AECC Technical Seminar on Emissions from Non-Road Mobile Machinery

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AECC Test Program
Emissions from Non-Road Mobile Machinery Engines
Results

Brussels – 27 November 2012

Association for Emissions Control by Catalyst AISBL

Association for Emissions Control by Catalyst (AECC) AISBL

AECC members: European emissions control companies

BASF

CORNING

EMITEC

IBIDEN CO., LTD.

JM Johnson Matthey

NGK
NGK Europe GmbH

Rhodia
Member of the Solvay group

umicore
Automotive Catalysts

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

Content

- Motivation: Views on Technology Development
- AECC Test Program Objectives and Test Plan
- Engine and Emissions Control System, Test Procedures
- Measured Regulated and Unregulated Emissions
- Summary and Conclusions

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Views on Technology Development (2009)

Matrix of substrates and engine ratings

The engine company. DEUTZ

Main route — Option depending on rating, customer demands and application — Agripower

Length [inch]

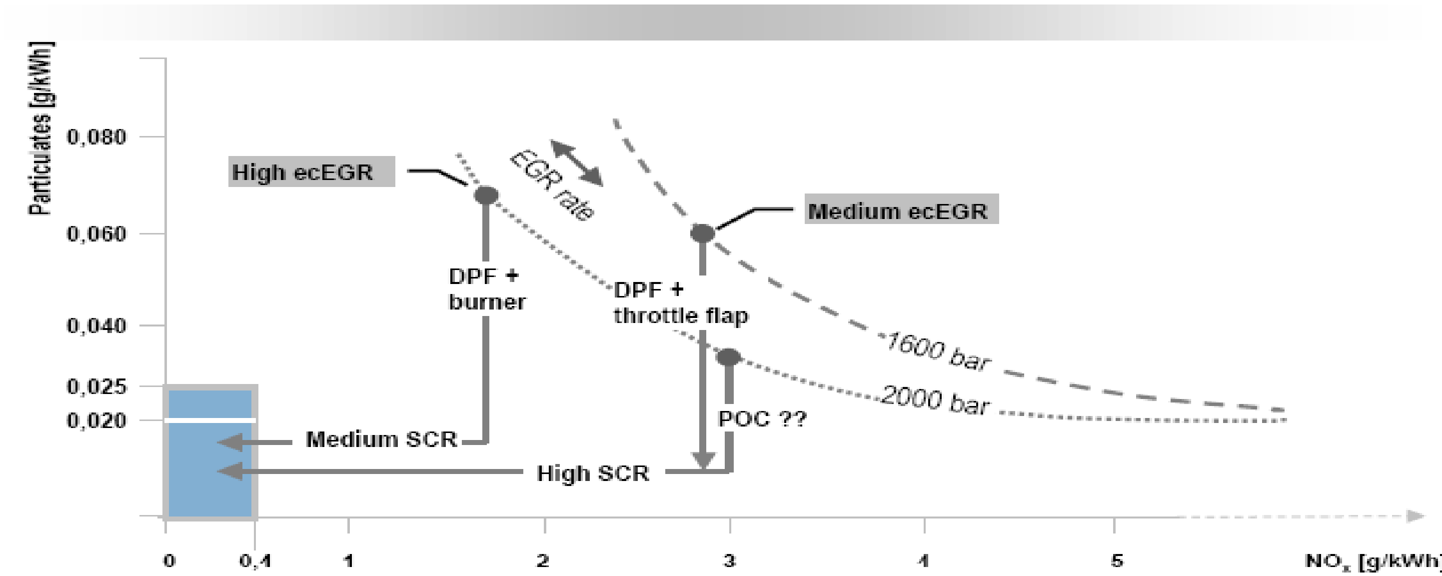
Engine	Max. Power [kW]	Diameter [inch]	POC		DPF		SCR + ASC
			DOC	Filter	DOC	Filter	
20xx/10 L04	35	5,66	5,0	6	5,0	6	
	41			7		7	
	56			9,5		9,5	
2010 -2012 L04	72	7,5	5,0	7,0	5,0	7,0	
	93			9,0		9,0	
	114			11,0		11,0	
2012 L06	133	9,5			4,5	8,0	11,0
	166					10,0	
	199					12,0	
2013 L06	233	11,25			9,5 x 5,5	10,0	11,0
	279					12,0	
	326					14,0	
2015 V06	404	13					12,0
2015 V08	528	13					16,0

Legend: Diesel oxidation catalyst (DOC), Particulate oxidation catalyst (POC), Selective catalytic reduction (SCR), Ammonia-slip catalyst (ASC)

Source: Schiffgens (Deutz); 4.MTZ conference – On/Off Highway Engines, November 2009

Views on Technology Development (2009)

Technology options to meet US Tier 4 for 56-560 kW



Legend: Externally cooled exhaust gas recirculation (ecEGR), Particulate oxidation catalyst (POC), Selective catalytic reduction (SCR)

Series Power	20XX / 2010 < 56 kW	20XX / 2010 56 – 85 kW	2012 L4 70 – 130 kW	2012 L6 130 – 180 kW	2013 L6 160 – 250 kW	2015 V6+8 300 – 520 kW
Tier 4						
POC	■					
Burner		optional	optional	■	■	■
DPF + SCR		■	■	■	■	■

Source: Schiffgens (Deutz); 4.MTZ conference – On/Off Highway Engines, November 2009

Views on Technology Development (2009)

	Stage IIIA / Tier 3	Stage IIIB / Tier 4i	Stage IV / Tier 4
56-130 kW	Base engine, iEGR or eEGRC (10% rate)	Add FIE (>1800bar) 15% cooled EGR. No aftertreatment	Add DOC and SCR (88-90% efficiency). No DPF
130-560 kW		Increase P_{max} FIE >2000bar e-EGR (rate ~25%) DOC and DPF	Add SCR (80-82% efficiency)
130-560 kW		SCR (78-80% efficiency)	Add DOC SCR (efficiency 93-94%) No DPF

Based upon : Conicella (Ricardo), Low particulate combustion development of a medium-duty engine for off-highway applications; 4. MTZ conference – On/Off Highway Engines, November 2009

Views on Technology Development (2012), typ. Example 4/6

AP Strategy to meet Tier 4Final

Technology Options

- Two competing technologies, SCR and EGR, were feasible to achieve Tier 4 Interim
- Tier 4 Final levels can be reached with or without EGR, but require SCR
- Aftertreatment alternatives for Tier 4 Final
  - cEGR + DPF + SCR
  - cEGR + PF + SCR
  - cEGR + DOC + SCR
  - DPF + SCR
  - PF + SCR
  - DOC + SCR

Chosen technology paths

AGCO's conclusion

- Tier 4 Final can be reached with either of these technology paths
- Optimal technology path has been selected for each application

