AECC HEAVY DUTY NRMM TEST PROGRAMME: PARTICLE MEASUREMENT AND CHARACTERISATION

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Introduction

With the increased interest in the control of emissions from non-road engines, AECC undertook an extensive technical project targeting levels inside the EU's Stage IV limits for non-road mobile machinery (NRMM), through the combined application of an integrated emissions control systems.

Engine and Emissions Control System

The base engine was a 4 cylinders, 4.4 litre, 93kW engine widely available globally. This project used a prototype NRMM Stage IIIB version of the engine, developed by Ricardo, with cooled, electronically-controlled EGR, high pressure common rail fuel injection and a variable geometry turbocharger. In the calibration used for this programme, the engine produced an engine out NOx level of around 3 g/kWh over the Non-Road Transient Cycle (NRTC) with approximately 35 mg/kWh PM.

The integrated emissions control system comprised a Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR) system with associated urea injection system and ammonia slip catalyst. The system was hydrothermally aged for 200 hours at 600°C prior to installation on the test bed. The Bosch deNOx 2.2 airless urea dosing systems was calibrated by Ricardo to optimise emissions on key non-road cycles.

Test Programme

A variety of non-road test cycles were studied. Test cycles used were the NRTC, NRSC C1, D2, F and proposed modifications to the F cycles (F-mod). Three further test sets were conducted at 'Not-To-Exceed (NTE) points based on US practice. NTE#1 was at 1200 rpm, 550 Nm, NTE#2 at 1200 rpm, 220 Nm and NTE#3 at 2200 rpm, 165 Nm.

In addition to determining regulated gaseous emissions, and real-time gaseous nitrogenous speciation at 3 locations in the exhaust system, the test programme included many particle analysis approaches: particle numbers (PN) to the PMP protocols, particle size distributions using a Differential Mobility Spectrometer (Cambustion DMS), and particulate mass (PM) by two methods plus the determination of Elemental Carbon (EC) and Organic Carbon (OC) content of collected particulate and the contributions of fuel and lubricant to particulate mass. The DMS system also provided particle number measurements from 5 nm to 1µm. To minimise test variability, specific preconditioning procedures were used. Each test was run three times.

This report presents PM emissions results and particle number measurement results over NRTC and NRSC tests, showing the effectiveness of the system both for the removal of particulate mass and the reduction in the number of ultrafine particles, over a variety of operating conditions. The effects of passive regeneration during certain individual NRSC modes and NTE points are also discussed.

Particulate Mass Measurement

Twin Horiba MDLT partial flow systems were used at the tailpipe position. An emissions system bypass was used to enable engine-out PM measurements on one additional test of each emissions cycle. One MDLT system was used for the standard PM measurement as described in the relevant EU Directive, with a 120cm/s filter face velocity and 1/400th exhaust split. 47mm diameter filters were used throughout. On 2 tests of each type these were standard TX40 filter material, but on one test of each type GF/A filters were used to allow chemical analysis.

This MDLT system was also used for particle number measurements to the heavy-duty PMP protocol. A software correction was incorporated to compensate for the additional flow drawn by particle number sampling system, which would otherwise have reduced the mass by 13%.

The second MDLT system was used for PM measurements to the heavy-duty Euro VI protocol. In this case the filter face velocity was 80cm/s and a 1/600th exhaust split was used. 47mm TX40 filters were used throughout on this sampling system.

There was no obvious significant effect on PM mass of either the PM sampling media (TX40 or GF/A) or the sampling system differences (split ration, filter face velocity and hence temperature differences). 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 when measured with the partial flow method.

Particle Number Measurement

Particle Number (PN) measurements were taken from the partial flow system according to the latest Heavy-duty PMP inter-laboratory correlation exercise guide and ECE R49. Results were not corrected for background.

Engine-out PN from all cycles ranged from ~$6x10^{13}$ to ~$3x10^{14}$/kWh.

Particle numbers at tailpipe for all cycles were in the range of ~10^{10} to <$1.8x10^{12}$/kWh. Cold and hot transient cycle (NRTC) tailpipe results well below 10^{11}/kWh whilst those for steady state cycles (NRSC variants) were all at PN levels of ~10^{11}/kWh or below. For the NTE points based on US protocols, however, PN emissions were all above 10^{11}/kWh, with NTE#2 in particular above 10^{12}/kWh. Some passive regeneration had been experienced during F and F-mod cycles preceding NTE#1, but on the highly loaded, low speed. NTE#1 test point, substantial passive regeneration was seen. This effectively removed the filter cake, resulting in the filtration efficiency on NTE#2 being at its lowest (92.3%) with consequent higher particle numbers than in other tests. By the time NTE#3 was reached, a soot cake had started to rebuild, and so the filtration efficiency had returned to 99.8%. It should be noted that despite this effect, tailpipe particle numbers were still more than an order of magnitude below engine-out levels. The order of the NTE tests, though, clearly affected the results.

Particle Size Distributions

The DMS system was used to provide results at engine-out (via the bypass system), tailpipe and, for one test, at a position between the DPF exit and the urea injector.

Transient cycle engine-out PN were high and substantial dilution ratios (c.1000) were required. Almost all operating conditions showed bimodal character. The highest engine-out nucleation mode was seen on the cold start NRTC. This mode also showed one of the highest engine-out accumulation modes, along with the NRSC F and NRSC F-mod cycles.

Transient cycle tailpipe PN were very low and at the limit of DMS detection (at DF=4). Transient cycle PN (always the initial cycles in the daily protocol) show lowest accumulation mode levels, possibly because of DPF fill during preconditioning. The NRSC cycles' accumulation mode results were higher, as some in-cycle passive regeneration reduces the soot cake.

The measurements at points throughout the system showed that the post DPF/pre-SCR and tailpipe levels are similar, although there is an indication of some accumulation mode reduction across the SCR.

Summary / Conclusions

The combined engine and representatively aged emissions control system met the NRMM Stage IV limits with engineering margin. The project showed substantial PM and PN reductions under a range of non-road transient and steady-state cycles. Compared with the existing engine population, the tailpipe results achieved in this demonstration project point the way to future low emissions solutions.

