Overview of the European "Particulates" Project on the Characterization of Exhaust Particulate Emissions from Road Vehicles

Results for Heavy-Duty Engines

Neville Thompson
CONCAWE
Leonidas Ntziachristos, Zissis Samaras
Laboratory of Applied Thermodynamics, Aristotle University Thessaloniki
Paivi Aakko
VTT, Finland
Urban Wass
Volvo Technology, Sweden
Stephan Hausberger
Technical University of Graz, Austria
Theodor Sams
AVL List GmbH, Graz Austria

"Particulates" – Results for HD Engines

- Outline of Heavy Duty test programme
- Heavy Duty Engines test matrix and methodology
- Results
  - Regulated particulate mass
  - Solid particle number
  - Size segregated particulate mass
  - Active surface
  - Total particle number
  - Particle size distributions
- Conclusions

Heavy Duty Test Programme

- Heavy duty engine testing was performed in 3 individual laboratories:
  - AVL List GmbH, Graz, Austria (Lab a)
  - Volvo, Sweden (Lab b)
  - VTT, Finland (Lab c)
- A range of engines from Euro-I to prototype Euro-IV and Euro-V systems, with advanced after-treatment such as SCR/urea and EGR plus particulate filters were tested
- Several heavy duty diesel vehicles were also tested by the Technical University of Graz, Austria in order to relate the engine data to real world driving
- Only the heavy duty engine test results are described here
  - Evaluation of the vehicle test data is on-going and will be reported separately

Heavy Duty Engines - Test Matrix

Engine	Year	Capacity [dm^3]	Power@speed [kW/rpm]	FIE type	Fuels
Laboratory a					
EURO-III	2002	12	300/1800	unit inj.	D2, D3, D4, D5, D6, D7
Prototype + SCR (EURO-V)	2002	12	300/1800	unit inj.	D3, D4, D5, D7
Prototype + CRT (EURO-IV)	2002	11	300/1900	unit inj.	D3, D4, D5, D7
Laboratory b					
EURO-I	1992	12.0	247/1900	DI	D1, D4, D5
EURO-III	2000	12.1	380/1800	DI	D1, D4, D5
EURO-III + CRT	2000	12.1	380/1800	DI	D4, D5
Laboratory c					
EURO-II	1996	9.6	210/2000	DI	D2, D4, D3, D5
EURO-II + CRT	1996	9.6	210/2000	DI	D4, D3
EURO-III	2000	10.6	250/1900	DI, EDC	D2, D4,
EURO-III + SCR	2000	10.6	250/1900	DI, EDC	D4

ENGINE TEST METHODOLOGIES: Tests were carried out using the standard EU regulatory test cycles: European Steady-state Cycle (ESC) and European Transient Cycle (ETC), plus selected steady-state points.

