Association for Emissions Control by Catalyst AISBL

Ricardo plc

Particle Number and Particulate Mass Emissions Measurements on a Euro VI DPF and SCR-equipped Heavy-duty Engine using the PMP Methodologies

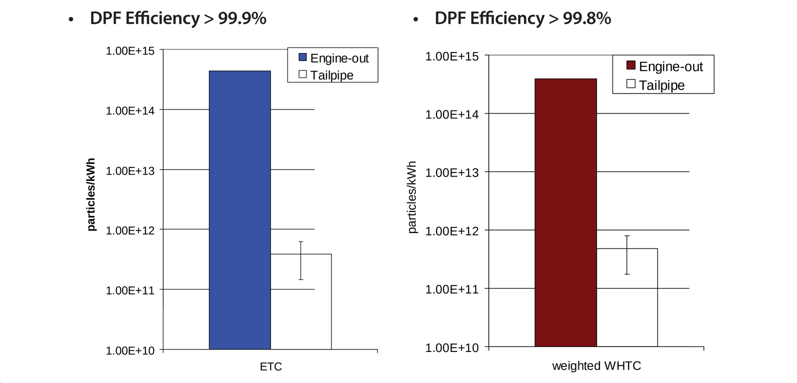
Objectives of the AECC heavy-duty Euro VI test programme

- Demonstrate the performance of an integrated emissions control system on a modern, low NOx engine to be less than 0.4g/kWh from the ETC Cycle
- Compare current European gravimetric and heavy-duty Particle Measurement Programme (PMP) methods for particulate mass (PM).
- Assess heavy-duty PMP particle number methodology.
- Provide data on European, World-harmonised and other major test procedures.

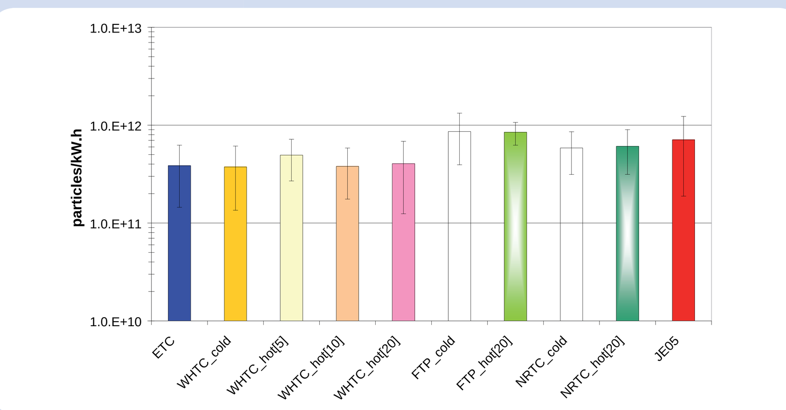
High Efficiency Wall-Flow DPF Employed

PMP Particle Number Results for ETC & WHTC Show >99% Filtration Efficiency

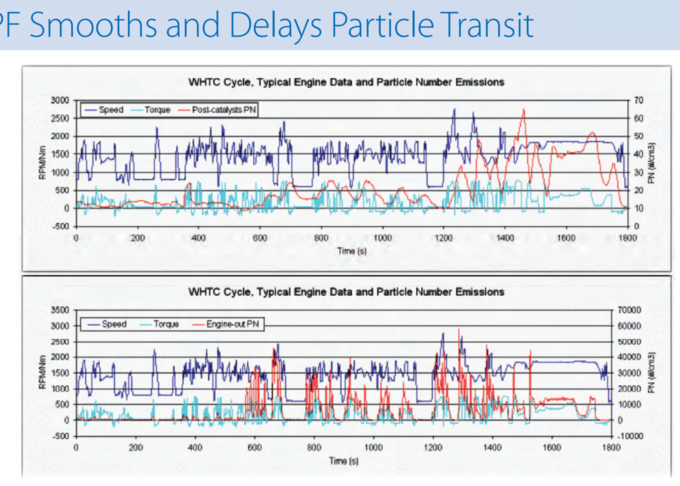
- ETC tailpipe emissions ~ 4 x 1011/kWh
- DPF Efficiency > 99.9%
- WHTC tailpipe emissions < 5 x 1011/kWh
- DPF Efficiency > 99.8%



Particle Numbers Measured From Transient Operation Are Almost Independent of Cycle – DPF 'Flattens' emissions



