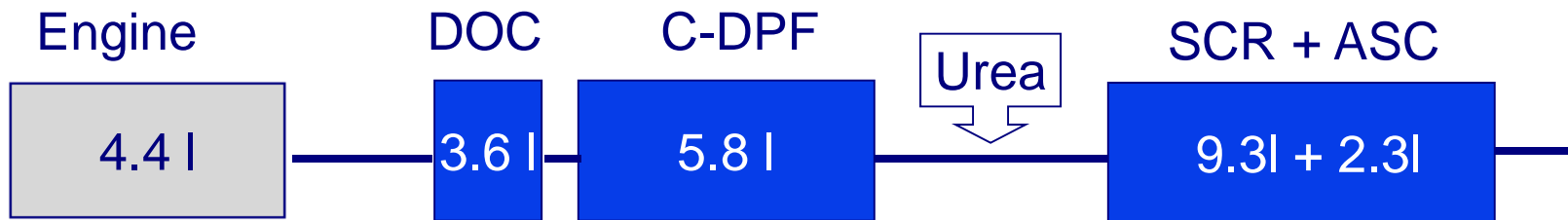
Test Engine

- 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)

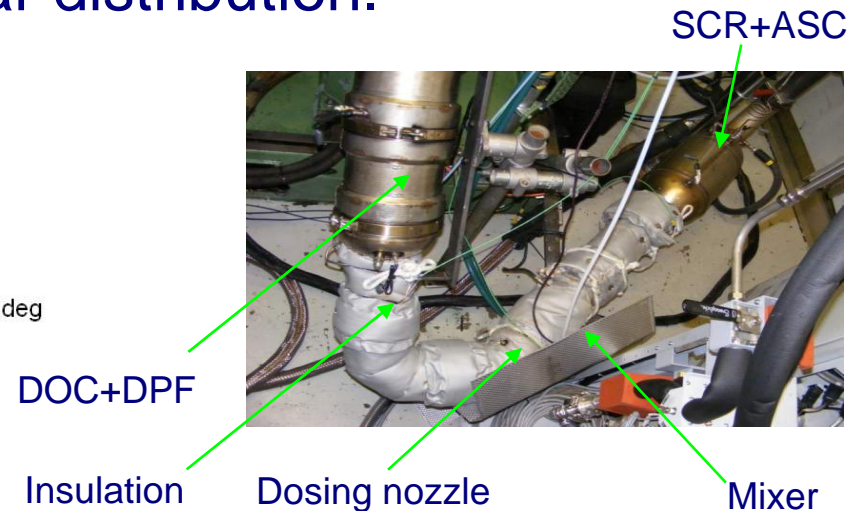
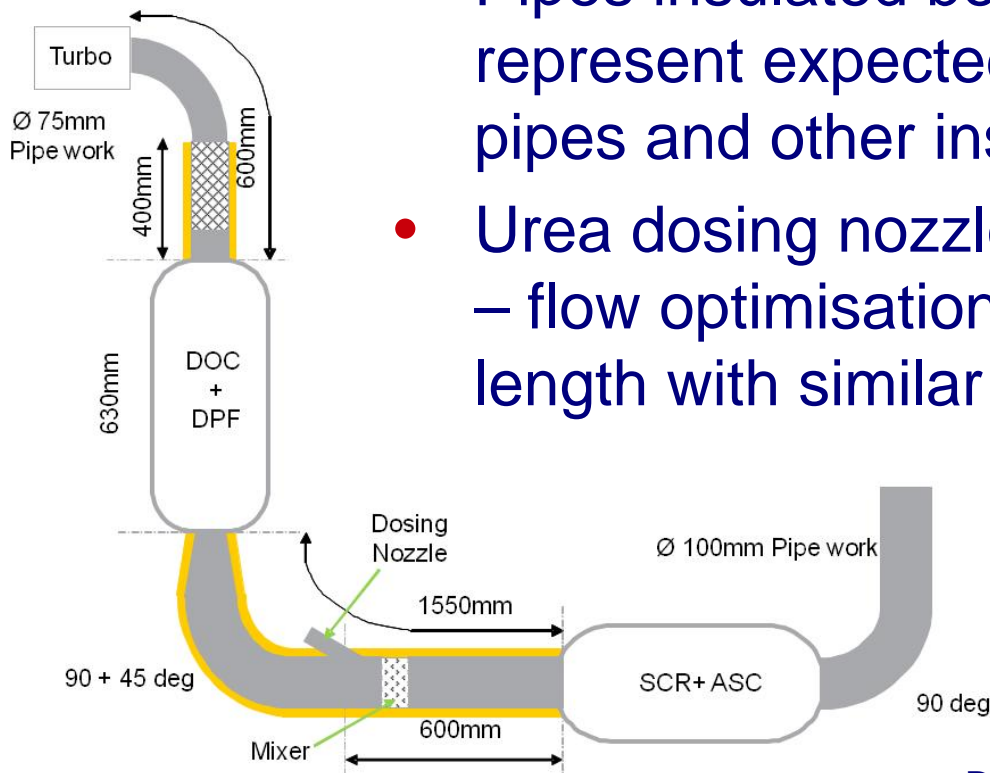
- Complete emissions control system supplied by AECC.
- Oxidation catalyst (DOC), catalysed particulate filter (C-DPF) and urea-SCR with ammonia slip catalyst (ASC).



- 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.