AECC Non-Road Mobile Machinery (NRMM) Test Programme: Particle Measurement and Characterisation

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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.

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- Test equipment and procedures
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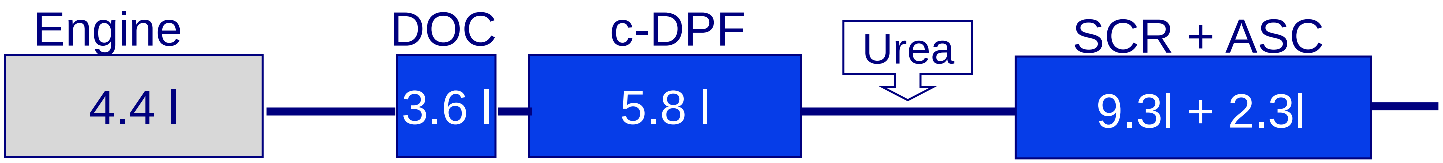
Test Engine & Emissions Control System

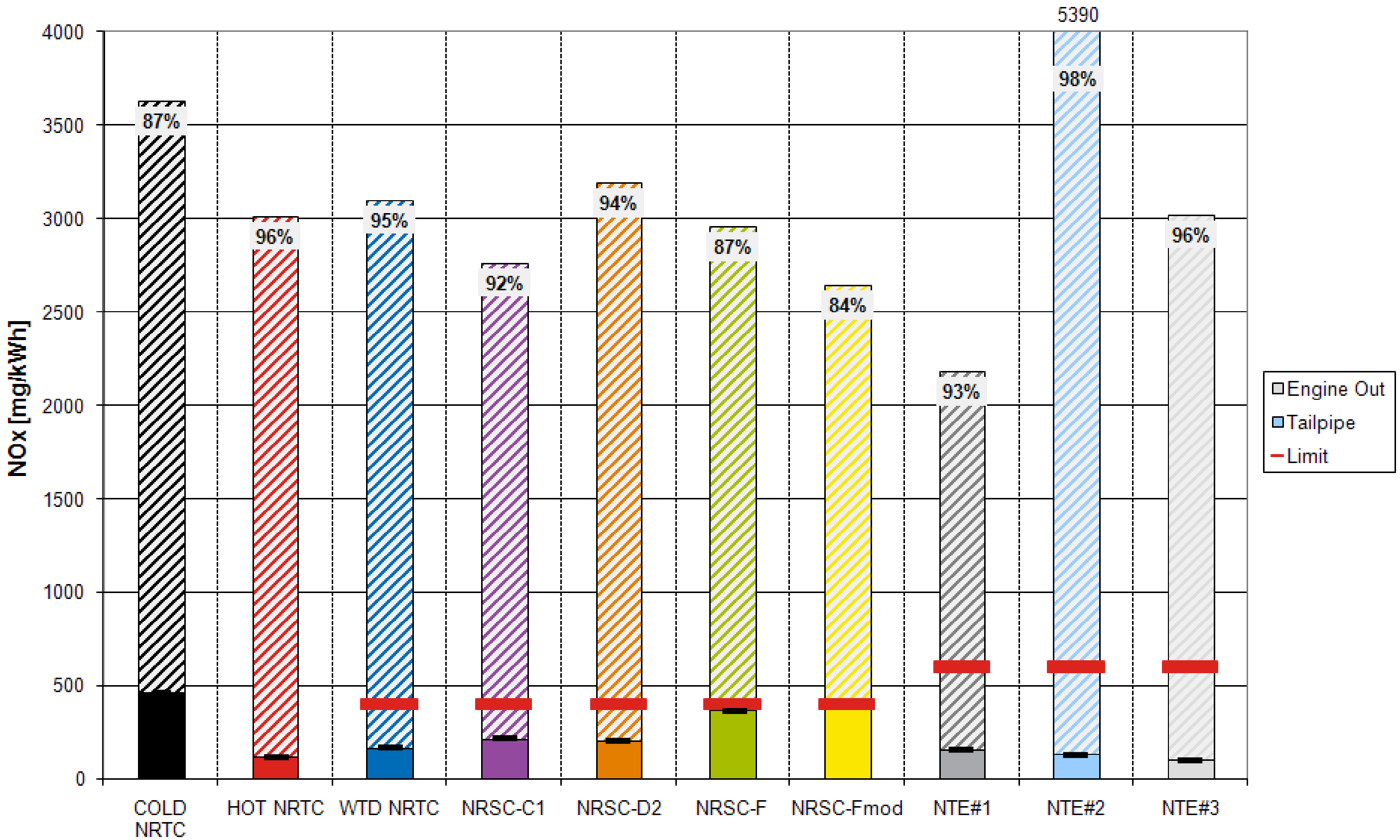
- 4 cylinder, 4.4 litre industrial prototype engine developed for NRMM Stage IIIB, provided by OE manufacturer.
  - High Pressure Common Rail (set at 160 MPa), Variable Geometry Turbocharger and cooled, electronically controlled EGR.
  - Modified Stage IIIB engine calibration to be compatible with AECC-supplied Emissions Control System on the NRTC.
  - PM ~ 35 mg/kWh, NOx ~ 3.0 g/kWh
- Emissions Control System (ECS) provided by AECC
  - System hydrothermally aged for 200hours at 600°C.



- Non-Road Transient Cycle (NRTC) and range of steady-state (NRSC) cycles plus 3 Not-to-Exceed (NTE) test points.
- Preconditioning regime to provide day-to-day repeatability for both NOx and PM without excessive loading.

Regulated Emissions

- Engine-out CO and HC Emissions below Stage IV limits.
- NOx conversion is high (85-95%) over most test cycles, limits are readily met with the exception of NRSC F & Fmod cycles which are close to the limits.



