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ABSTRACT AND SUMMARY

Title: **Overview of the Results and Conclusions of the EU "Particulates" Project**

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This presentation provided an overview of the results on light duty vehicles and heavy duty engines, collected in the EU "PARTICULATES" project, which aimed at the characterization of exhaust particle emissions from road vehicles. A novel measurement protocol, developed to enable study of the production of nucleation mode particles over transient cycles, has been successfully employed in several labs to evaluate a wide range of particulate properties with a range of vehicles, engines and fuels. The measured properties included particle number, with focus separately on nucleation mode and solid particles, particle active surface and total mass.

The light duty vehicle sample consisted of 22 cars, including conventional diesels, particle filter equipped diesels, port fuel injected and direct injection spark ignition cars. Four diesel and three gasoline fuels were used, mainly differentiated with respect to their sulfur content which ranged from 300 to below 10 mg/kg. Additional diesel fuels were tested by some partners to evaluate the effects of changes in other fuel properties. All data (both real time and integrated) were collected in a common data base and centrally analyzed using common formats and methodologies, in order to eliminate inconsistencies and optimize comparability. Results show that particulate emissions are dramatically reduced by the combination of particulate traps and low sulfur fuels. However, particulate emissions patterns are also shown to differ between type approval and motorway driving conditions; this applying to both vehicle technology and fuel sulfur effects; the latter becoming more obvious under high temperature conditions.

The heavy duty engine sample consisted of 10 engines, ranging from Euro-1 to prototype Euro-5 technologies. Measurements were made in three labs to evaluate a wide range of particulate properties with a range of heavy duty engines and fuels. The same core diesel fuels were used as in the light duty programme, with additional fuels tested by some partners to evaluate the effects of changes in other fuel properties. Engine tests were mainly conducted over the standard regulatory ESC and ETC cycles, though additional steady state conditions, including some off-cycle points, were also assessed. As for light duty vehicles, the results show that particulate emissions from heavy duty engines are markedly reduced by advanced technologies, most notably by the combination of particulate traps and sulfur-free fuels. Particulate emissions patterns are also shown to be influenced by operating conditions; in particular fuel sulfur effects are most obvious under high temperature operation. The study provides evidence that particulate number measurement offers the potential for greater sensitivity in evaluating particulate emissions. It also demonstrated that the "Particulates" dedicated sampling procedure is capable of delivering repeatable results even in the case of the unstable nucleation mode, also for heavy duty engines.

Overall it is concluded that:

The “Particulates” measurement protocol has been successfully applied in multiple labs to evaluate both LDVs and HDEs on a number of fuels. A database for future development of emissions factors for a wide range of technologies and particulate properties has been generated.

DPF-equipped diesel engines can produce very low particulate mass emissions, low numbers of solid particles and low total numbers of particles when operating on sulphur-free fuels. This represents a much larger step than Euro-I to Euro-III and brings DPF-equipped diesel engines to a level comparable with conventional gasoline vehicles.

DI gasoline vehicles gave measurable emissions in most particle properties, though particulate mass emissions were well below Euro-4 diesel limits.

A heavy duty prototype Euro-V diesel engine with SCR/urea, without a DPF, gave very low particulate mass, but number emissions remained higher than the DPF option.

The effect of diesel fuel sulphur was greatest under high temperature operation; under these conditions, lower sulphur fuels reduced particle mass and number emissions. In the advanced engine technologies, fuel effects other than sulphur on particulate emissions were small in absolute terms.

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. On the other hand, particle number measurement techniques offer the potential for greater measurement sensitivity and discrimination, and are valuable for further research into cleaner vehicles and fuels.

There is some evidence that the number of “solid” particles does not always correlate with mass. However, further methodology development, including definition of suitable instrument calibration procedures and multi-lab validation, would be required prior to use of “solid” particle number measurements in regulation.

Both solid accumulation mode and volatile nucleation mode particles have been successfully measured under laboratory conditions. However, it should be remembered that 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.