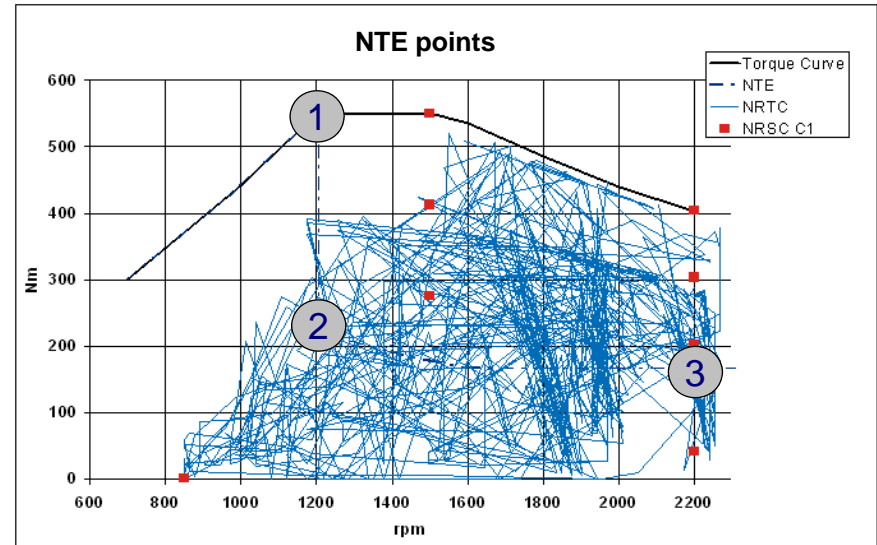
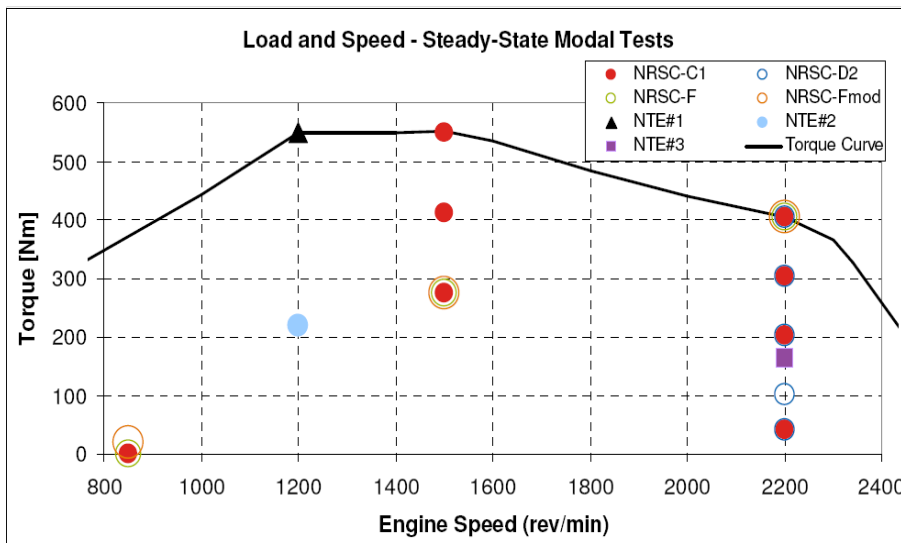
Exhaust System Layout

- 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.