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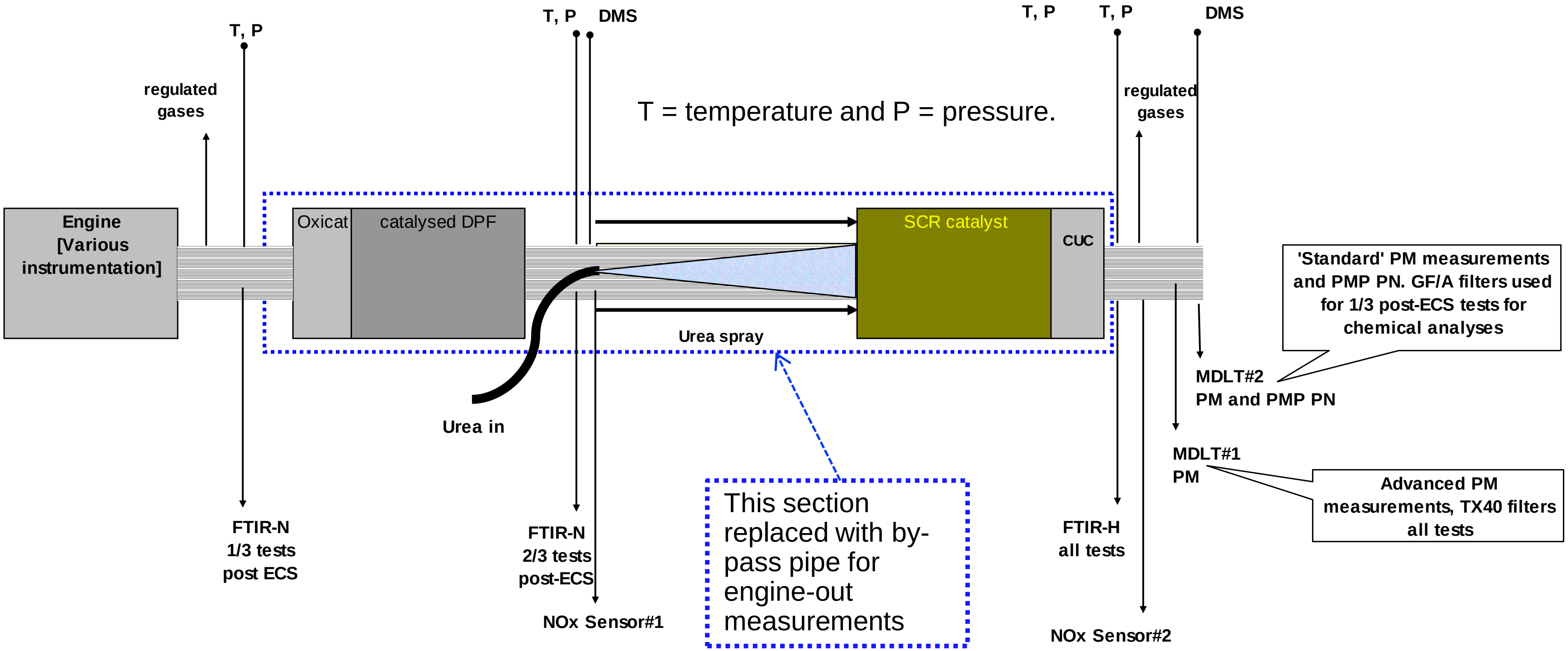
Particulate Analyses

- Twin Horiba MDLT partial flow systems at tailpipe position. Emissions system bypass used for engine-out data.
  - One MDLT for standard PM and PMP PN measurements.
    - 47mm filters; TX40 for most tests, GF/A for chemical analysis.
    - 120cm/s filter face velocity and 1/400th exhaust split.
    - Software correction to compensate for additional flow drawn by SPCS.
  - One MDLT for advanced PM measurements (to Euro VI).
    - 47mm TX40 filters.
    - 80cm/s filter face velocity and 1/600th exhaust split.
- Particle Number (PN) measurements were taken from the partial flow system according to the latest Heavy-duty PMP inter-laboratory correlation exercise guide and ECE R49.
    - Horiba MEXA2000-SPCS system used.
    - PN data have not been corrected for background.
- Differential Mobility Spectrometer (Cambustion DMS500)
    - size distribution and number concentration from 5 nm to 1µm.

Exhaust System Layout - Sampling Points



	Standard Particulate Mass (PM)	Particulate for chemical analysis	'Advanced' Particulate Mass (PM)	Particle Numbers to PMP (PN)	Differential Mobility Spectrometer
Direct engine-out	0	0	0	0	0
Engine-out via by-pass	1	1	1	1	1
Post-DPF/pre-SCR	0	0	0	0	1
Tailpipe after ECS	2	1	3	3	2