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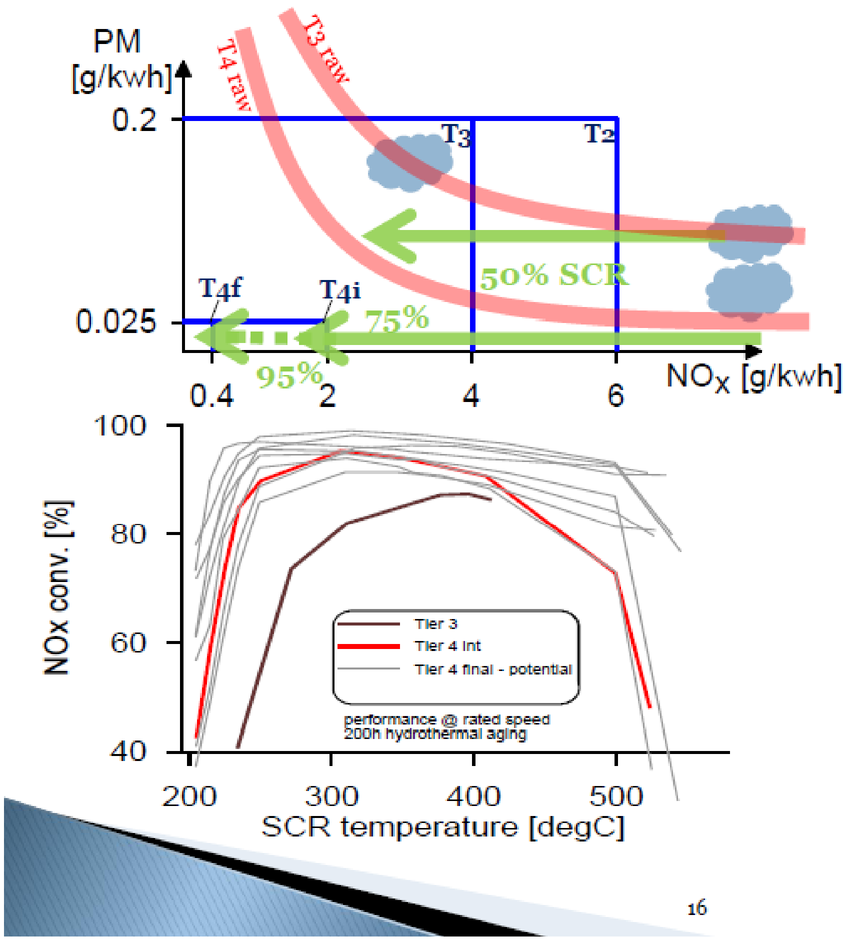
Source:

SAE International

HDD Symposium
Gothenburg, Sept 12th 2012

Jarno Ratia, AGCO Power Inc.

SCR technology evolution



- NOx-conversion requirement increased 50→95 % in 6 years
- SCR technology has developed significantly in past years

Source:

SAE International

HDD Symposium
Gothenburg, Sept 12th 2012

Jarno Ratia, AGCO Power Inc.

Views on Technology Development (2012), typ. Example 6/6

Advantages between two strategies

SCR only

- Lower heat rejection
- Cost
- Simplicity
- Space claim

SCR+cEGR

- Fluid economy
- For higher BMEP

DPF can be avoided with both technology paths
SFC similar to Tier 4interim level with both strategies

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Source: SAE International
HDD Symposium
Gothenburg, Sept 12th 2012

Jarno Ratia, AGCO Power Inc.

Review of Publications (update 10/2012) on Aftertreatment Technologies for Stage IIIB and Stage IV

Stage IIIB:

- Engines 56 < P < 75 kW
  - No aftertreatment
  - DOC
  - DOC/POC
- Engines 75 < P < 130 kW
  - DOC or DOC/POC
  - DOC + DPF or DPF w/ burner
  - DOC + SCR
  - SCR
- Engines 130 < P < 560 kW
  - DOC + DPF or DPF w/ burner
  - SCR
  - DOC + SCR
- Engines > 560 kW
  - Not covered by NRMM Stage IIIB
  - i.e. no aftertreatment

Stage IV (planned/expected):

- Engines 56< P < 75 kW
  - DOC + SCR
  - SCR
  - DOC/POC + SCR
- Engines 56 < P < 130 kW
  - DOC/POC + SCR
  - DOC + DPF + SCR
  - DOC + SCR
  - SCR
- Engines 130 < P < 560 kW
  - DOC/POC + SCR
  - DOC + DPF + SCR
  - DOC + SCR
  - SCR
- Engines > 560 kW
  - Not covered by NRMM Stage IV
  - i.e. no aftertreatment

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AECC Project Objectives

- Demonstrate the regulated emissions levels achievable on an integrated Emission Control System (ECS) and up-to-date engine technology of the type expected for the NRMM diesel engine emissions standards (Stage IV and beyond).
- Provide data on regulated, non-regulated, Particulate Mass and Particle Number emissions from a range of emissions cycles.
- Provide NTE (not-to-exceed) data for appropriate test points.
- Provide input to the Particle Measurement Programme (PMP).

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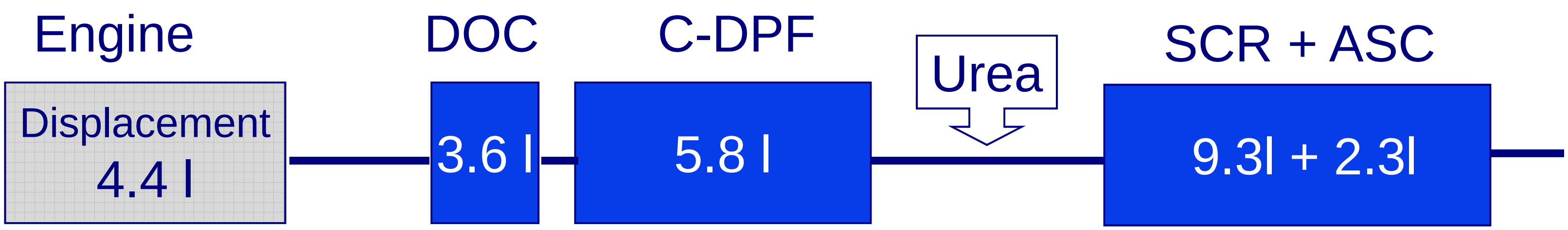
Test Engine

- 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 slightly modified Stage IIIB engine calibration for engine-out emissions to be compatible with ECS on the NRTC.
  - Engine-out emissions: PM ~ 0,035 g/kWh and NOx ~ 3,0 g/kWh
- Fuels, Lube oil, AdBlue
  - Carcal Reference 725A diesel fuel (max. 10ppm S) for calibration and test phases.
  - Low ash 15w-40 engine lubricant.
  - AdBlue® aqueous urea to ISO 22241 specification

Emissions Control System (ECS)