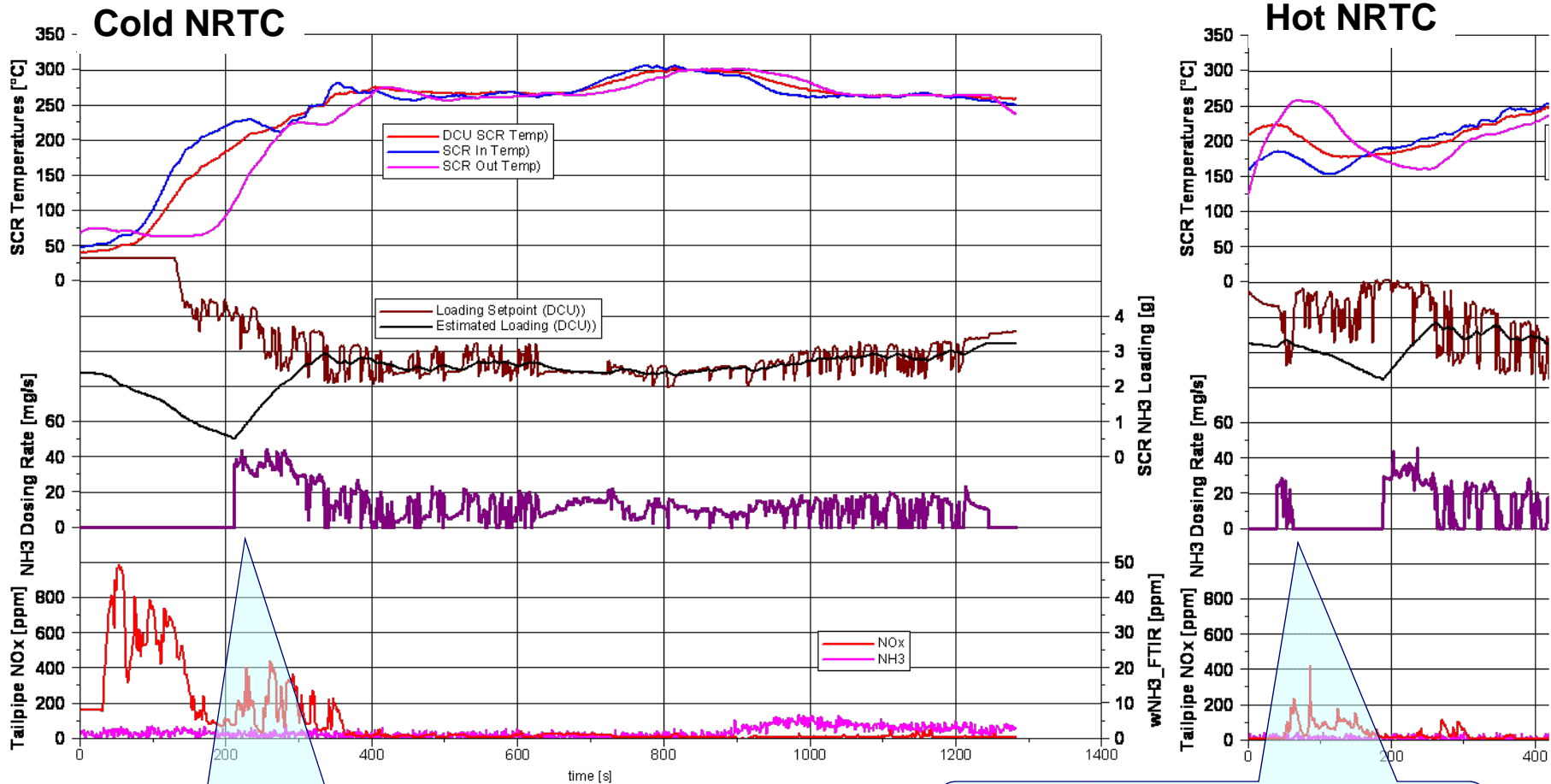
Urea Calibration and Consumption

- 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.



urea dosing starts when
SCR temperature > 190°C

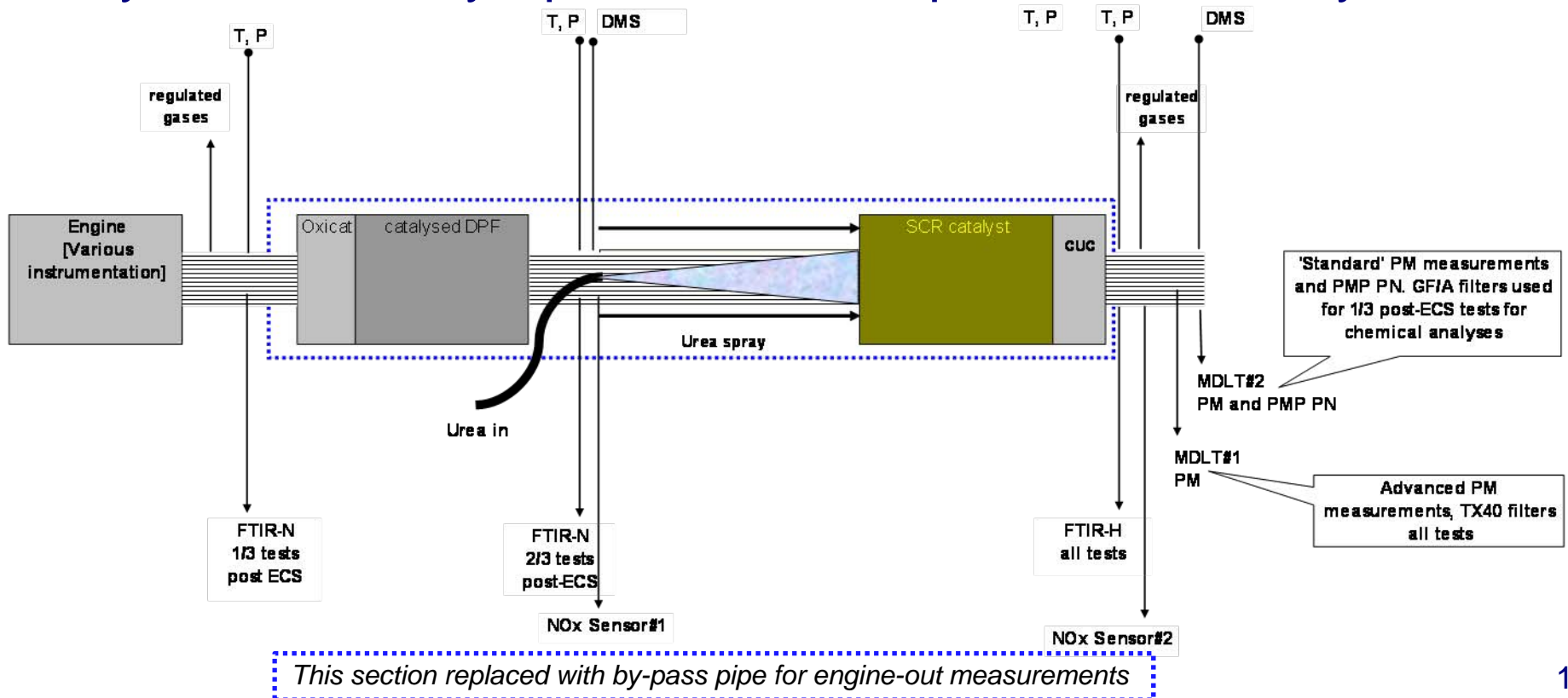
urea dosing interrupted when
SCR inlet temperature < 180°C

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.