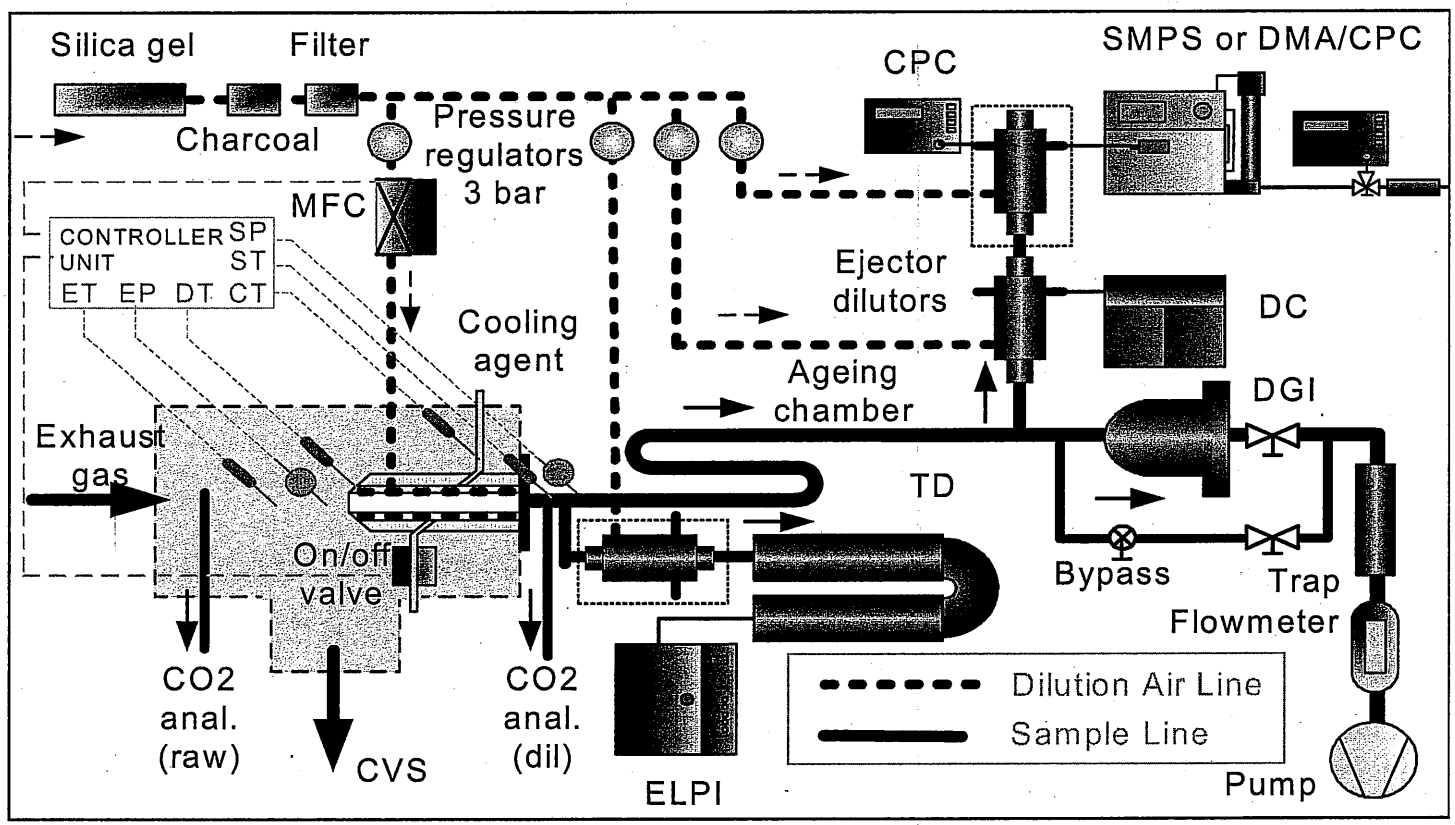
Diesel Fuel Qualities Tested

- In order to be applicable for emissions factors and to provide an overall assessment of diesel fuel quality effects, a range of diesel fuels representative of fuels from Euro-I generation through to 2005 and beyond were tested. Swedish Class 1 diesel was included as an example of an extreme fuel change. Fuels coded:

❑ D1	Euro-I Diesel: 1550 ppm S
❑ D2	EN 590 Diesel: 280 ppm S
❑ D3	EN 590 Diesel: 38 ppm S
❑ D4	EN 590 Diesel: 8 ppm S
❑ D5	Swedish Class 1 Diesel
❑ D6	Pre-2000 Diesel
❑ D7	D4 + 5% RME