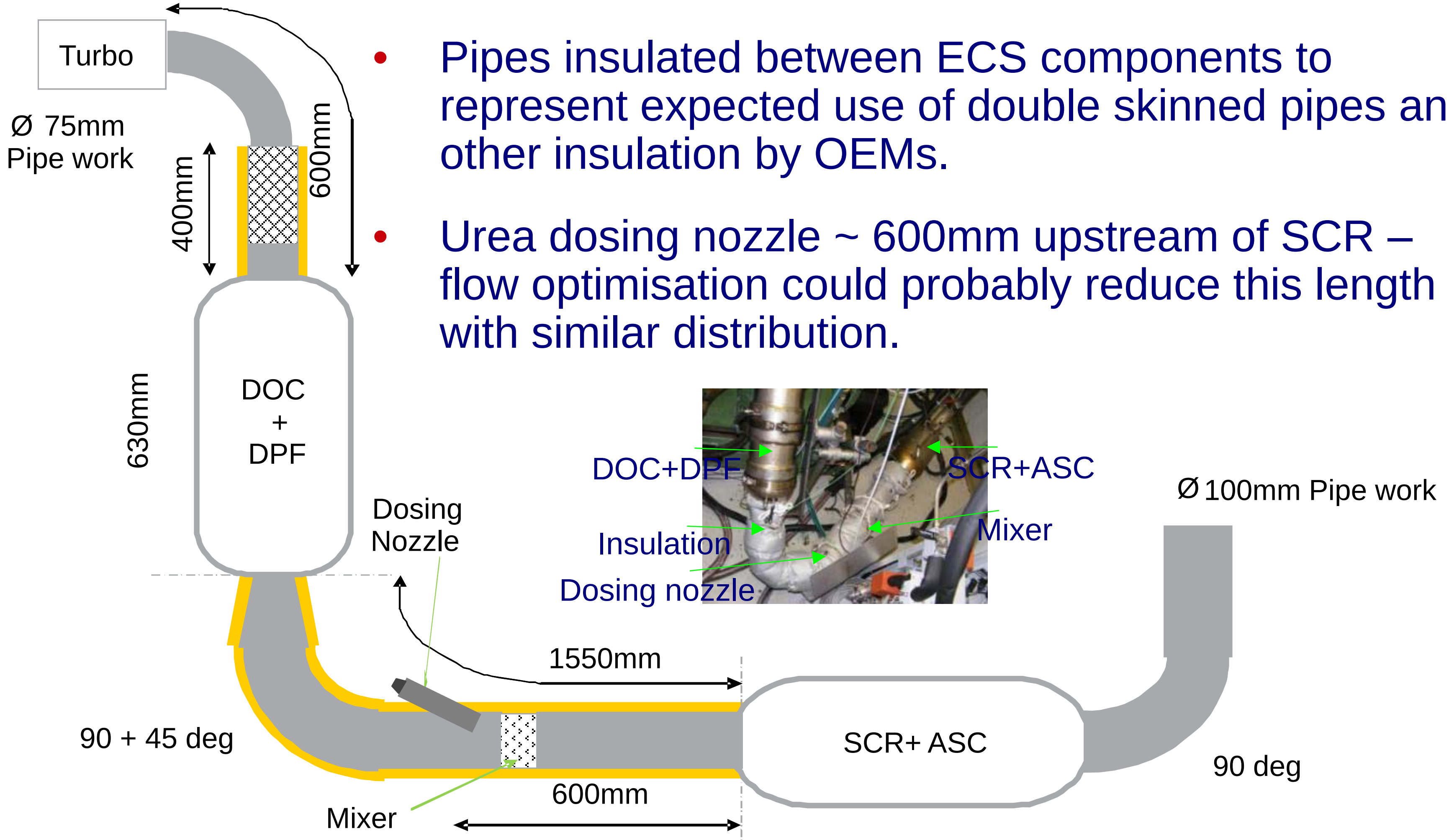
- Oxidation catalyst (DOC), catalysed wall-flow particulate filter (C-DPF) and urea-Selective Catalytic reduction (SCR) with ammonia slip catalyst (ASC). ECS provided by AECC.



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

Exhaust System (1)

- 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.



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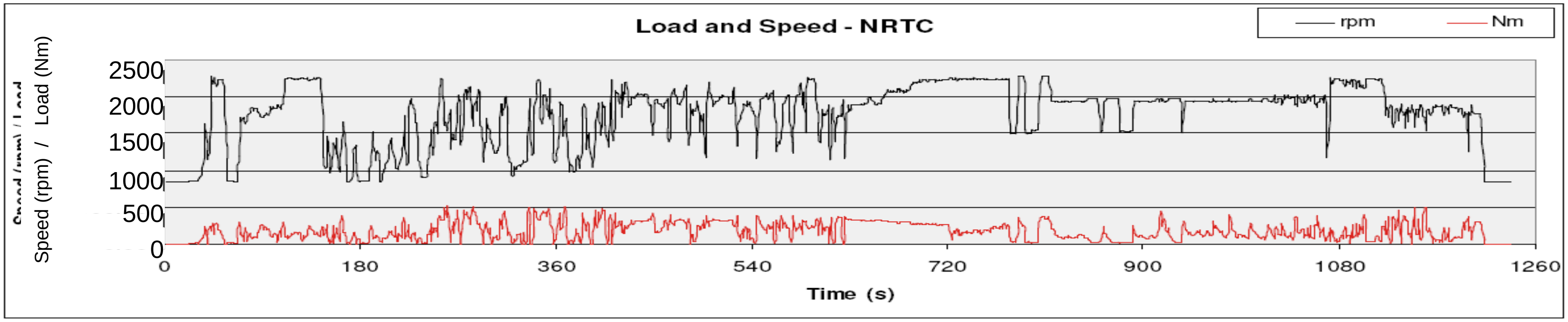
Test Cycles (1)

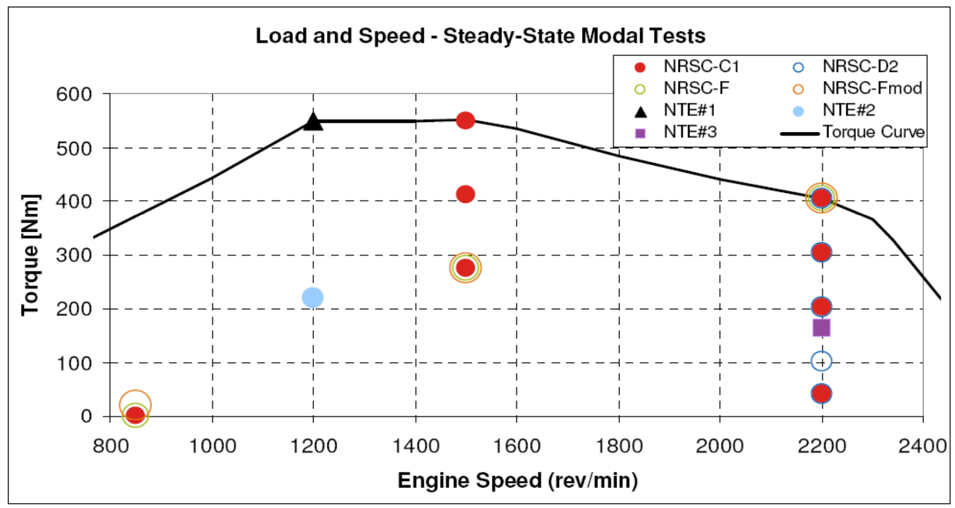
NRTC World Harmonised Non-Road Transient Cycle.

- Engine soaked for 20 min following cold test.
- Weighted result calculated 10% cold, 90% hot in accordance with EU Directives 2004/26/EC and 2010/26/EU.



Steady State Cycles

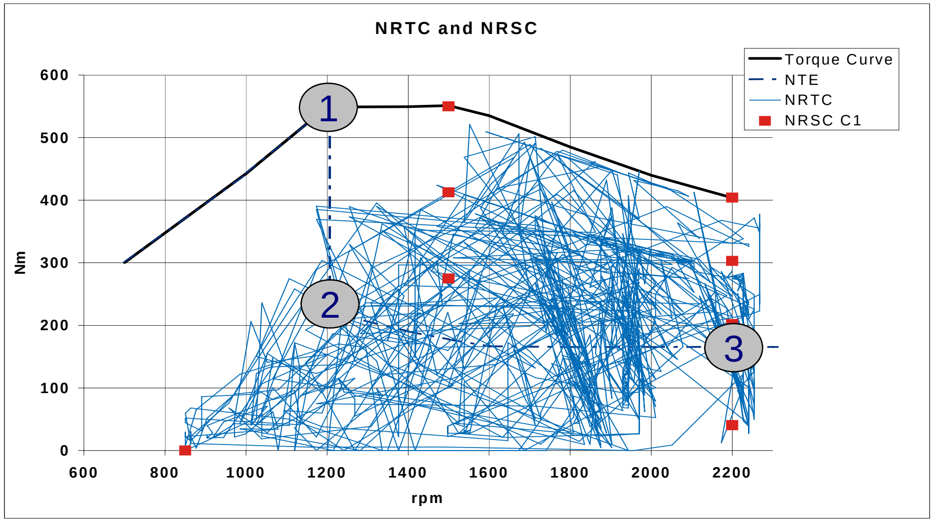
- NRSC World Harmonised Non-Road Steady-State Cycle (ISO-8178 C1).
- ISO-8178 C1 ramped cycle (used in US). Different mode order from NRSC.
- ISO-8178 D2 cycle used for constant-speed engines.
- ISO-8178 F and F-mod rail cycles (to evaluate proposed changes).