Continuous Particle Number Traces – DPF Smooths and Delays Particle Transit



Experimental Background

Background to Improved PM and PN Measurement Procedures

- **In the mid-1990's it was widely recognised that the current filter-based mass measurement method is at or near its limit of detection for the cleanest Diesel engines and vehicles**
- **European Govts: Germany, Switzerland, UK, France, Holland, Sweden wished to enforce DPFs to eliminate carbon**
  - Strong relationship between carbon and negative health events
  - Substantial historical data
- **PMP Programme started to explore new methods for the "***development of improved type-approval test protocols for assessing vehicles fitted with advanced particulate reduction technology that would complement or replace the current legislative measurement procedure for particulate mass***"**

Particle Number Measurements Made to Latest PMP Protocol

- **Particle measurements from all tests according to the latest draft of the heavy-duty PMP inter-laboratory correlation exercise guide**
- **Particle number measured engine-out on additional tests from partial flow system**
  - measurements from Horiba MDLT.
- **Delivers**
  - Particle number emissions.
  - Real-time particle emissions traces
  - DPF filtration efficiency for solid particle numbers.
- **PMP does not currently address particle number from partial flow, hence no partial flow tailpipe number measurements.**

AECC heavy-duty Euro VI test programme

- **Engine designed for US2007, provided by an engine manufacturer**
  - 6 cylinder 7.5 litre engine
  - Common rail
  - Turbocharged (fixed vane)
  - Max. injection pressure 180Mpa
  - Cooled lambda-feedback EGR.
- **Emissions control system provided by AECC:**
  - Oxidation catalyst (DOC), catalyst-based particulate filter and urea-SCR with ammonia slip catalyst (ASC).
- **Fluids:**
  - Diesel reference fuel CEC RF-06 (max. 10ppm S)
  - Low ash 10w-40 engine lubricant
  - AdBlue® aqueous urea to DIN 70070 specification.

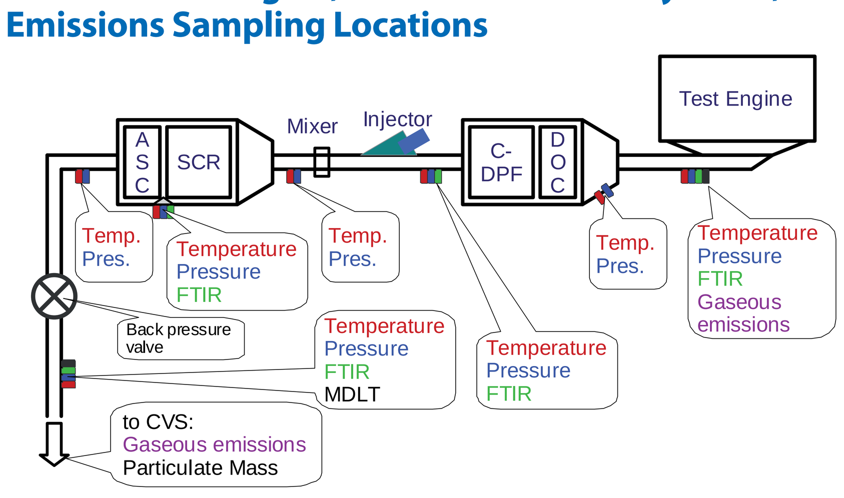
Detailed Preconditioning Procedures Employed to Ensure Consistent ECS State for Each Day's Testing

- **For repeatability, the daily test regime started with a cold start test (WHTC, FTP or NRTC) and finished with a standard preconditioning regime.**
- **The end-of day preconditioning consisted of**
  - mode 4 warm-up: 15 min. 2130 rev/min. 560 Nm
  - followed by: 60 min. 2575 rev/min. 700 Nm
  - then: 60 min. 1300 rev/min. 150 Nm
- **Following each test cycle the engine was run at a Mode 4 standardisation condition for 15 minutes.**
- **Pre-test conditioning**
  - ETC, JE05, ESC: 7.5 min. mode 4 (2130 rev/min, 560 Nm)
  - WHSC: 10 min. mode 9 (1816 rev/min, 373 Nm) followed by 5 min. soak.