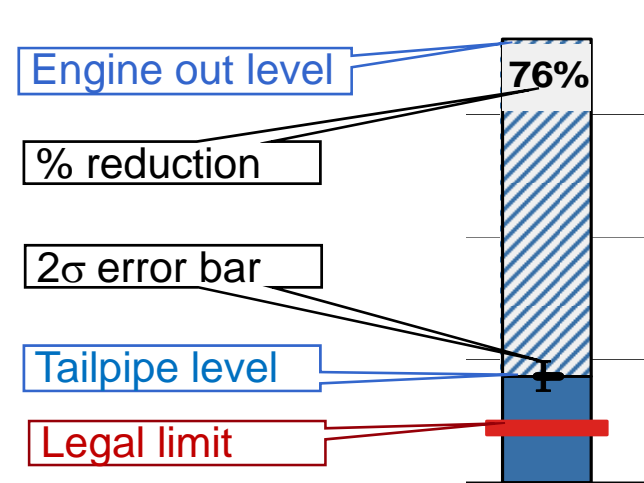
Exhaust System - Sampling Points

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



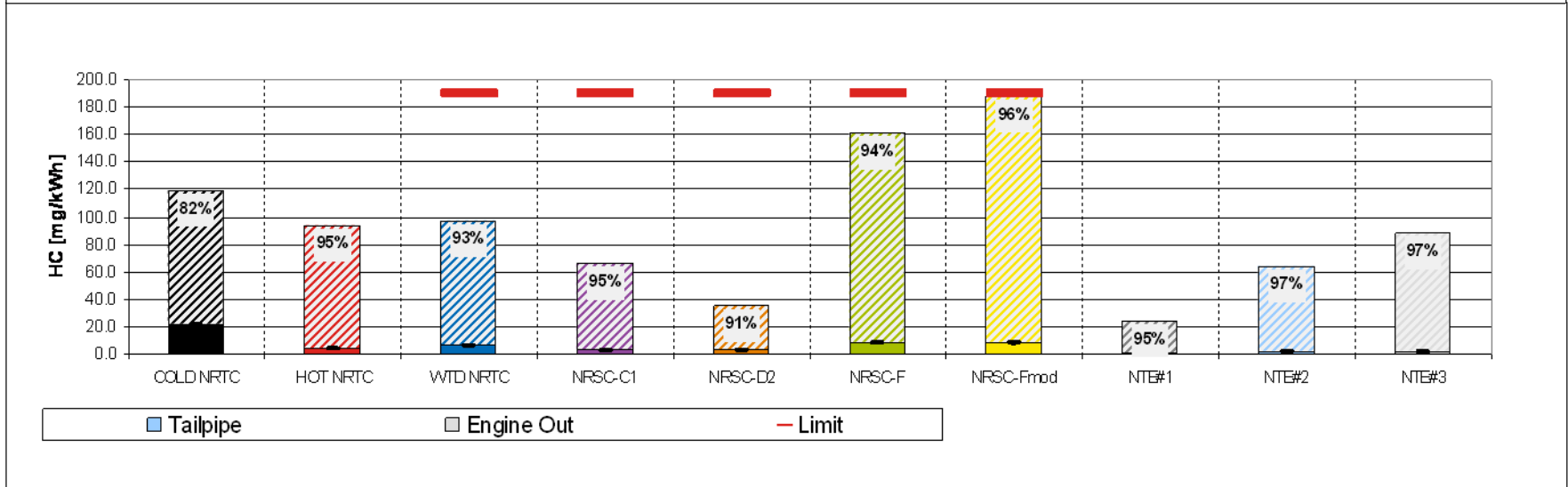
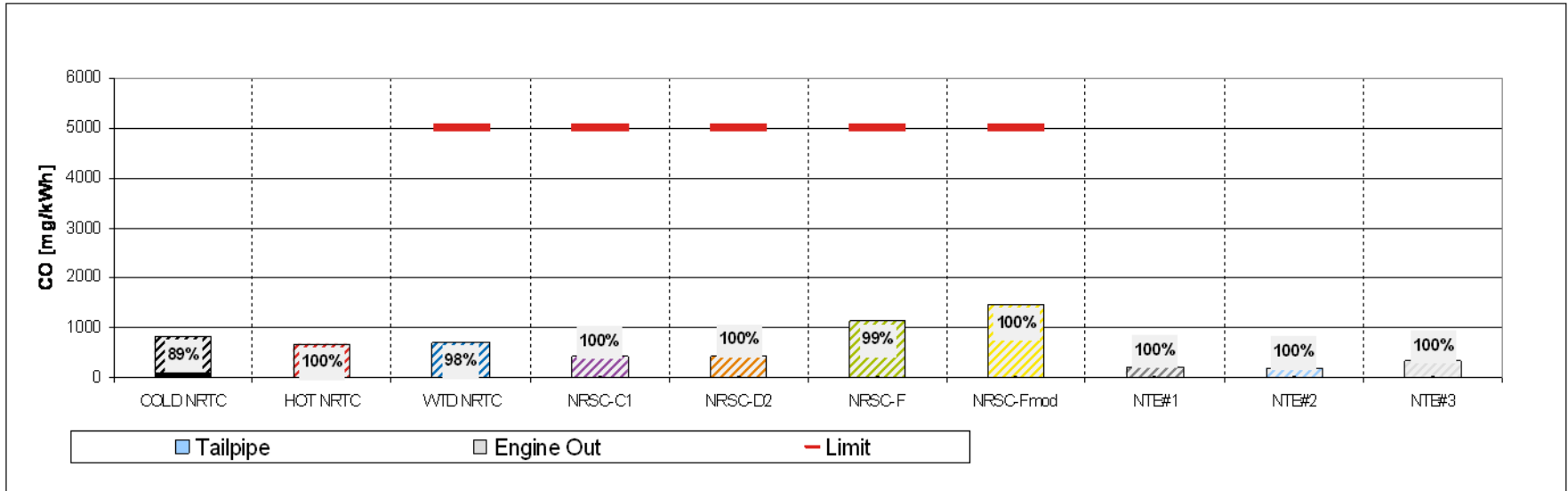
Regulated Emissions Measurement

- 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.