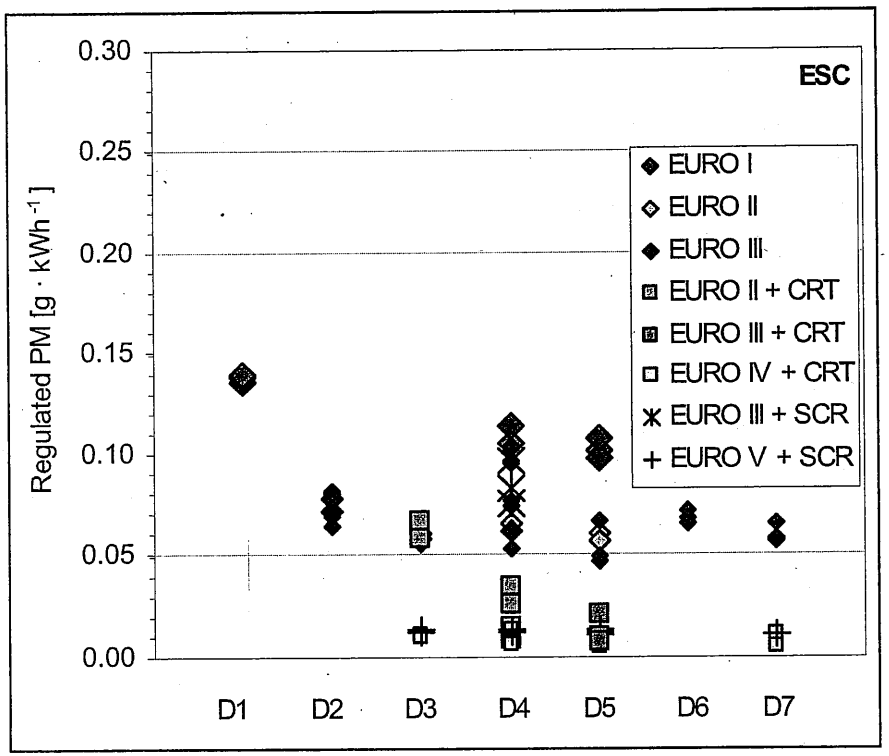
Particulates Sampling and Measurement

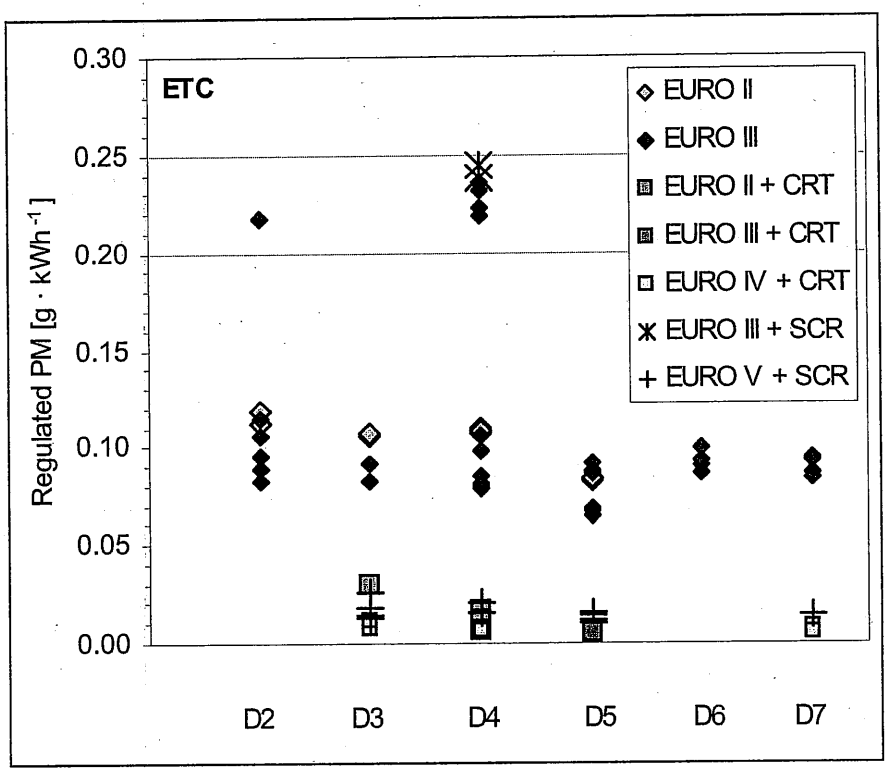
- The standard "Particulates" sampling and measurement system was utilised as far as possible in order to provide measurements of both "accumulation" and "nucleation" mode particles



- One partner carried out additional measurements using DDMPS & TrDMPS

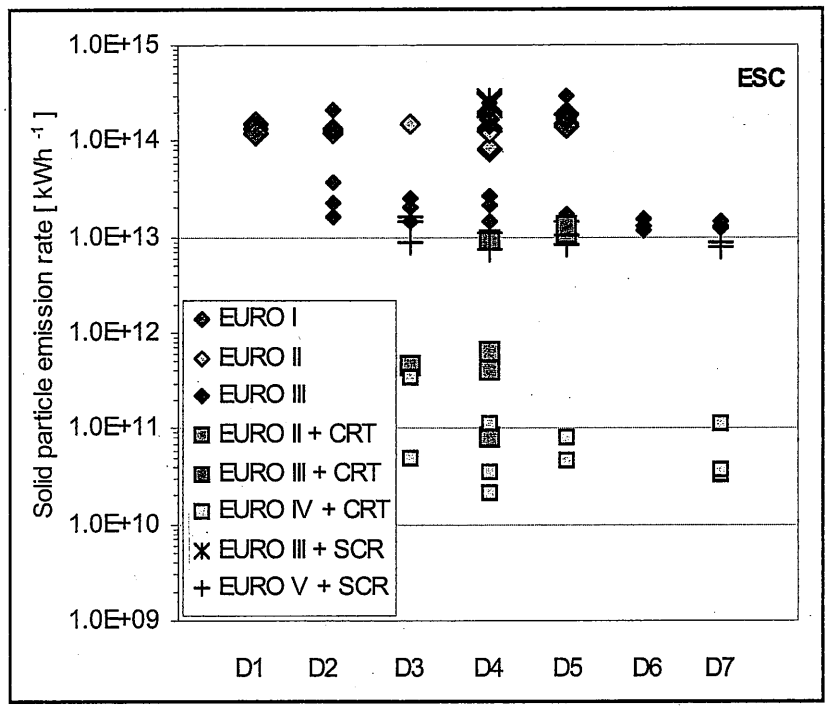
Regulated Particulate Mass (PM)

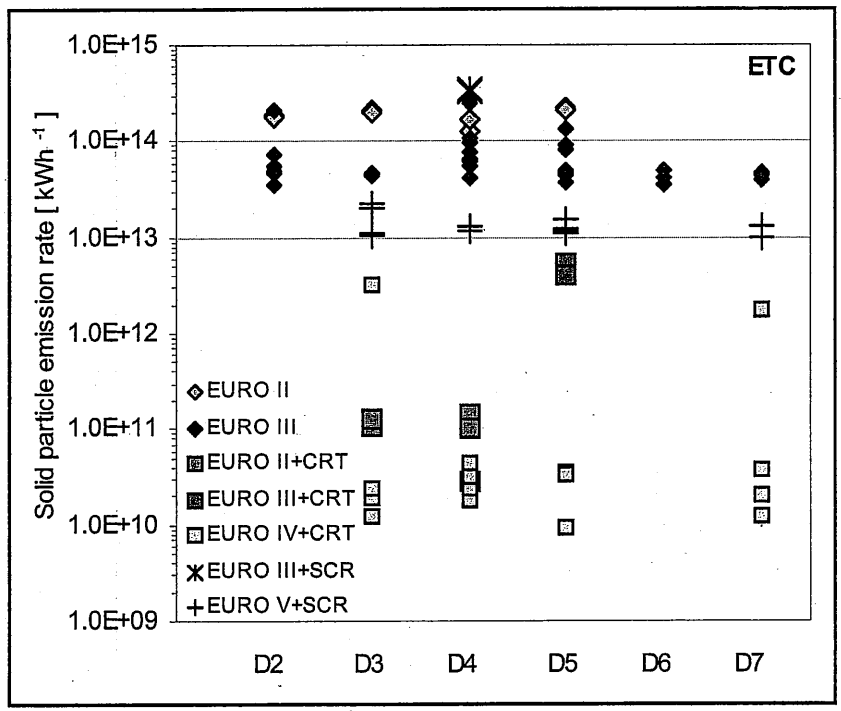




- Very low PM emissions achieved with DPF equipped systems on low sulphur fuels, & with Euro-V SCR/urea prototype without DPF
- Benefits of fuel sulphur reduction also evident