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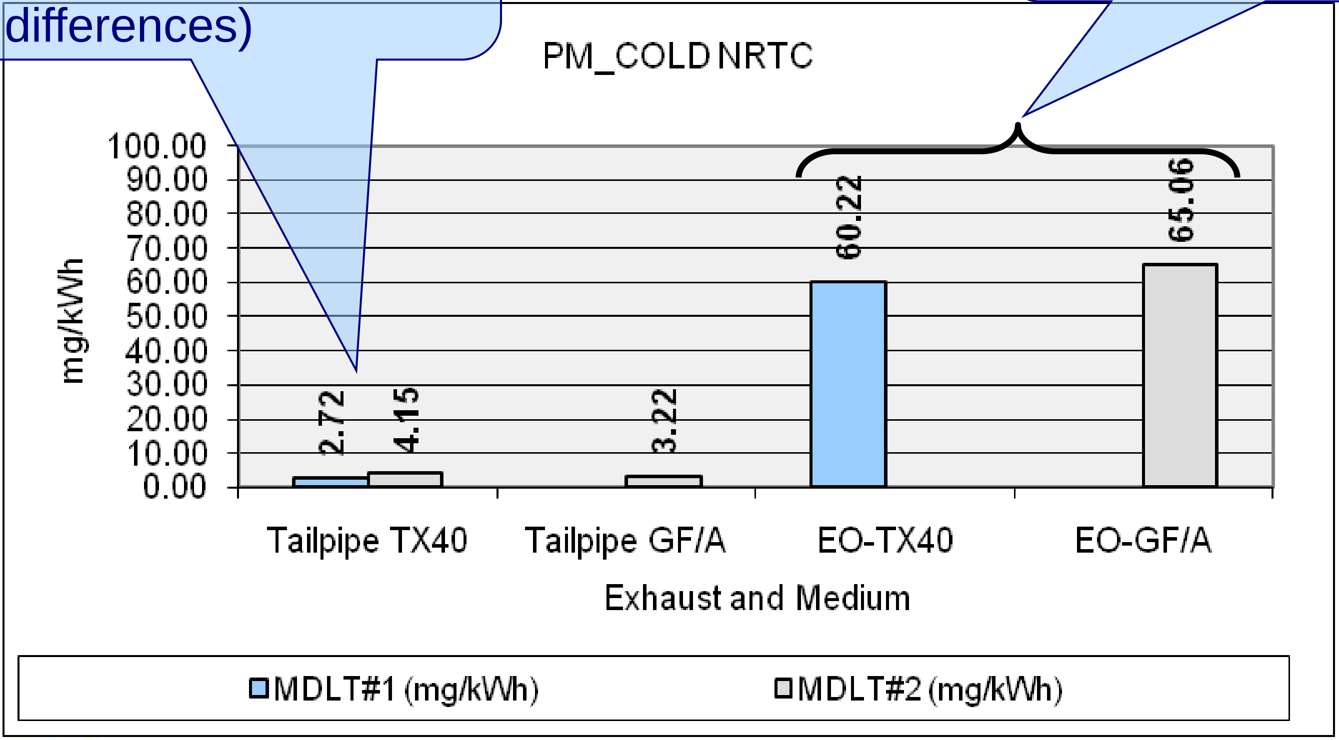
Partial-Flow Particulate Measurements

- No obvious effects of PM sampling or media on measured PM Tailpipe emissions levels.
  - 3-4 mg/kWh on Cold NRTC and 1.5 to 2.5 mg/kWh on hot NRTC.

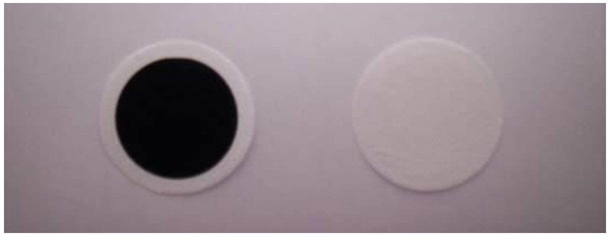
No discernible effect between MDLT#1 and MDLT#2 (ffv and split ratio / temperature differences)

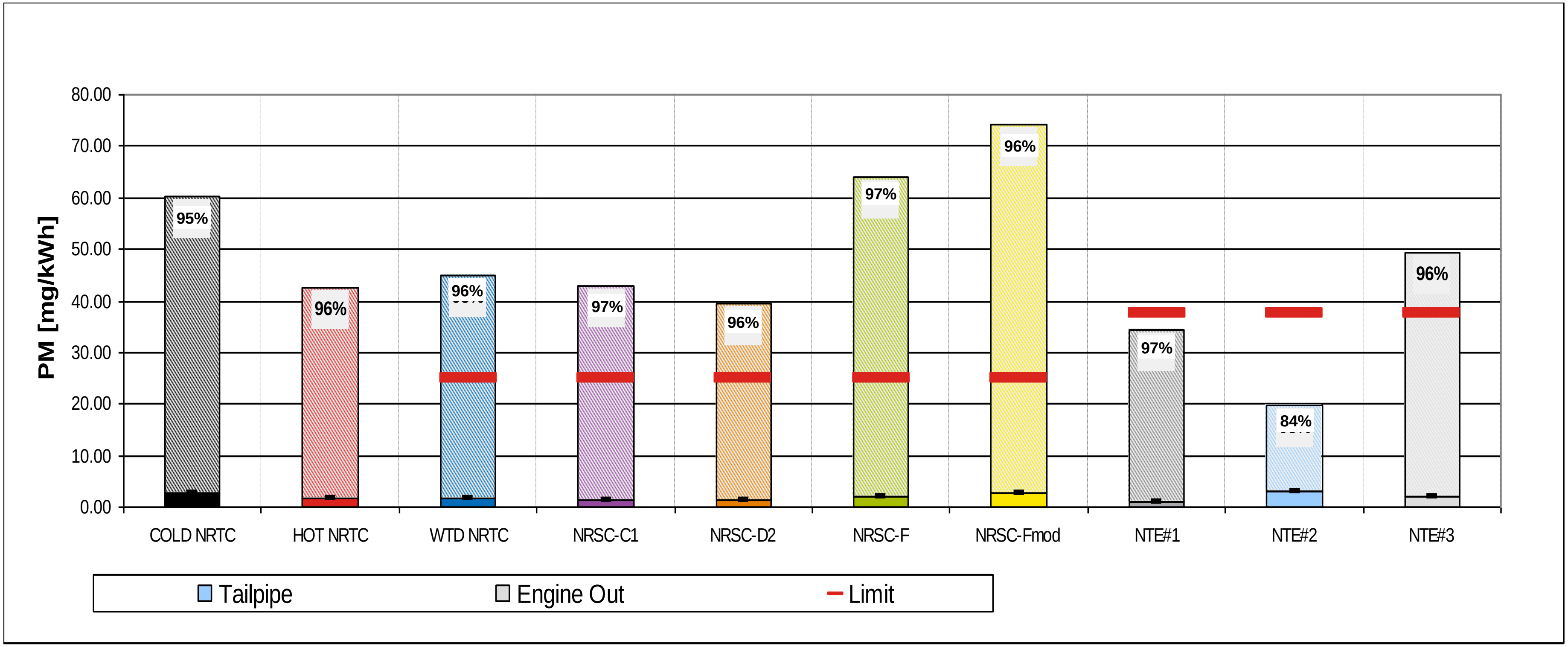
No obvious filter medium effect between TX40 and GF/A