Test Cycles (2)

Three Not-to-Exceed (NTE) points

- selected on the basis of current United States definition of NTE zone.
- all points are on the edge of the NTE zone, represent extremes of peak torque speed, high load, low load, lowest AFR and lowest temperature operation.



Preconditioning

- Preconditioning regime to provide day-to-day repeatability for both NOx and PM without excessive loading

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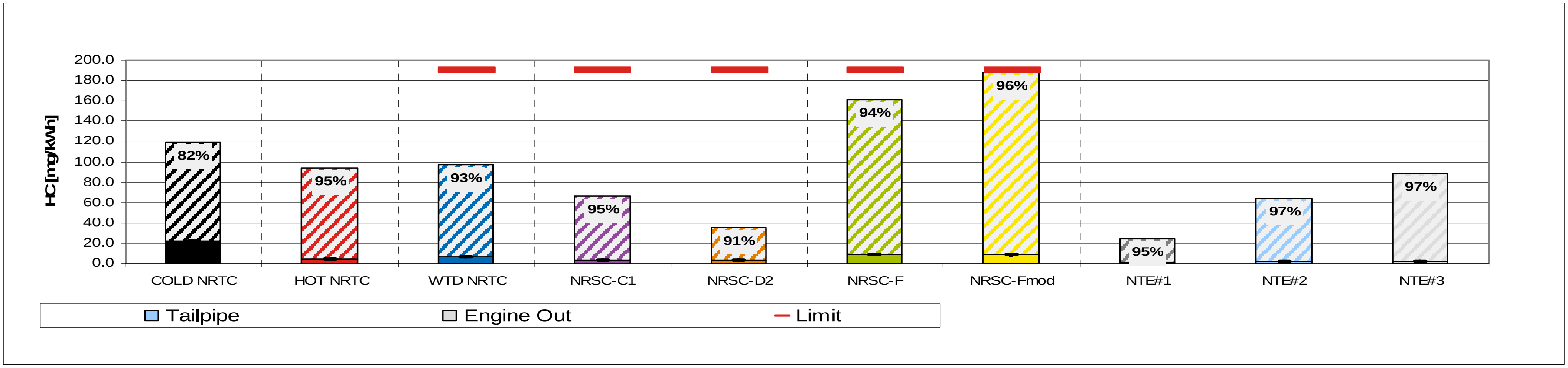
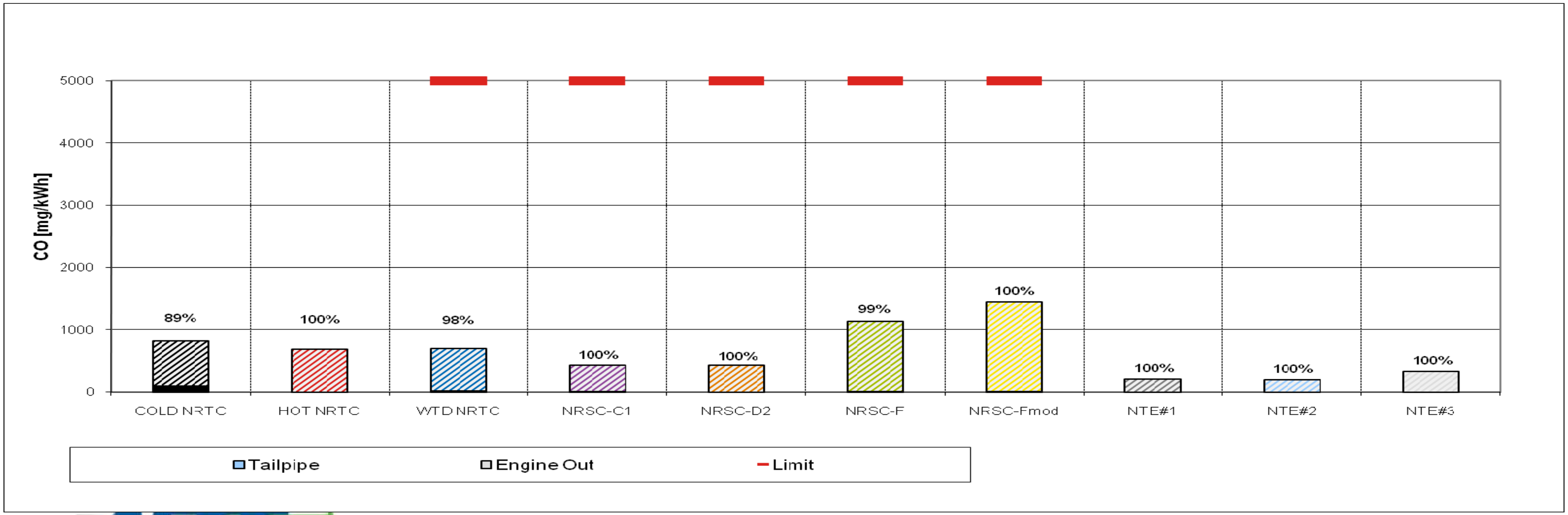
HC and CO Emissions