Solid Particle Number (ELPI + Thermodenuder)

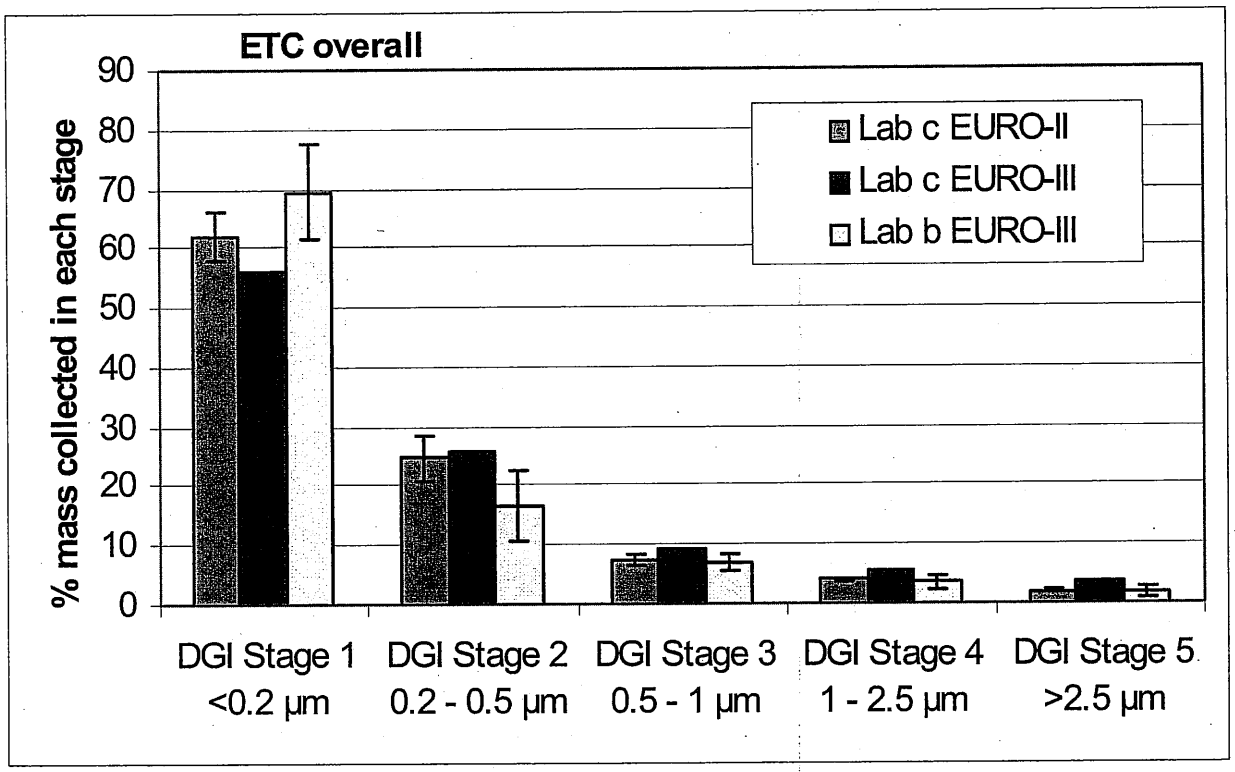




- Conventional Euro-I to Euro-III engine technologies produced total solid particle number emissions in the range of 10^{14} particles/kWh
  - Results for one Euro-III engine ca. an order of magnitude lower, needs further explanation
- DPF systems offer the potential to reduce solid particle numbers by 3-4 orders of magnitude
- Euro-V system with SCR/urea (without DPF) produced around 10^{13} particles/kWh, ca. 90% < typical Euro-III cases, but 2 orders of magnitude higher than best DPF systems