PM Regulated Emissions

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





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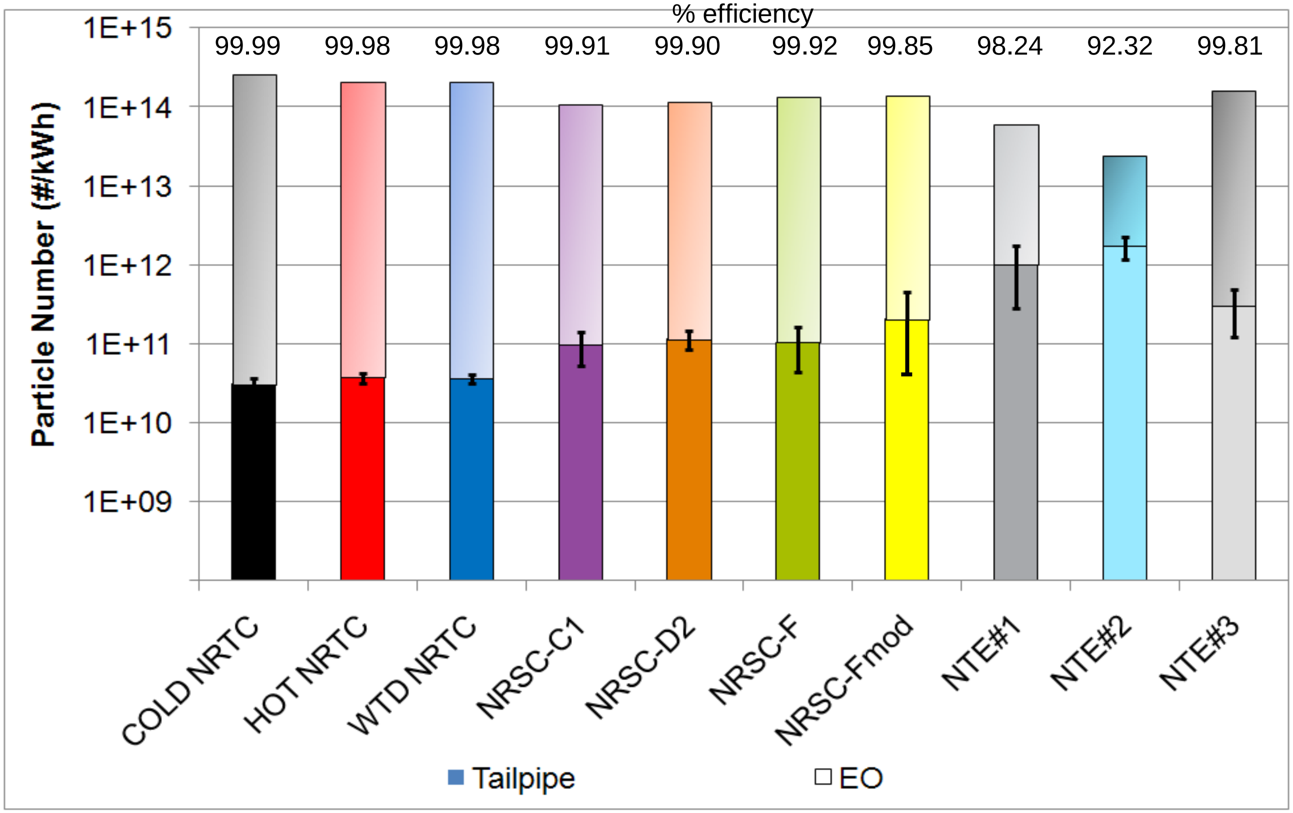
PMP Particle Number Results

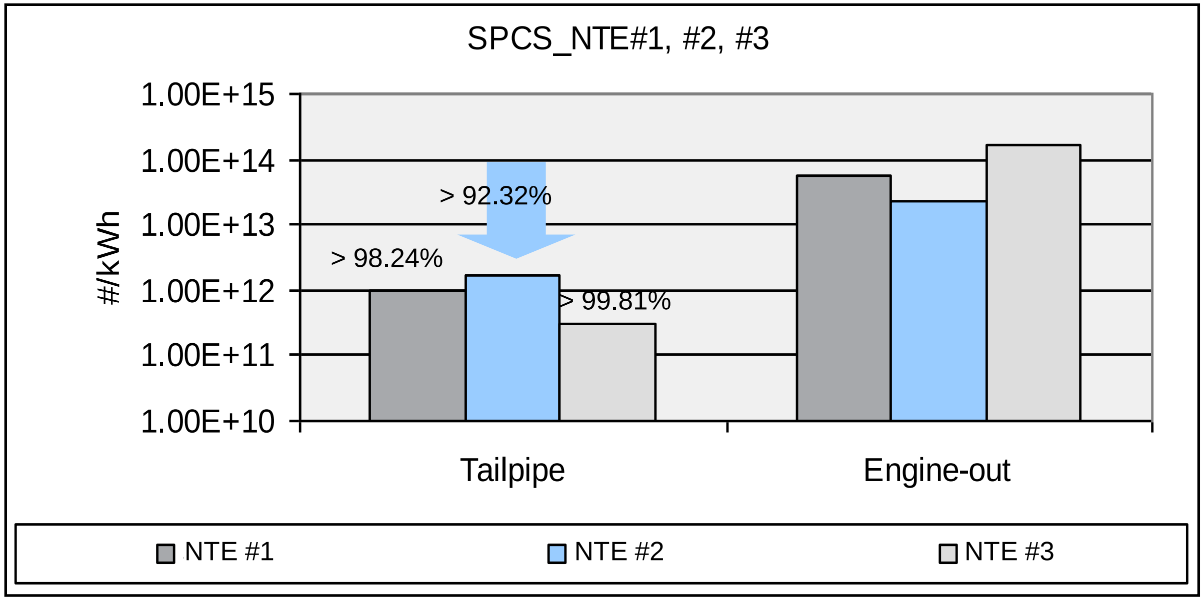
- Cold and hot transient cycle tailpipe PN results well below 10^{11}/kWh.
- Steady state cycles (NRSC variants) all at PN levels ~10^{11}/kWh or below.
- NTE points PN emissions all >10^{11}/kWh and NTE #2 >10^{12}/kWh.
- Engine-out PN from all cycles ranged from ~$6x10^{13}$ to ~$3x10^{14}$/kWh.