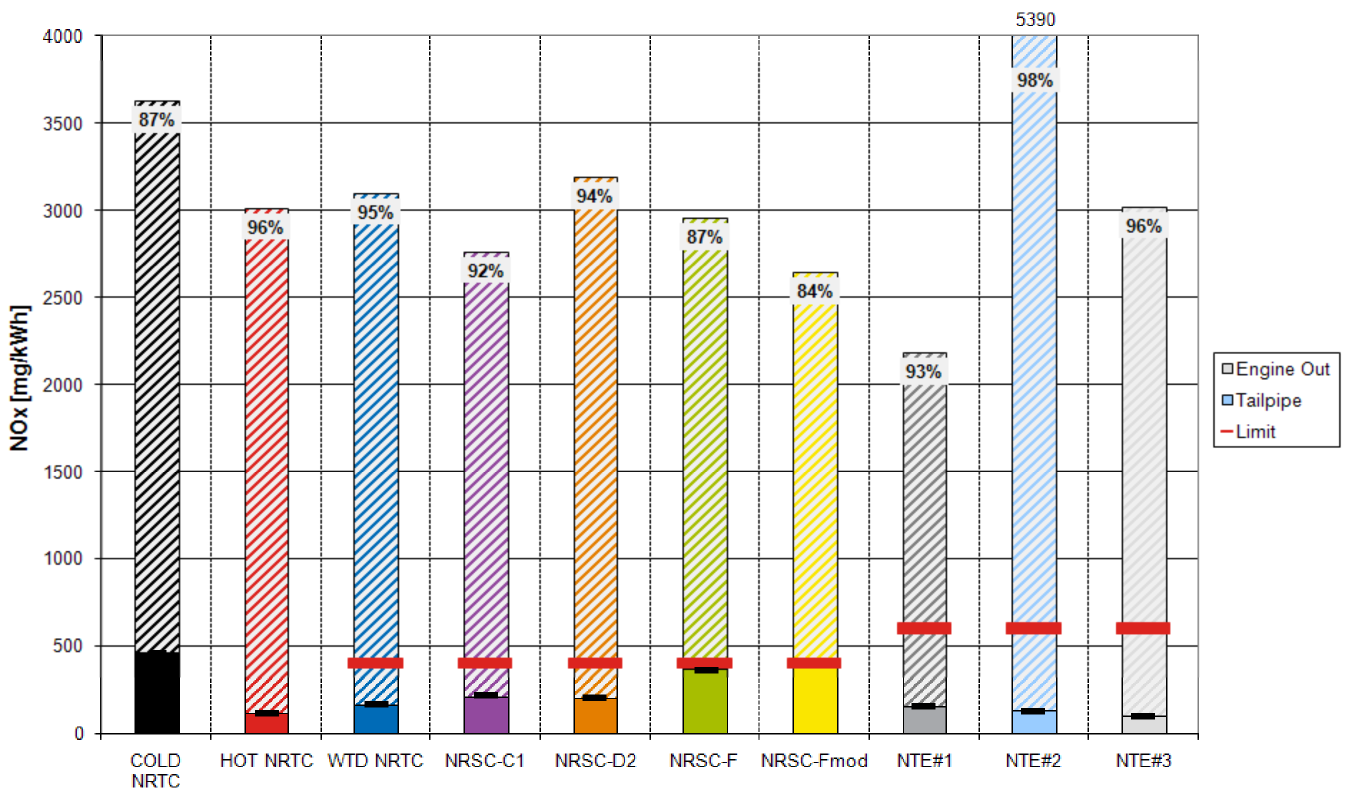
- HC and CO conversion is very high and limits are readily met.
- Engine-out emissions are below limit for most cycles.





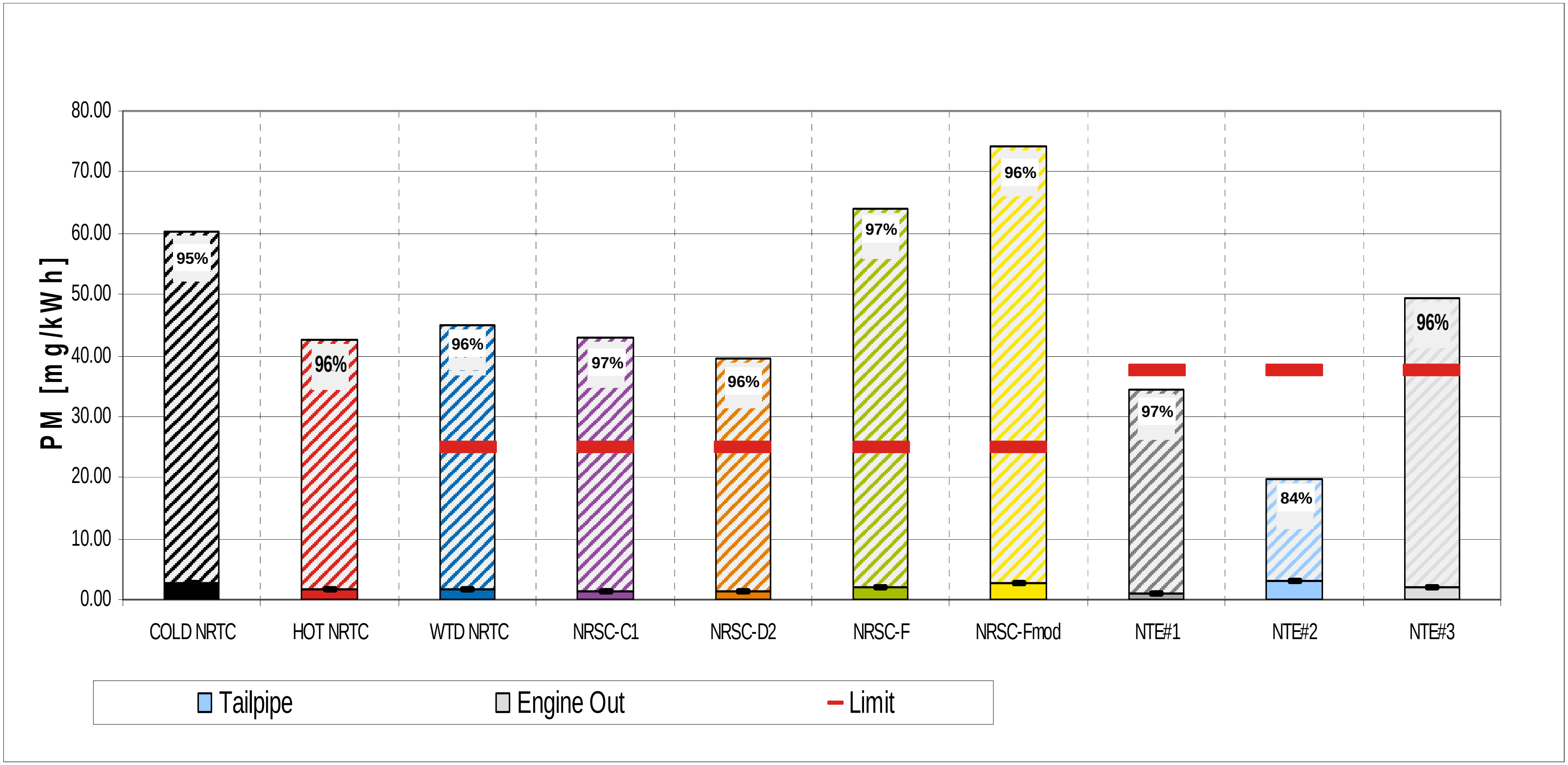
NOx Regulated Emissions

- 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.



PM Regulated Emissions

- PM after DPF, measured using the current methodology, meets limits with considerable margin over all cycles.



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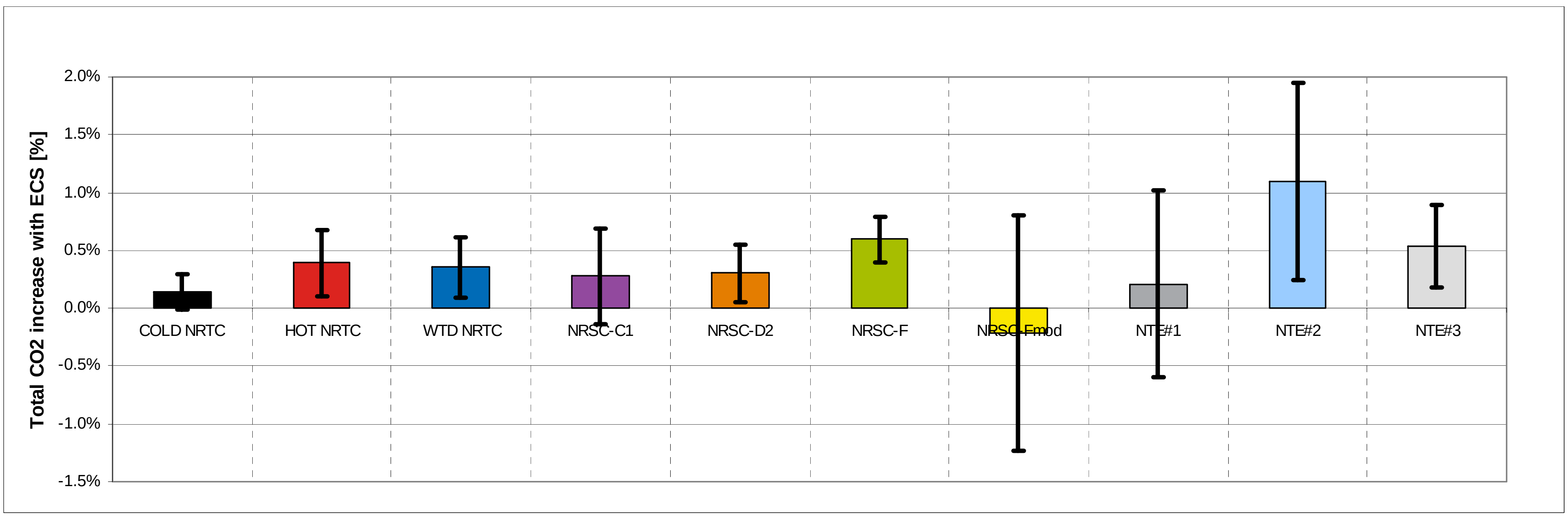
CO_2 Increase Attributable to ECS & Urea