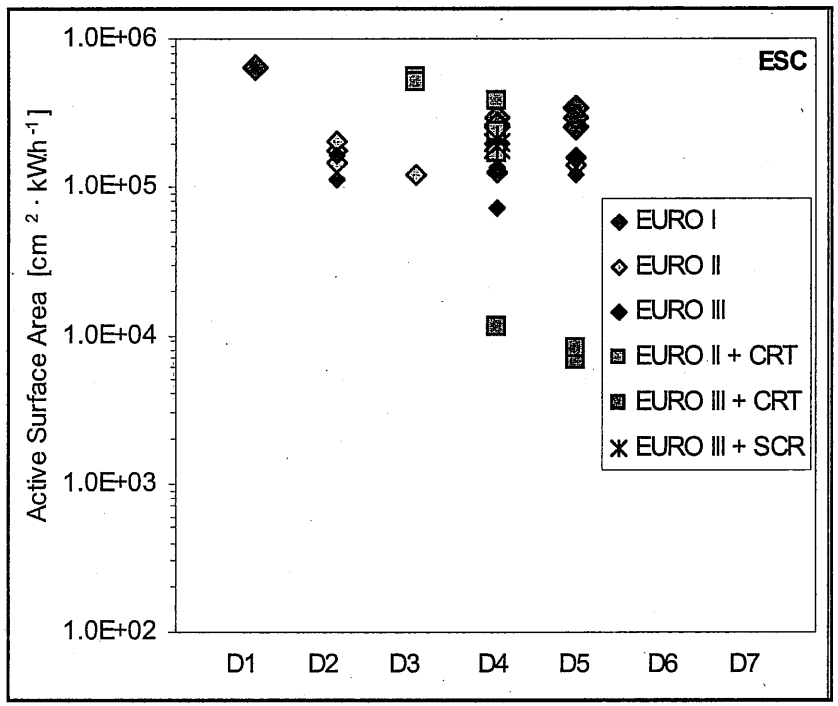
Size Segregated Particulate Mass

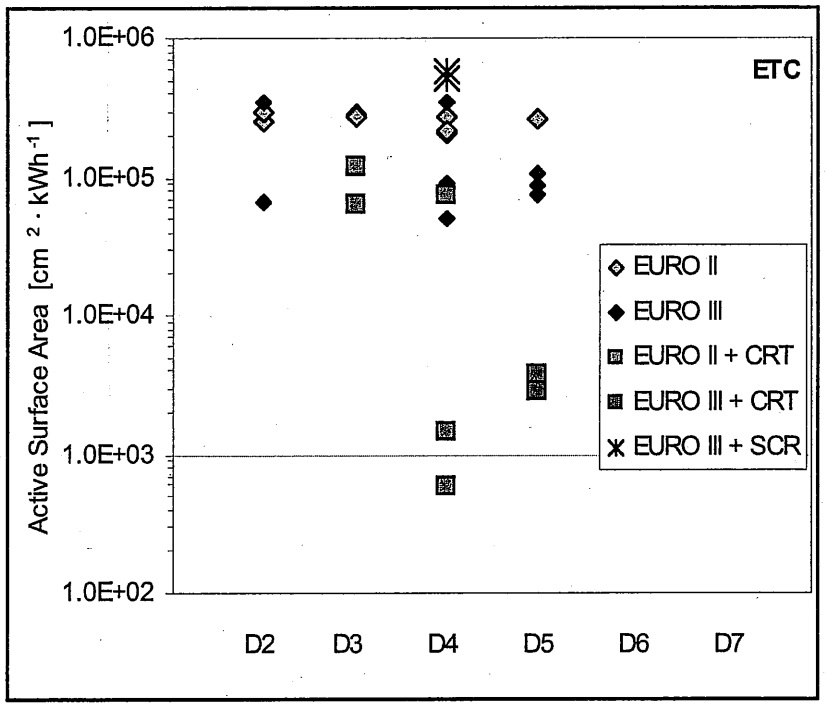
- Size segregated particulate mass was measured by two of the labs using a gravimetric impactor (DGI)



- The largest portion of the total mass collected was below 0.2 µm
  - 90% of the mass is of a size below 0.5µm

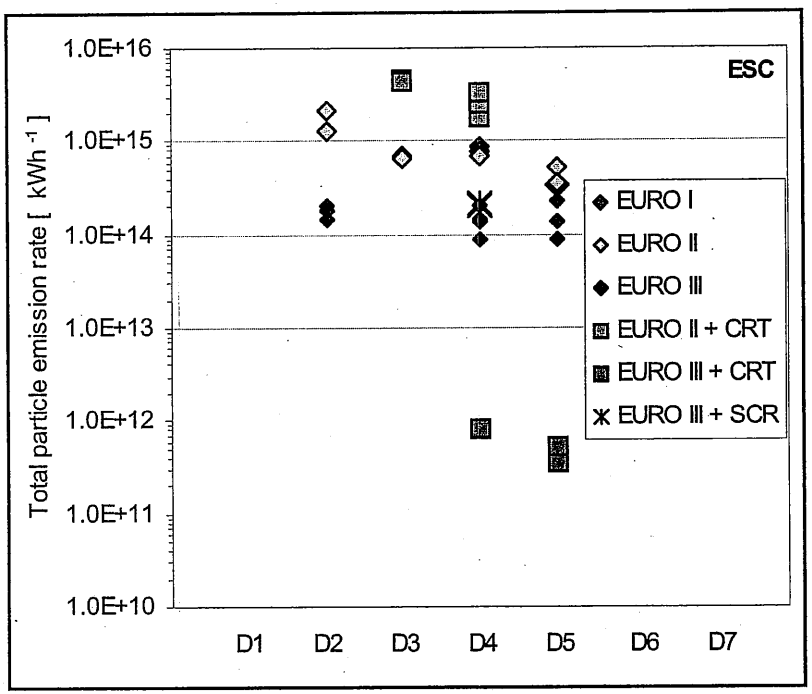
Active Surface (Diffusion Charger, "wet" branch)