Multiple Particulate Mass Measurement Methods Used Simultaneously

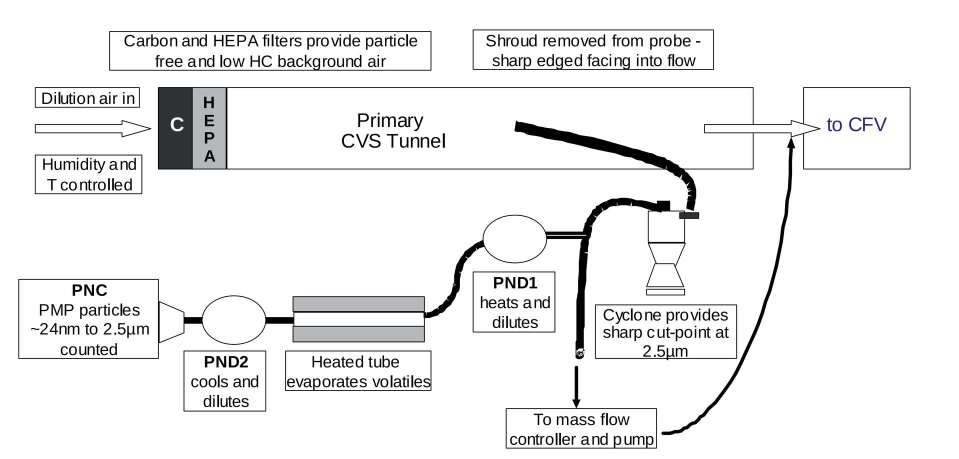
- **3 particle mass methods were tested.**
- **Partial flow system using mini dilution tunnel (MDLT)**
  - Sample taken directly from exhaust, before CVS system and diluted (variable rate) in the MDLT before collection on sample filter.
  - current legislation allows this system to be used as alternative to full flow.
- **Current full-flow legislative method**
  - Diluted sample taken from the CVS system, further diluted in 2nd tunnel, sample collected onto 70mm TX40 filter paper from this secondary tunnel.
- **PMP method**
  - Sample is taken from the secondary dilution tunnel, as for current method.
  - Same principle as current method, but with improved control such as single TX40 sample filter, smaller (47mm) filter, tighter temperatures controls etc.

Schematic of Test Engine, Emissions Control Systems, Measurement and Emissions Sampling Locations



DOC – Diesel Oxidation Catalyst
SCR – Selective Catalytic Reduction
C-DPF – catalyst based Diesel Particulate Filter
ASC – Ammonia Slip Catalyst

PMP Particle Number System Employs Heating, Dilution and Size Classification to Define the Particle Measured



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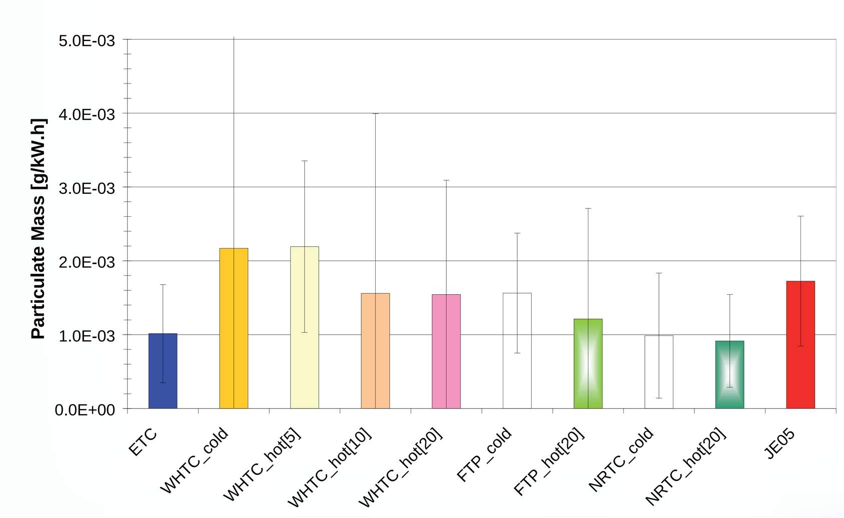
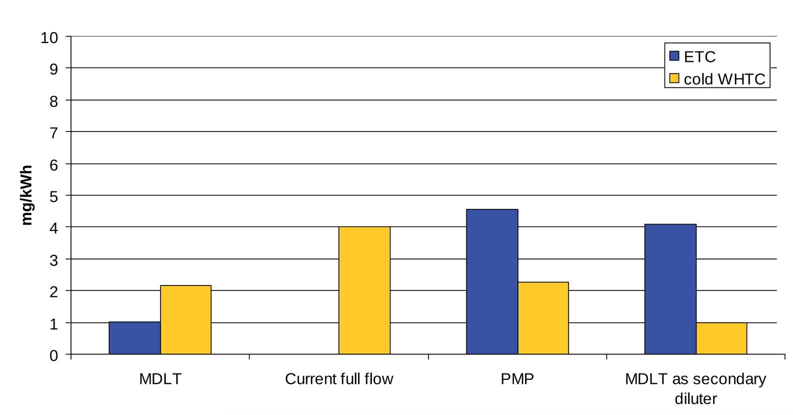
Post DPF PM Levels at <10mg/kWh