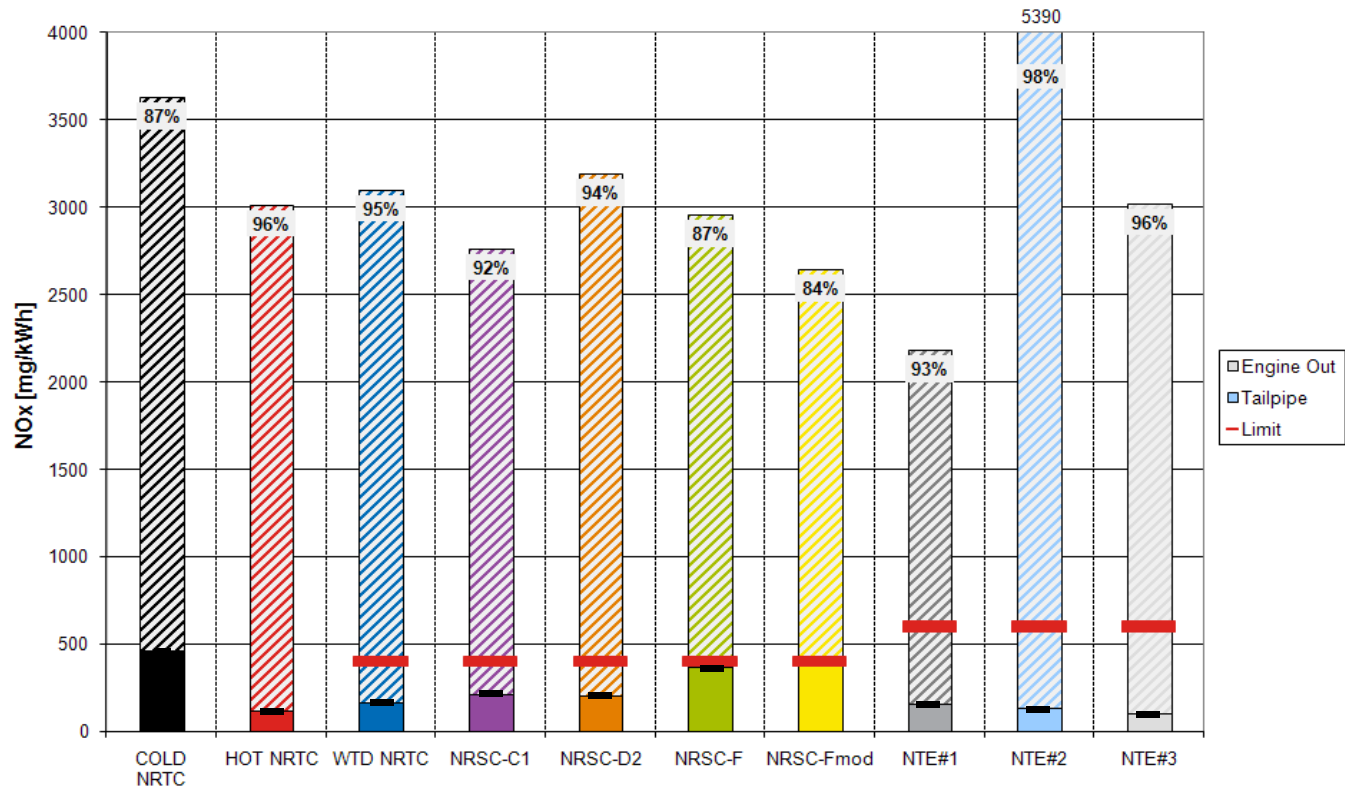
HC and CO Emissions

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

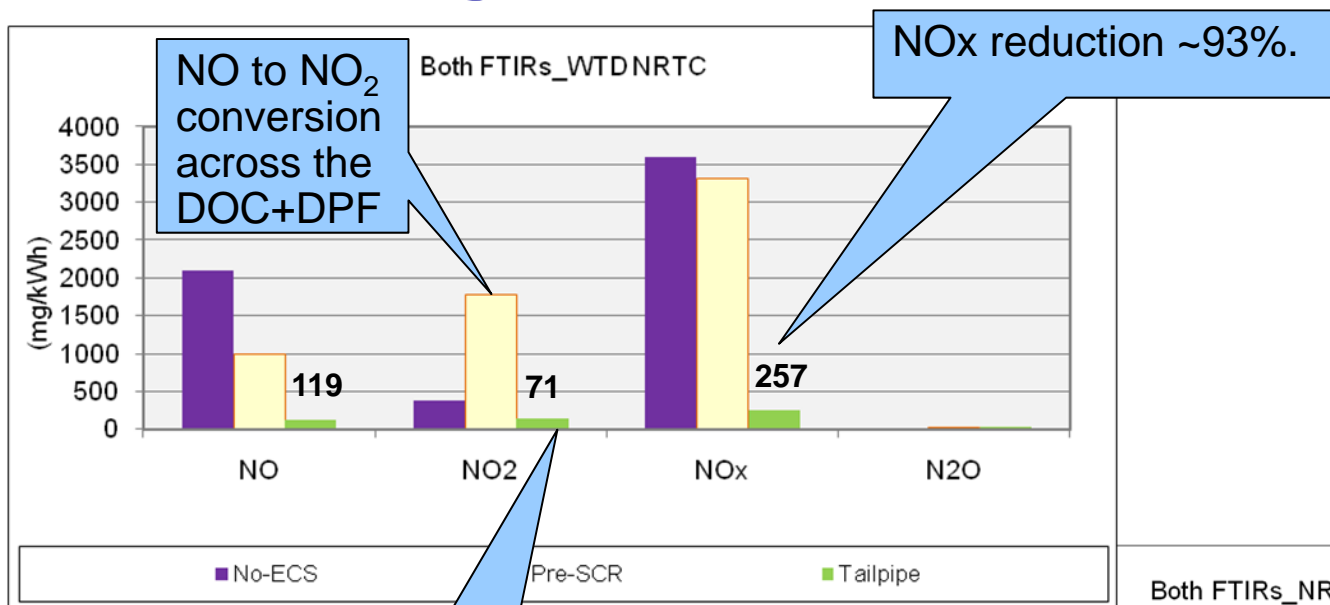


NOx Emissions

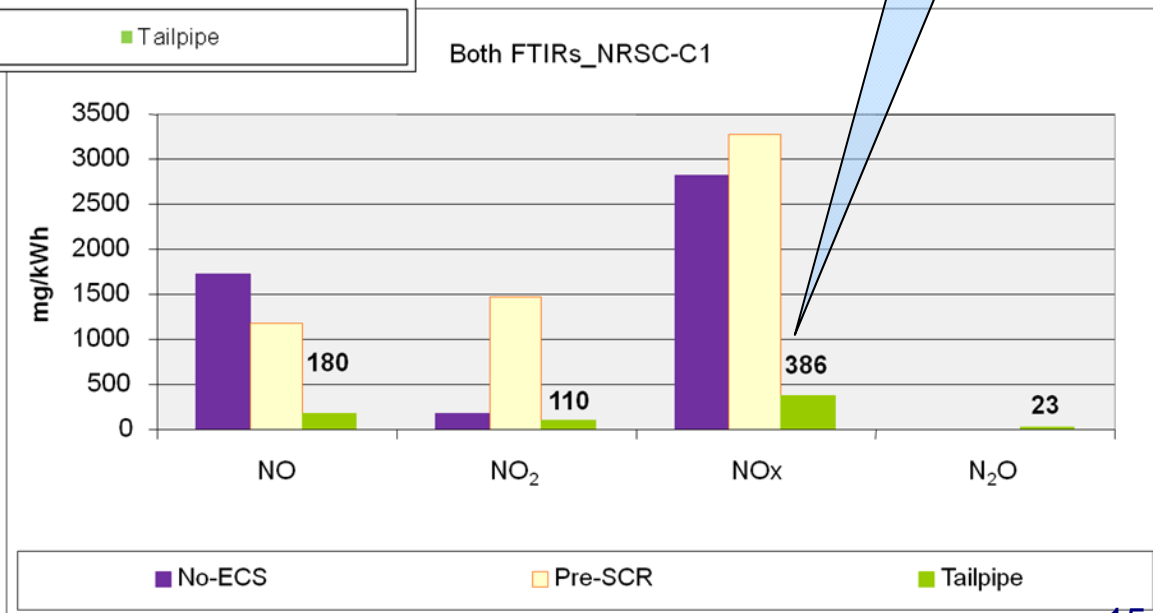
- NOx conversion is high (85-95%) over most test cycles, limits are readily met with the exception of NRSC F & Fmod which are close to the limits.
- NOx conversion efficiency highly dependent on test cycle temperature.