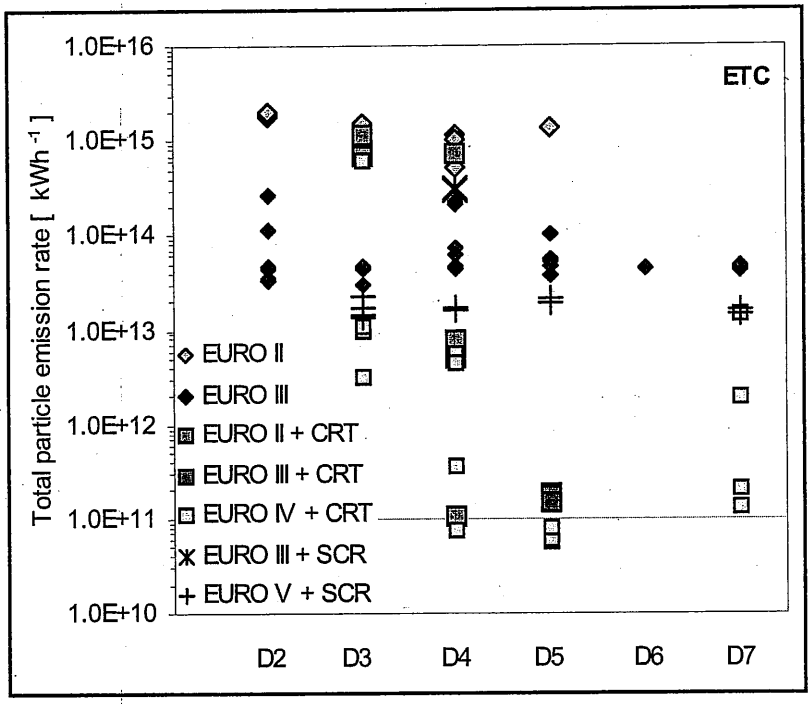




- Euro-I to Euro-III engines produced active surface values in the range 10^5 to 10^6 cm²/kWh. The Euro-III engine with CRT gave 1-2 orders of magnitude reduction, broadly in-line with its ELPI performance.
- The Euro-II engine with CRT gave active surface values in the same range as the Euro-I to Euro-III conventional engines, indicating formation of high number of nucleation mode particles

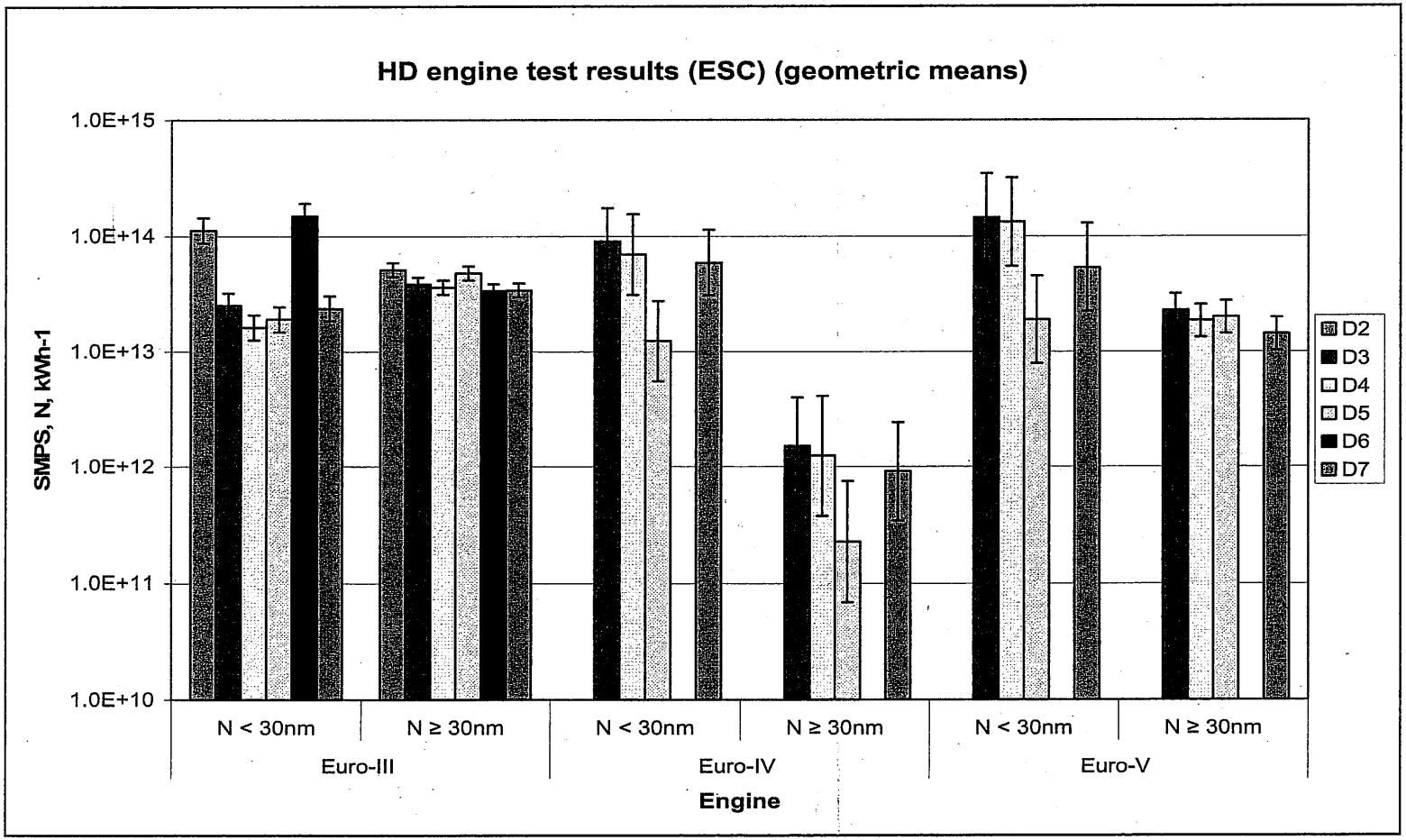
Total Particle Number (CPC, "wet" branch)