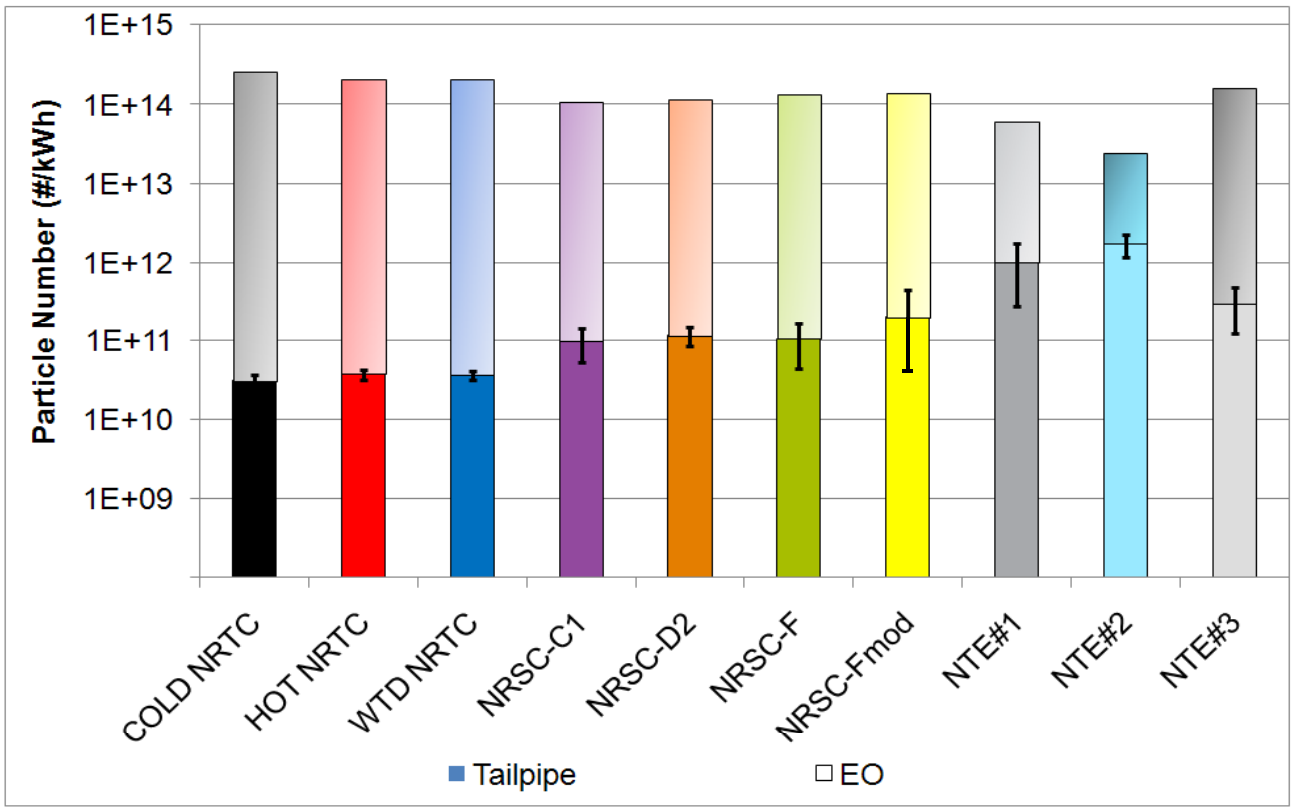
- AdBlue consumption varies from 2-5% of fuel consumption for all cycles and NTEs.
- CO_2 calculated from fuel and AdBlue consumptions added to give a total CO_2 value (assuming 1 mol Urea converted to 1 mol CO_2).
- In practice the differences are small:
  - a small increase (<1%) is seen in fuel consumption with ECS fitted.
  - AdBlue contribution adds < 0.5% to this.



PMP Particle Number Results

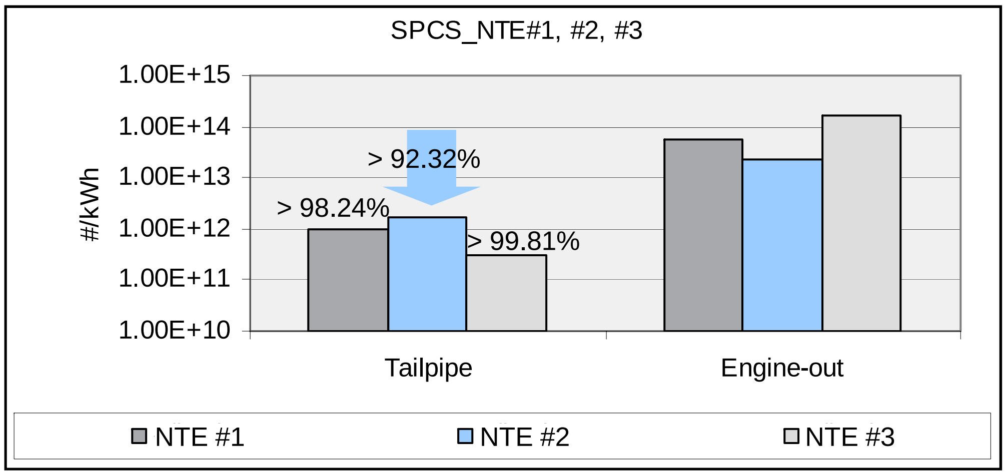
- Cold and hot transient cycle tailpipe PN results well below 10^{11}/kWh.
- Steady state cycles (NRSC variants) all at PN levels ~10^{11}/kWh or below.
- NTE points PN emissions all >10^{11}/kWh and NTE#2 >10^{12}/kWh.
- Engine-out PN from all cycles ranged from ~$6x10^{13}$ to ~$3x10^{14}$/kWh.