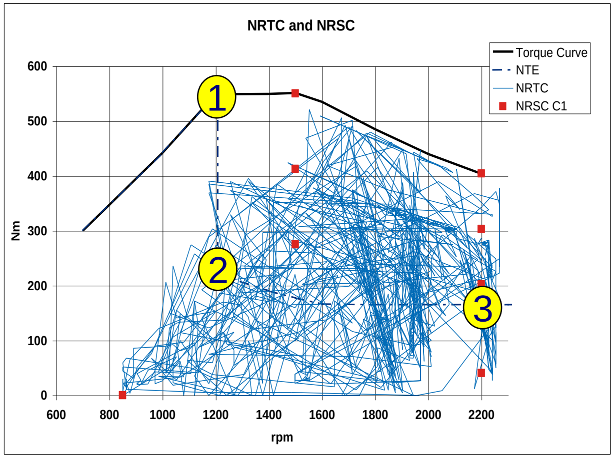
- Tailpipe PN range ~10^{10} to <$1.8x10^{12}$
- Engine-out PN range ~10^{13} to >10^{14}
- ECS efficiency always >92%.



PMP Particle Number for NTE #1, 2, 3

NTE#1	NTE#2	NTE#3
1200 rpm, 550 Nm	1200 rpm, 220 Nm	2200 rpm, 165 Nm





- Some passive regeneration during F and F-mod cycles preceding NTE #1.
- NTE#1: substantial passive regeneration.
- NTE #2: filtration efficiency lowest.
- NTE #3: no passive regeneration.

Mean Exhaust temp [°C]	DPF	SCR
COLD NRTC	283	234
HOT NRTC	285	261
NRSC-C1	335	333
NRSC-D2	346	338
NRSC-F	323	342
NRSC-Fmod	326	342
NTE#1	411	378
NTE#2	388	343
NTE#3	319	300

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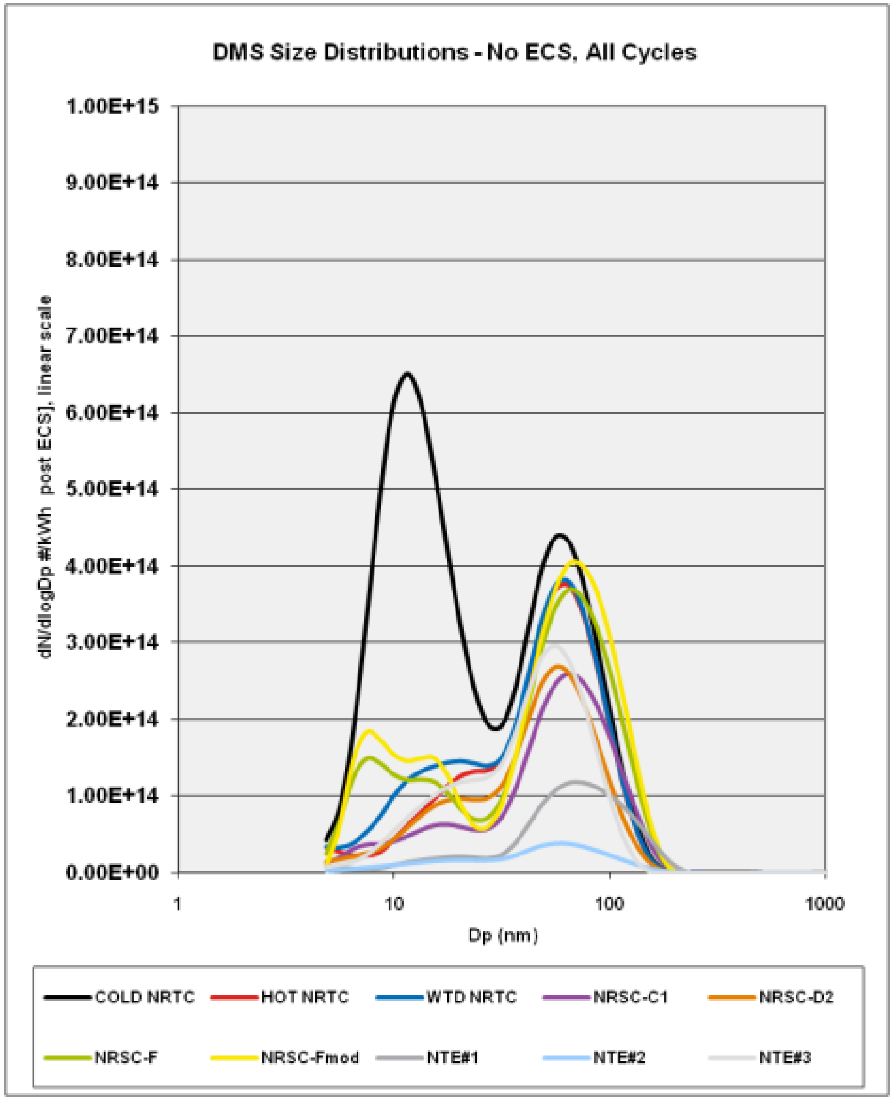
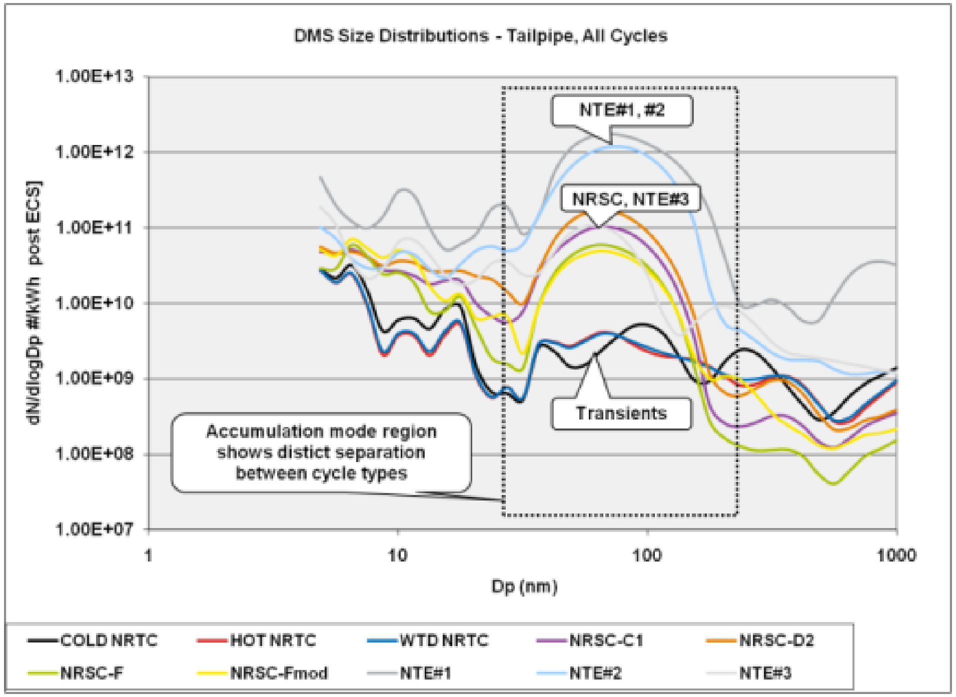
DMS Size Distribution Results – Engine-out