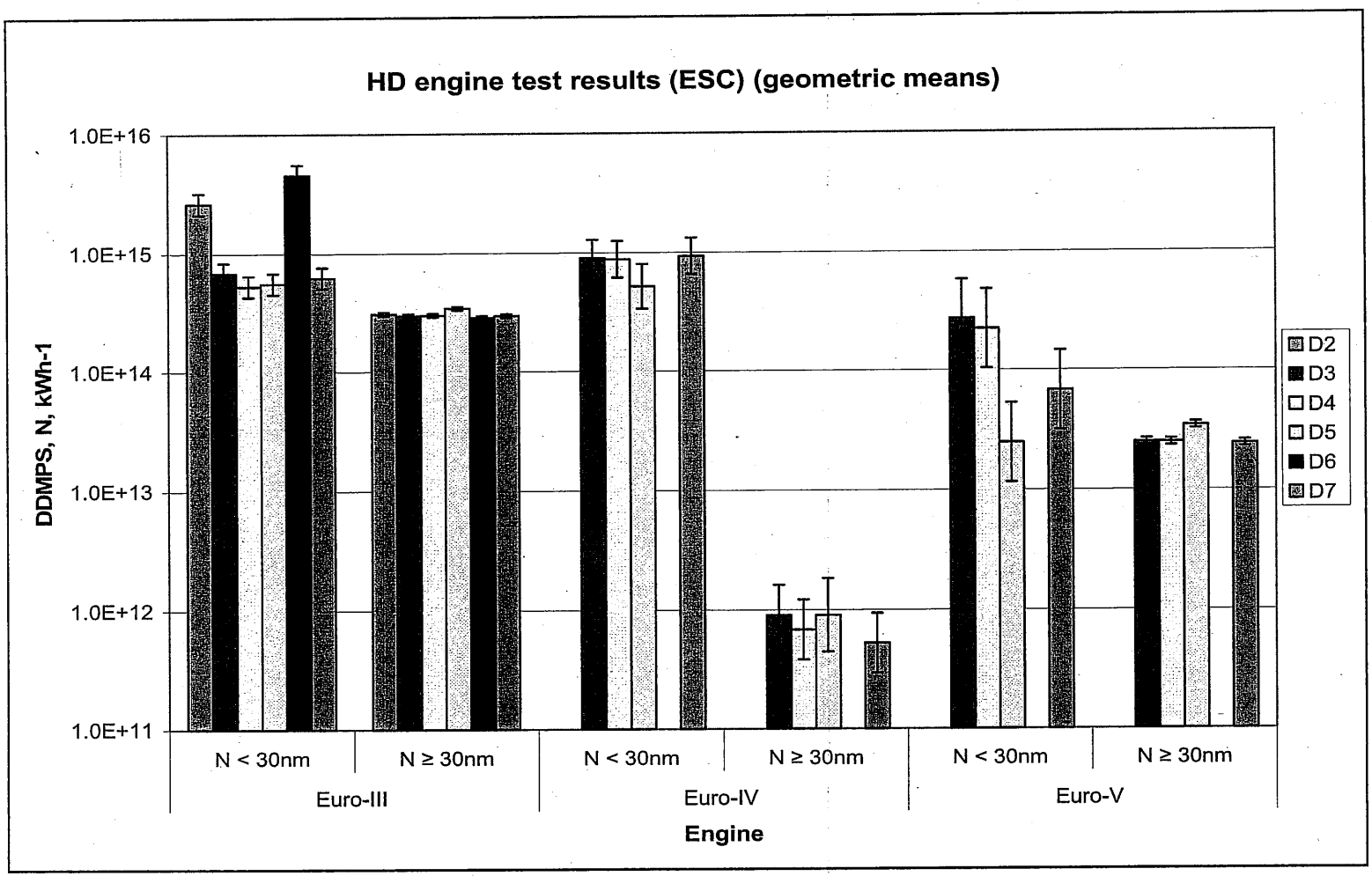
- Total particle number (CPC) emissions of conventional Euro-I to Euro-III heavy duty diesel engines were in the range 10^{14} to 10^{16} particles/kWh
- DPF systems operating on low sulphur fuels have the capability to reduce the total number count by ca. 3 orders of magnitude. However, some cases showed high numbers of nucleation mode particles, particularly at high temperatures
- Sulphur effects also evident

Particle Size Distributions (SMPS)