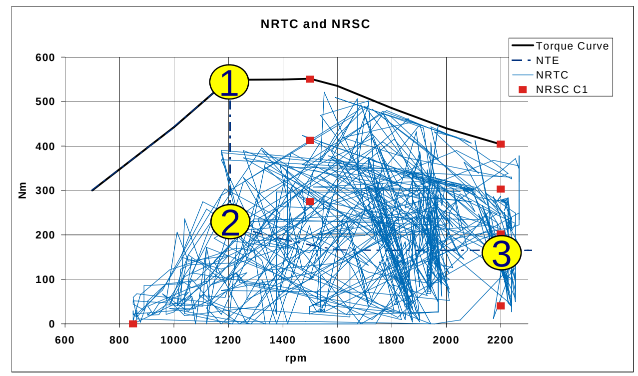
- Tailpipe PN range ~10^{10} to <$1.8x10^{12}$
- Engine-out PN range ~10^{13} to >10^{14}



PMP Particle Number for NTE points

	NTE #1	NTE #2	NTE #3
Engine speed	1200 rpm	1200 rpm	2200 rpm
Torque	550 Nm	220 Nm	165 Nm
Tailpipe PN emissions (#/kWh)	~1.2×10^{12}	~1.7×10^{12}	~2.5×10^{11}
Tailpipe CoV	73%	33%	69%
Engine-out PN (#/kWh)	~5.8×10^{13}	~2.4×10^{13}	~1.6×10^{14}
DPF efficiency	98.24%	92.32%	99.81%



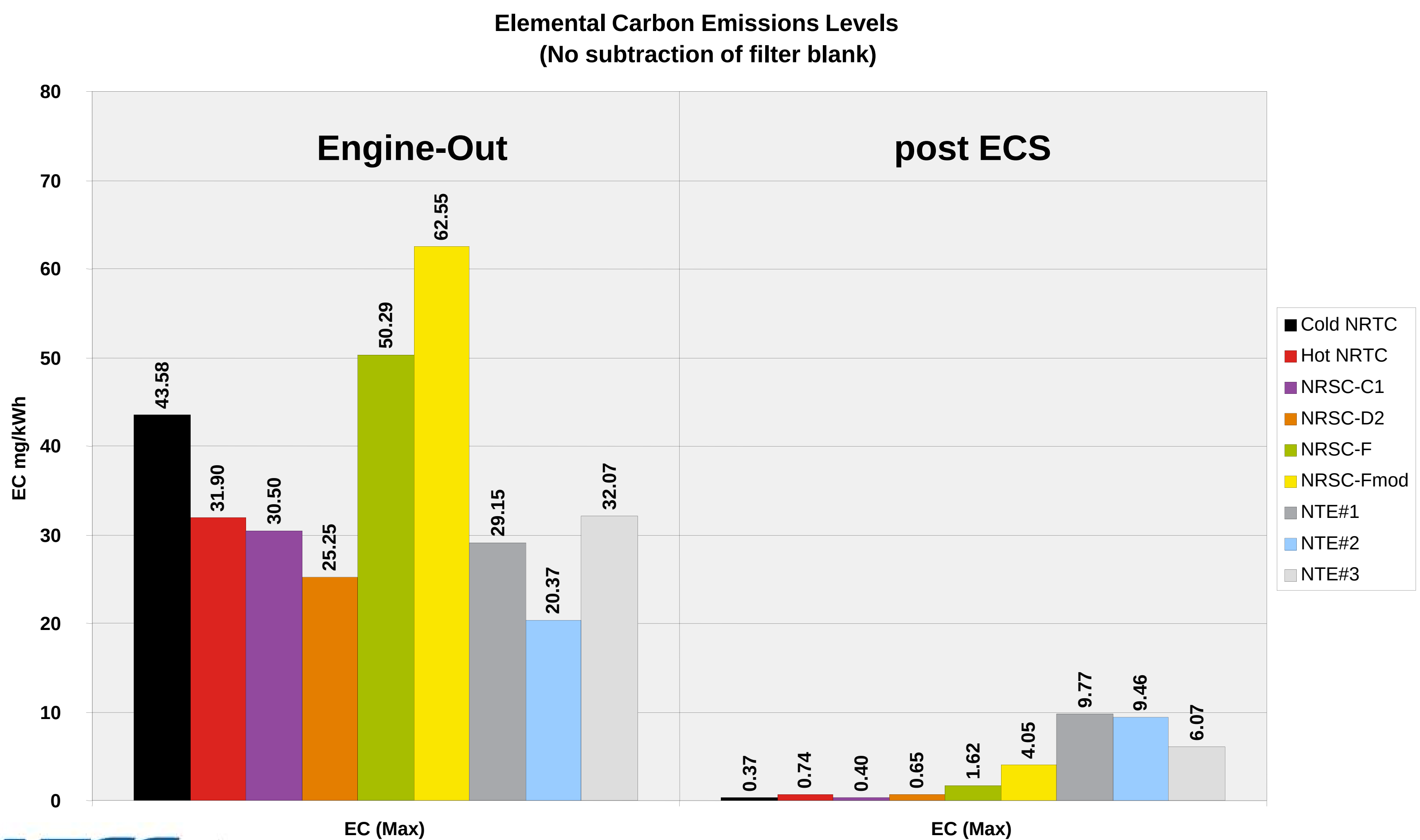


Mean Exhaust temp [°C]	DPF	SCR
COLD NRTC	283	234
HOT NRTC	285	261
NRSC-C1	335	333
NRSC-D2	346	338
NRSC-F	323	342
NRSC-Fmod	326	342
NTE#1	411	378
NTE#2	388	343
NTE#3	319	300

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.

Emissions Levels of Elemental Carbon

- Substantial reduction in EC from engine-out to tailpipe.
- Highest post-ECS levels from NTE points (but not highest engine-out).



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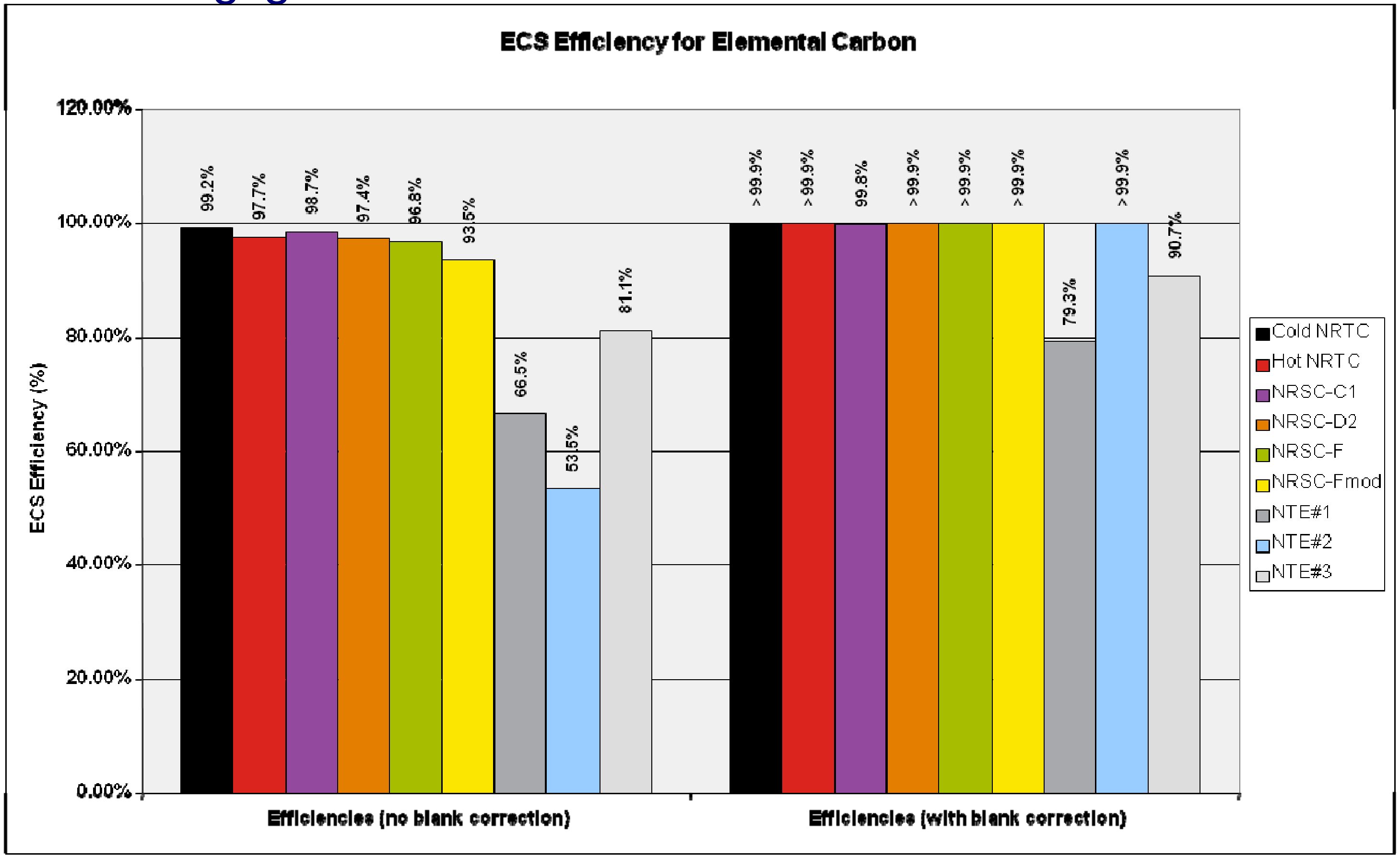
ECS Efficiency for Elemental Carbon