- Transient cycle engine-out PN were high and substantial dilution ratios were required (c.1000).
- Almost all operating conditions showed bimodal character.
  - Consistent with low PM (low EC) calibration for this engine.
- Highest nucleation mode with cold start NRTC.
- Highest accumulation modes with cold NRTC, NRSC F and NRSC F-mod.
- Lowest specific PN emissions from NTE #1 and #2.

DMS Size Distribution Results - Tailpipe

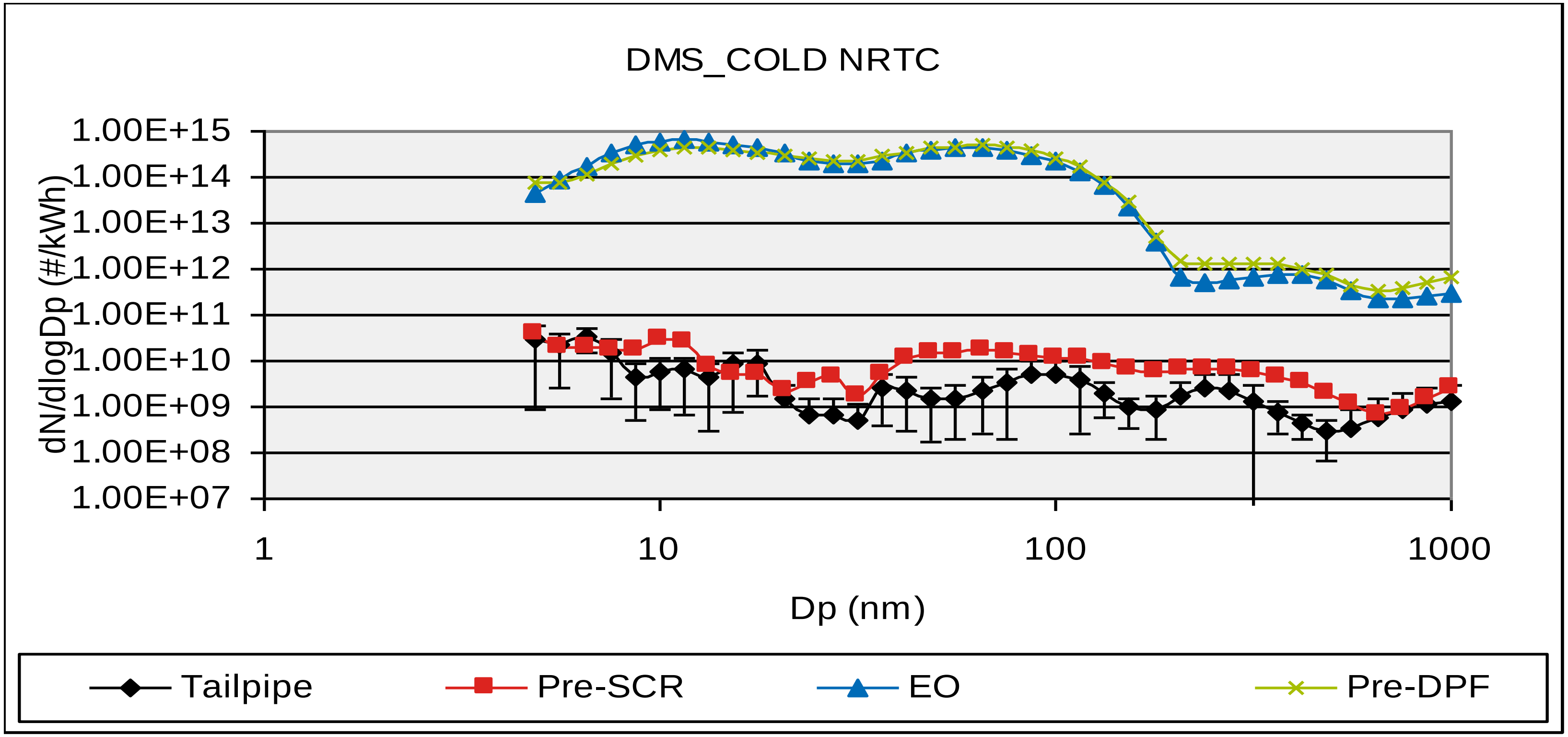
- Transient cycle tailpipe PN were very low and at the limit of DMS detection (at DF=4).
- Particle size distributions still reasonable in the accumulation mode region.