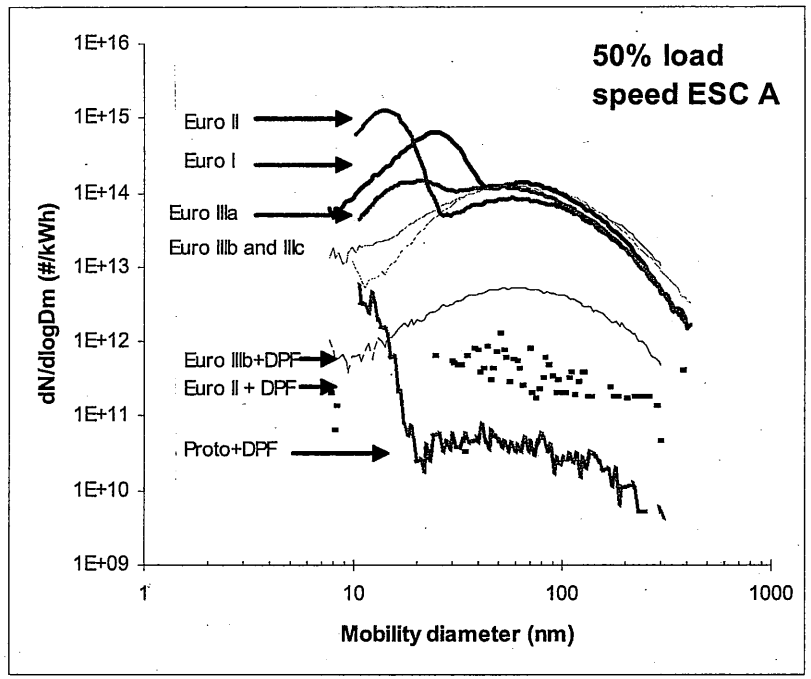
- Clear benefit from sulphur reduction on nucleation mode particles (D2 & D6)
- Lowest number of accumulation mode particles with Euro-IV DPF system

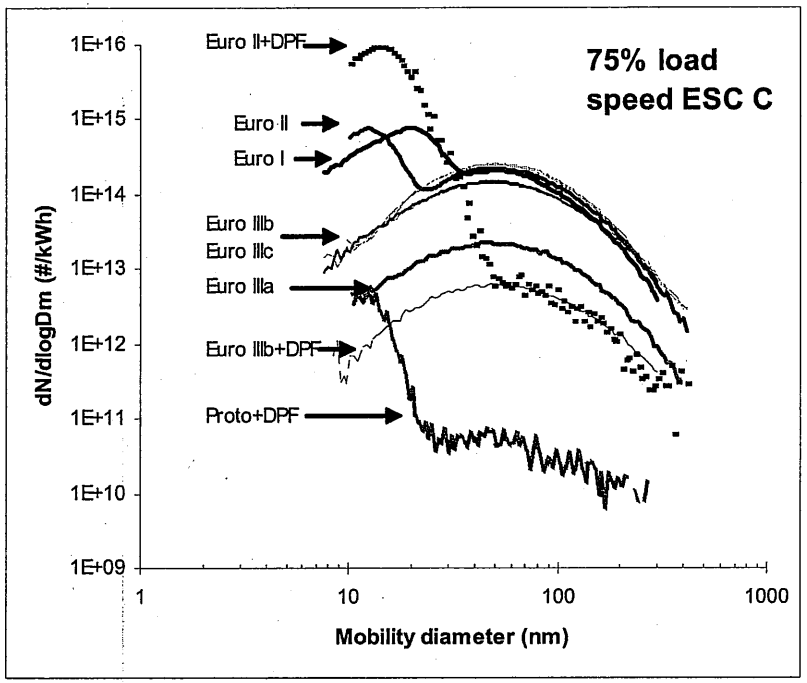
Particle Size Distributions (DDMPS)



- Similar overall trends as seen with SMPS

Particle Size Distributions (SMPS)





- Fairly consistent size distribution profile for the accumulation mode for the conventional diesel engines
- Nucleation mode is evident at high load conditions, (even on the low sulphur fuel D4), especially on the DPF-equipped Euro-II engine
- Some lab-lab differences highlight calibration issues

Conclusions (1)

- The "Particulates" measurement protocol has been successfully applied to the testing of heavy duty diesel engines in 3 different laboratories
- Euro-IV & V HDEs with after-treatment systems operating on sulphur-free fuels should bring dramatic improvements in PM emissions. A much larger step than the steps taken from Euro-I to Euro-III. The transient test cycle brings an additional level of control versus steady state only testing
- Heavy duty diesel engines equipped with particulate traps produced very low particulate mass emissions, low numbers of carbonaceous particles and low total numbers of particles when operating on low sulphur fuels
- A heavy duty prototype Euro-V engine equipped with SCR/urea, but without a particle trap, produced very low particulate mass, within the Euro-V limits, but its particle number emissions remained higher than the DPF-equipped option
- The effect of fuel sulphur was greatest under high temperature operation
  - Under these conditions, lower sulphur fuels reduced both particle mass and number emissions
- In the more advanced engine technologies, fuel effects other than sulphur on particulate emissions were small in absolute terms.

Conclusions (2)

- Particle mass measurement is capable of distinguishing between engine technology levels up to DPF-equipped systems. Its continued use in regulation has the advantage of providing continuity with previous data
- Particle number measurement techniques offer the potential for greater measurement sensitivity and discrimination, and are of particular value for research into cleaner vehicles and fuels
- There is some evidence that the number of "solid" particles emitted does not always correlate with mass. However, further methodology development, including definition of suitable instrument calibration procedures and standards and multi-lab validation exercises would be required prior to use of "solid" particle number standards in regulation
- Both solid accumulation mode and volatile nucleation mode particles have been successfully measured under laboratory conditions. However, nucleation mode particles are highly dependent on sampling conditions
- Further research continues to be needed on the health relevance of measurements of "nucleation" mode particles, their chemical composition and their fate in the atmosphere.