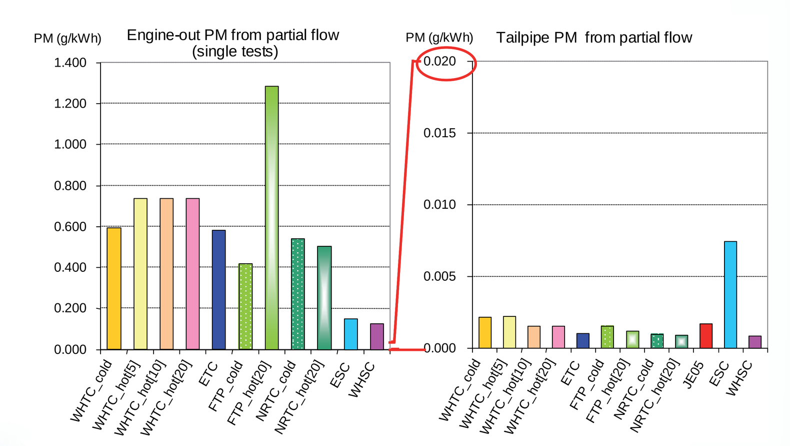
Particulate Mass From Partial Flow System During Transient Operation – Very Low Mass but Poor Repeatability



Comparison of average PM results using different methodologies shows <5mg/kWh in all cases

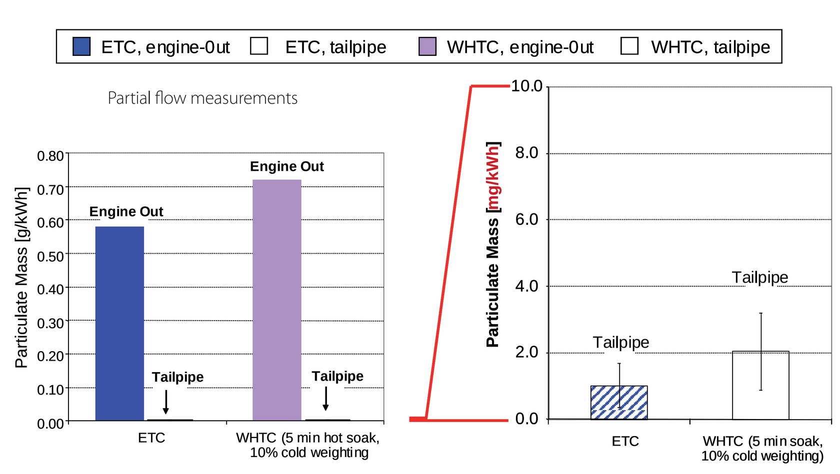


Average PM results for engine-out and tailpipe



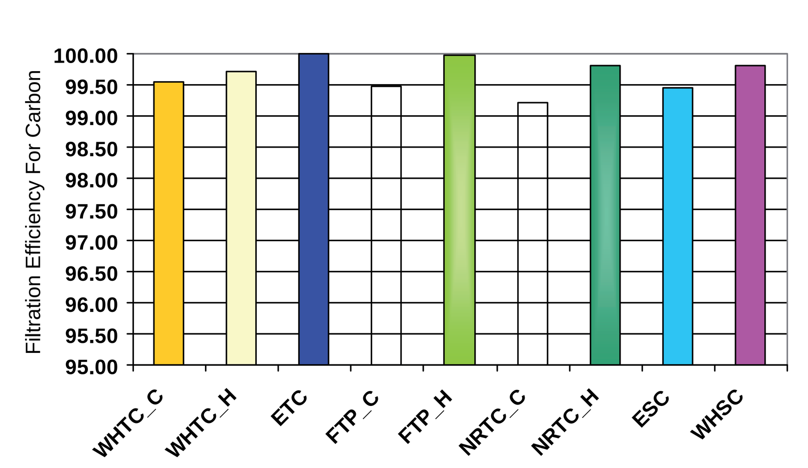
Higher ESC results were believed to be due to mode 10 desorbing low volatility materials.