- Transient cycle PN (always initial cycles in the daily protocol) show lowest accumulation mode levels.
  - DPF fill during preconditioning has limited PN emissions.
- NRSC cycles' accumulation mode results higher, as some passive regeneration reduces soot cake.
- NTE points always highest
  - Tested at the end of the day, following NRSC and transients.
  - Important passive regeneration during NTE #1.
  - NTE #3 levels at the high end of NRSC results.

DMS Size Distribution through the ECS

- The cold-start NRTC shows the high nucleation mode and accumulation mode levels at Engine-out.
- Pre-SCR and tailpipe levels are similar, although there is possibly some acc. mode reduction across the SCR.



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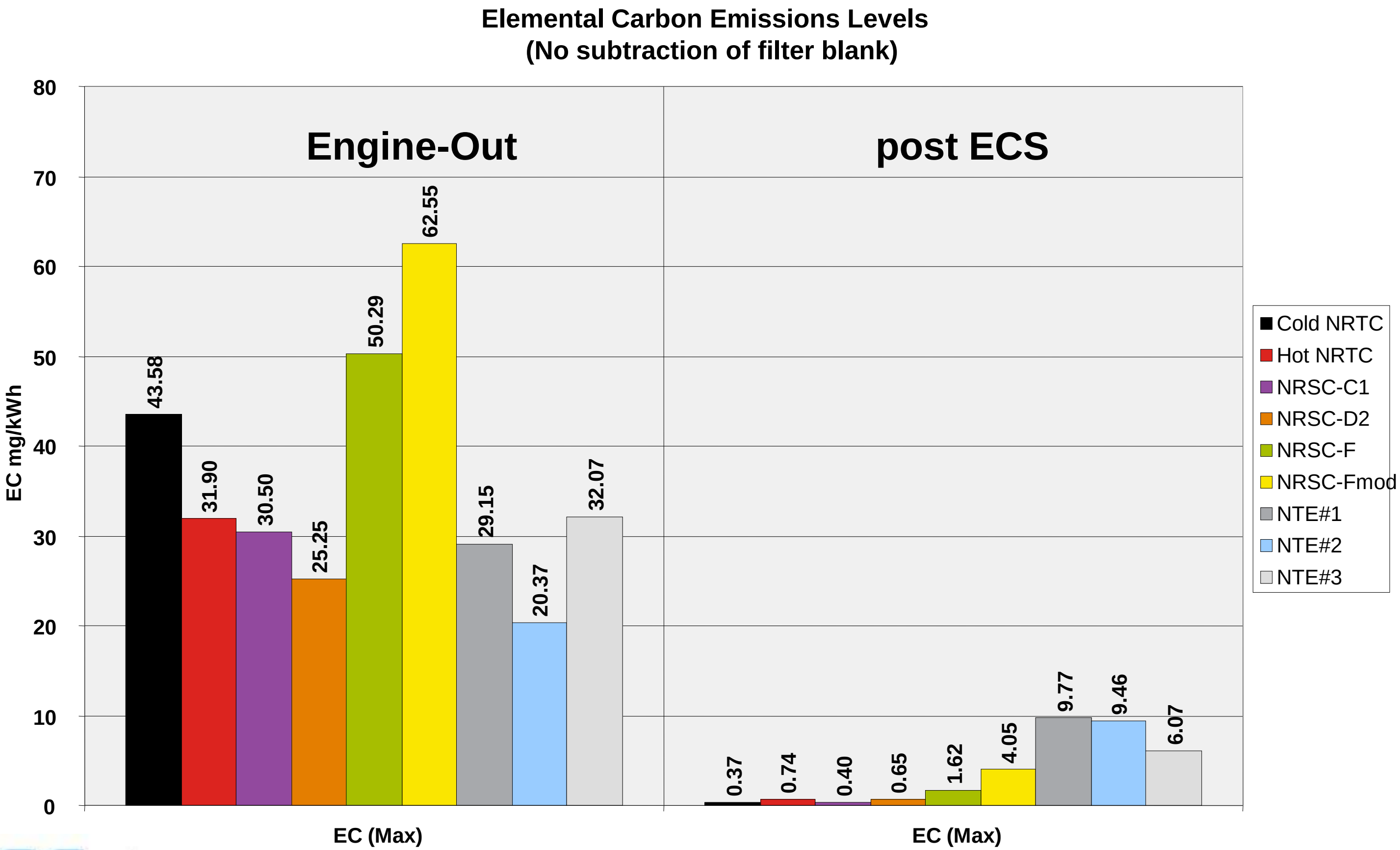
Emissions Levels of Elemental Carbon (EC)

- Substantial reduction in EC from engine-out to tailpipe.
- Filtration efficiencies similar to PN
  - Elemental carbon comprised ~45% to ~70% of engine-out PM.
  - Volatiles dominated post-DPF filters, carbon fraction negligible.



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Summary (1)

- 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 when measured with the partial flow method.
- Tailpipe Particulate Mass emissions from two different sampling media appeared broadly similar.
- Withdrawing a sample from a partial flow dilution system for PN measurements can result in a substantial reduction in measured Particulate Mass , if a correction is not made.
  - In this program, 13% of mass was removed.
- Elemental carbon emissions were reduced by the ECS.
  - >99% for all transient and steady state cycles once the filter background for EC was taken into account.
  - With subtraction of EC blank, tailpipe EC levels were negligible.

Summary (2)

- The HD-PMP method as developed by UN-ECE GRPE for on-road HD engines could readily be used to measure particle emissions (PM and PN) of NRMM engines.
- All transient cycles' data showed tailpipe Particle Number emissions well below 10^{11}/kWh.
- Steady state cycles' data showed emissions below 10^{12}/kWh.
- Passive regeneration occurring during one NTE point influenced PN emissions for the following NTE point. Tailpipe particle numbers were still more than an order of magnitude below engine-out levels.
- ECS efficiency for PMP Particle Numbers was >99.8% for all transient and steady state cycles.
- The production-intent Stage IIIB prototype engine fitted with the AECC Emissions Control System readily met Stage IV emissions limits over a range of test cycles.

Acknowledgements

Thank you…

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… and you for your attention