- Filtration efficiencies similar to PN, better than for PM (>93% except NTE's).
  - Elemental carbon comprised ~45% to ~70% of engine-out PM.
  - Volatiles present on filter dominated post-DPF, carbon fraction was negligible.



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.

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Summary (1)

- 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.

(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

nd: not detectable

Summary (2)

- The 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 0,17 and 0,22 g/kWh.
- 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 NO_2 emissions were 50% or less of engine-out levels over all cycles.
- Tailpipe peak ammonia levels were <4 ppm from all regulated cycles – well within legislative requirements.

Summary (3)

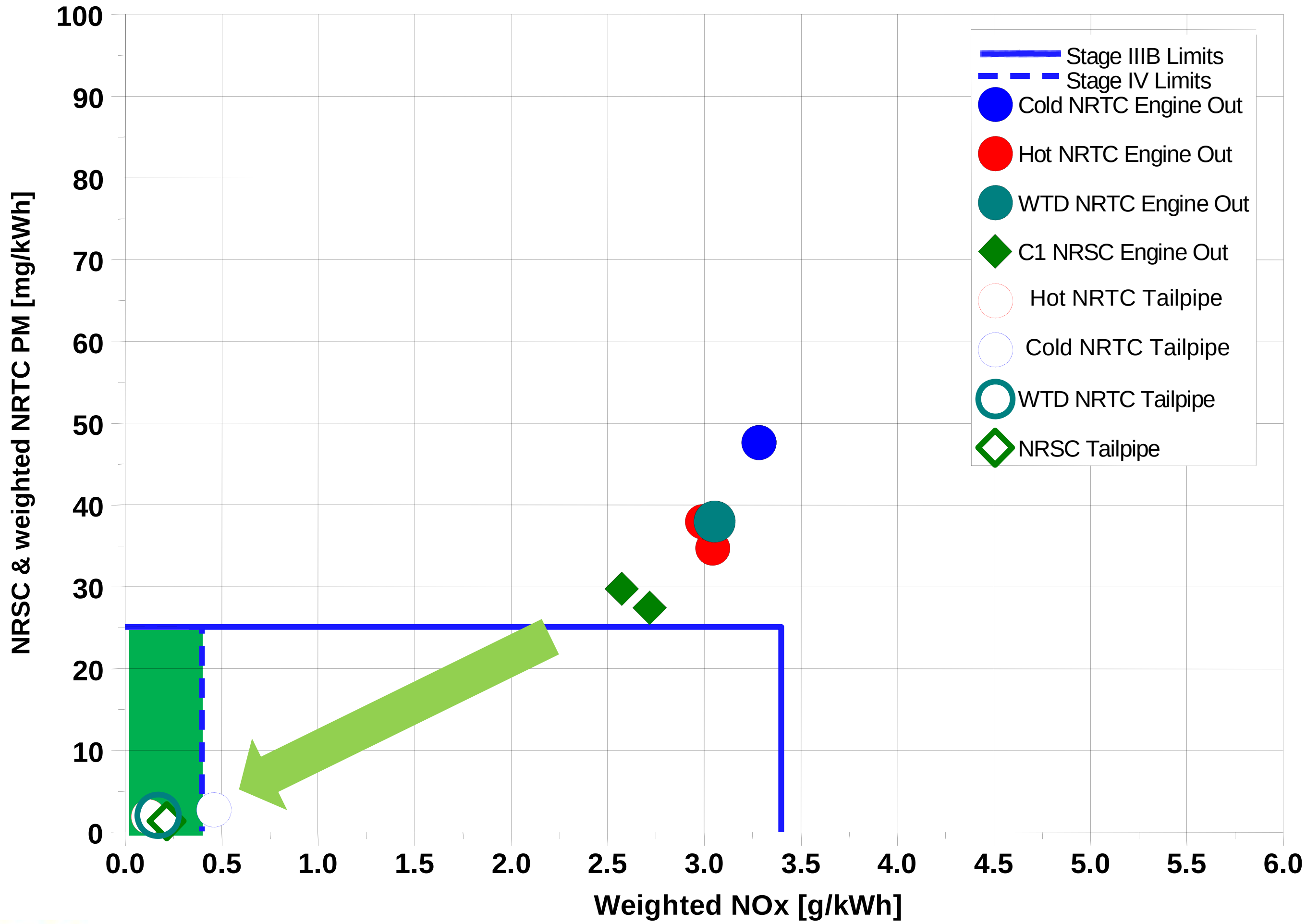
- The HD-PMP PN method proved robust even at near-ambient particle emissions levels and the method proved directly transferrable to non-road applications.
- Engine-out PN data were similar to other diesel engines tested in previous PMP & AECC HD programs: 0.6 to 3 $x10^{14}$/kWh.
- All transient cycles' data showed tailpipe PN emissions well below 10^{11}/kWh.
- Steady state cycles including NTE showed PN emissions below 2 x 10^{12}/kWh.
- System efficiency for PMP PNs was >99.8% for all transient and steady state cycles.
- Elemental Carbon emissions were reduced by the system in parallel with PN reductions.

Overall Conclusions

- The AECC NRMM test project demonstrates the technical feasibility of the Stage IV emissions limits for 56-130kW.
- The HD-PMP method as developed by UN-ECE GRPE for on-road HD engines can be readily used to measure particle emissions (PM and PN) of NRMM engines.
- The HD-PMP method proved very robust for measuring PM and PN emissions.
- Non-regulated and greenhouse gas emissions were well controlled during the AECC NRMM test project. Tailpipe NO_2 emissions were always lower than engine-out levels.
- Future on-road HD Euro VI-like PM and PN emissions levels are demonstrated as technically feasible.

PM and NOx (NRSC & NRTC)

- Tailpipe results with ECS are well within Stage IV limits.



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Acknowledgements

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… and you for your attention