ETC and WHTC PM emissions for engine-out and tailpipe show >99% reduction



Filtration efficiency for elemental carbon >99% for all emissions cycles

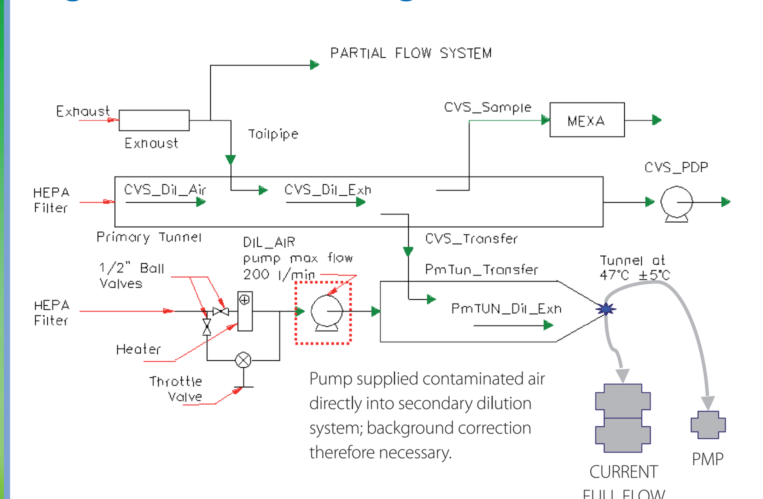
- Particulate filter efficiency for removal of elemental carbon is > 99%.
- Efficiencies for particle numbers and elemental carbon are very similar



Summarised Emissions Data

Test Procedure		THC Engine Out	THC Tail pipe	THC Conv. Effy.	NOx Engine Out	NOx Tail pipe	NOx Conv. Effy.	CO Engine Out	CO Tail pipe	CO Conv. Effy.	PM Engine Out	PM Tail pipe	PM Conv. Effy.
		Emissions [g/kW.h]											
Current European Test Cycles													
ETC	hot start, transient	0.43	**0.16**	63%	1.10	**0.15**	86%	8.59	**0.87**	90%	0.581	**0.001**	99.8%
ESC	Steady state	0.15	**0.06**	63%	1.54	**0.15**	90%	1.10	**0.00**	100%	0.151	**0.009**	94.3%
Worldwide Harmonised Cycles													
WHTC	cold, +5 min, +hot transient	0.63	**0.20**	69%	1.25	**0.30**	76%	9.09	**1.92**	79%	0.72	**0.002**	99.7%
WHSC	Steady state	0.19	**0.01**	95%	1.33	**0.18**	87%	1.00	**0.02**	98%	0.128	**0.001**	99.3%

Background Contamination Derived From Dilution Air Led to High Apparent Emissions – Regulations Allow Background Subtraction



Partial Flow Particulate Measurements Gave Extremely Low Filter Masses From All Cycles

- **Partial flow PM measurements from mini dilution tunnel (MDLT) show very low levels of mass**
  - Maximum total mass collected on filter was only 41μg (ESC)
  - Other cycles' results typically 10 to 20μg, similar to background levels
  - Typical uncorrected specific emissions from ETC/WHTC/JE05 cycles ~ 1 to 2mg/kWh.
  - ESC results were higher, believed to be due to mode 10 desorbing low volatility materials that are captured by the filter
  - Particle number counting was used to verify MDLT operation.
  - Subtraction of background reduces all masses to zero.

Overview

- **The PMP particle number method proved very repeatable even at near-ambient particle emissions levels.**
- **Engine-out particle number data was in the range of 2.5 to 5 x 10^{14}/kWh.**
- **All transient cycles data showed tailpipe particle number emissions below 10^{12}/kWh.**
- **Particle numbers were essentially cycle-independent.**
- **Background-corrected PM from PMP method gave results below 5mg/kWh.**
- **PM measurements from MDLT show very low mass levels**
  - Maximum 41μg total mass on filter (ESC).
  - Typical uncorrected emissions from ETC and WHTC: ~ 1 to 2 mg/kWh
- **Background contamination problem encountered on both full flow methods but**
  - Masses indistinguishable from background levels from all tests.
  - Subtraction of background reduces all masses to zero.
- **Filtration efficiencies for PM, Particle number and Elemental Carbon were all in excess of 99%**