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

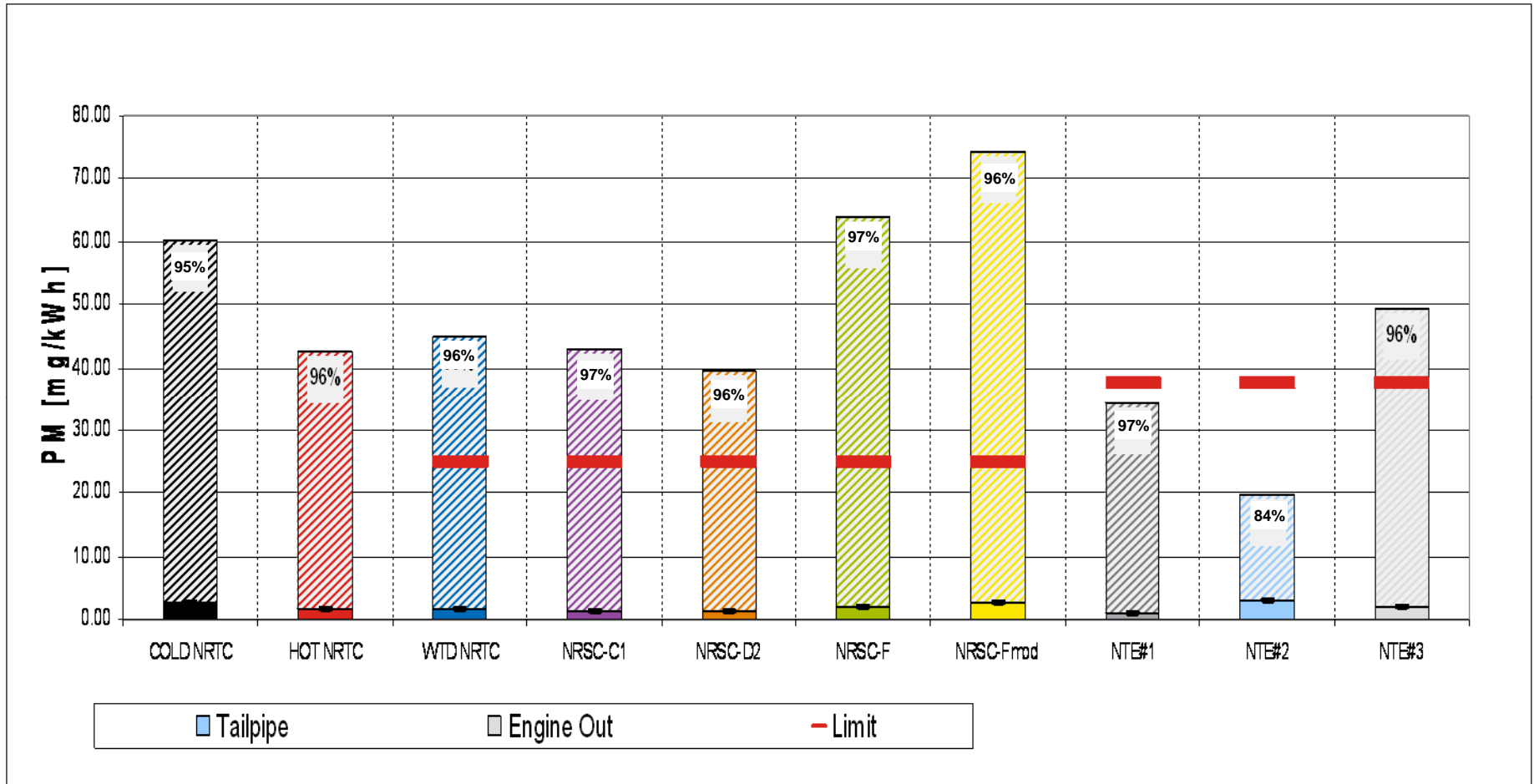


NO₂ well below engine-out levels at tailpipe



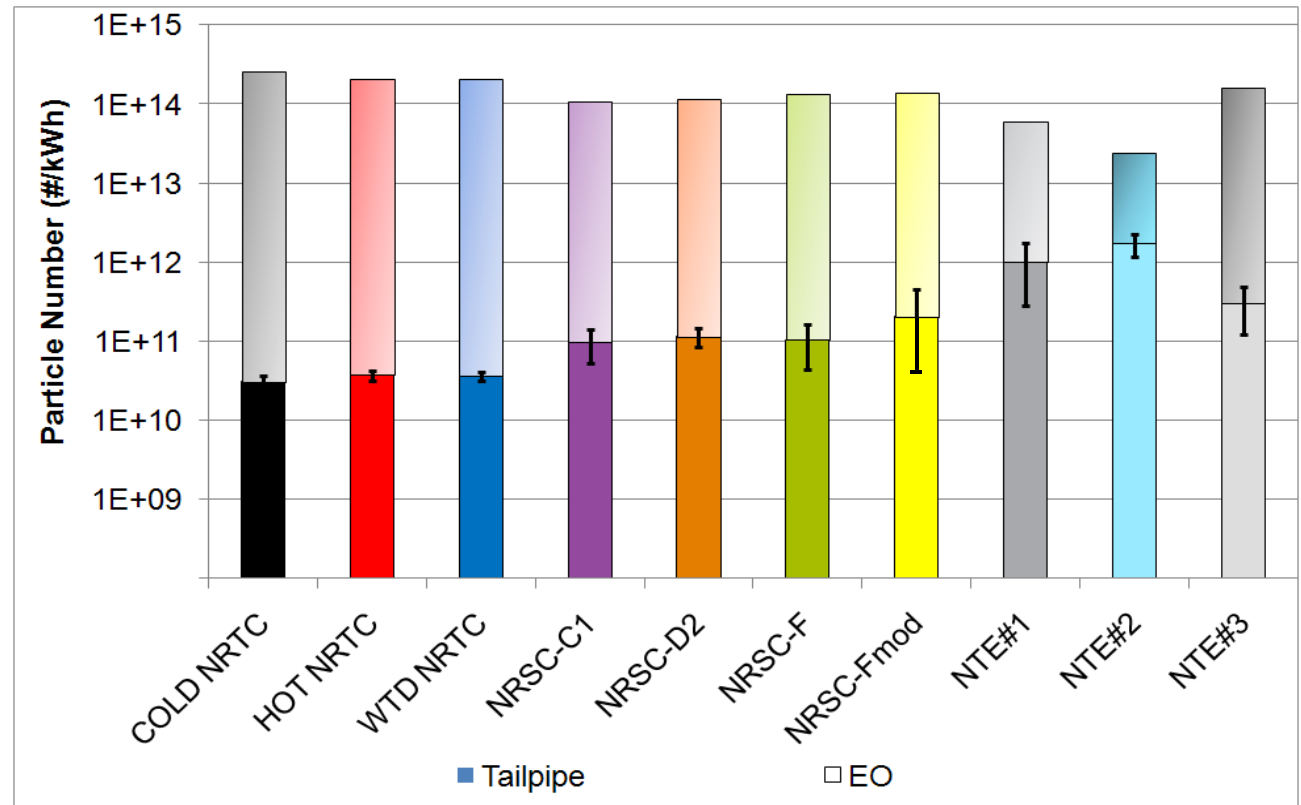
PM Emissions

- 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 $>10^{14}$



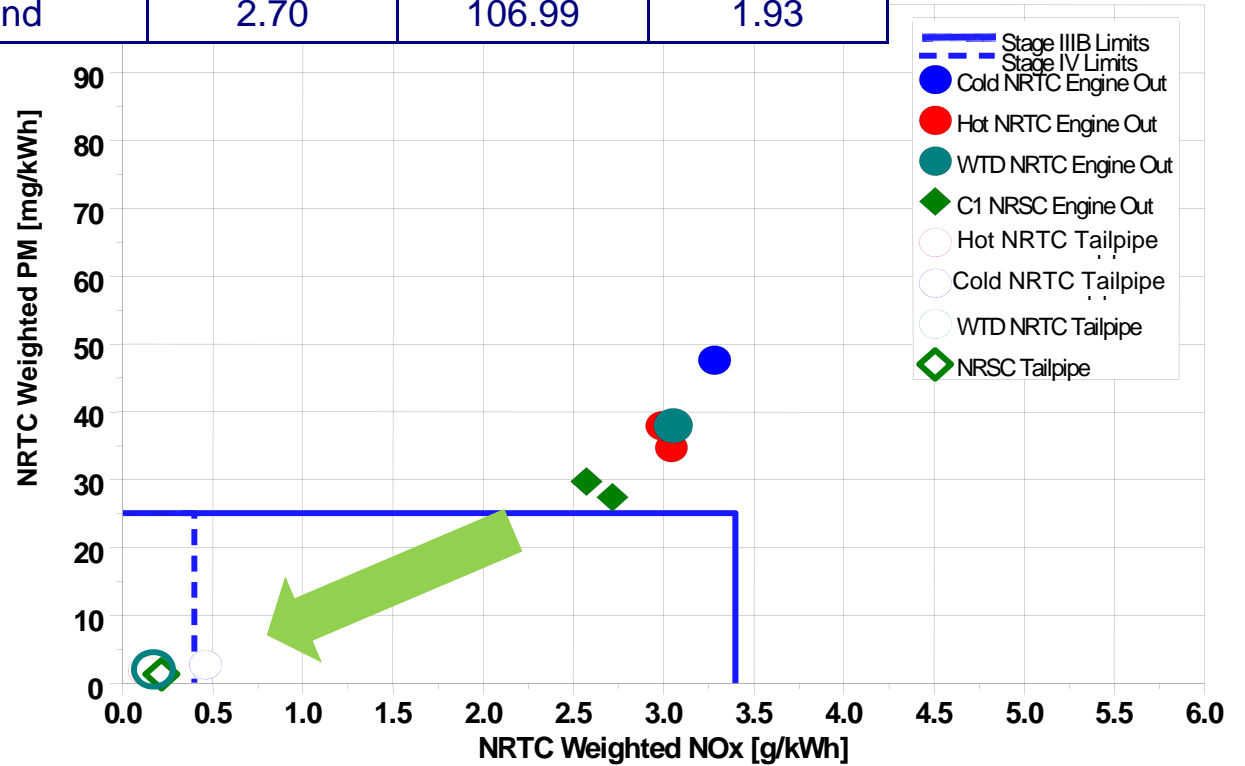
Further Optimisation Potential

- 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 IIB 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.
- NO_x conversion efficiencies were 95% and 92% over the NRTC and NRSC C1 cycles respectively, resulting in tailpipe NO_x levels of 169 and 216 mg/kWh.
- Tailpipe NO₂ 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





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Thank you...

OE engine manufacturer Yara International, urea supplier Ricardo UK and the AECC Members ... and you for your attention.

Who are AECC and what do we do?

The Association for Emissions Control by Catalyst (AECC) is an association of European companies making catalytic converters for diesel engines.

The members of AECC are companies operating worldwide in the research, development, testing and production of catalytic converters for engine emissions control.

Their products are the ceramic and metallic substrates for catalysts and filters; autocatalysts (substrates with catalytic materials incorporated or coated); adsorbers; filter-based technologies to control particulate emissions from diesel and other lean burn engines; and speciality materials incorporated into the catalytic converter or filter.

Catalyst-equipped cars were first introduced in the USA in 1974 but only appeared on European roads in 1985 and in 1993 legislation forced their use on cars. Now more than 275 million of the world's 500 million cars and over 85% of all new cars produced worldwide are equipped with autocatalysts. Catalytic converters and filters are also fitted to heavy-duty vehicles, motorcycles and non-road engines and vehicles.

What are the emission control technologies?

Exhaust gas contains carbon monoxide, hydrocarbons, nitrogen oxides (NOx) and particulate matter (PM). The main pollutants in exhaust to remove harmful gases and particles are:

- autocatalysts
- adsorbers (traps)
- filters

There are more details on the technology pages.