Overview of the Results and Conclusions of the EU *Particulates* Project

- Characterisation of Exhaust Particulate Emissions from Road Vehicles -

Neville Thompson

CONCAWE

On behalf of the Particulates Consortium

Partners:

Aristotle Univ. (GR) – Coordinator
CONCAWE (B)
Volvo (S)
Tampere University (FIN)
EMPA (CH)
AEATechnology (UK)
Institut Français de Pétrole (F)
AVL (AUT)
AVL-MTC (S)
Graz Technical University (AUT)
Aachen University (D)
Joint Research Center (NL)
VTT (FIN)
Ford Research Center Aachen (D)

Associate partners:

Renault (F)
INRETS (F)
Dekati (FIN)
Stockholm Univ. (S)
Athens Univ. (GR)
TRL (UK)
INERIS (F)
LWA (UK)

Consultants

D. Kittelson
G. Reischl

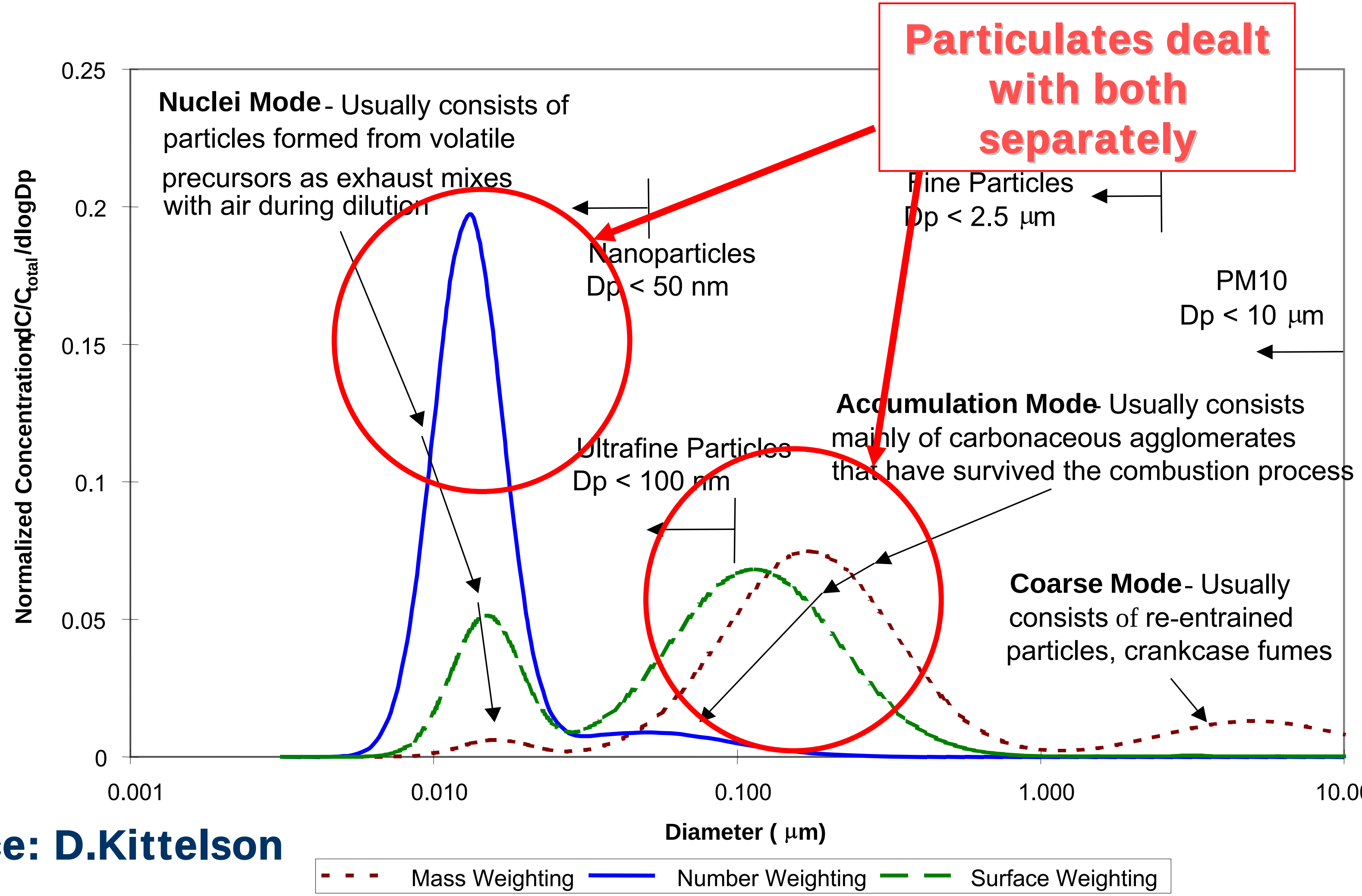
Contents of the presentation

- Scope and Objectives
- Overview of the sampling system
- Results for LDVs
- Results for HDEs
- Conclusions

Scope and Objectives

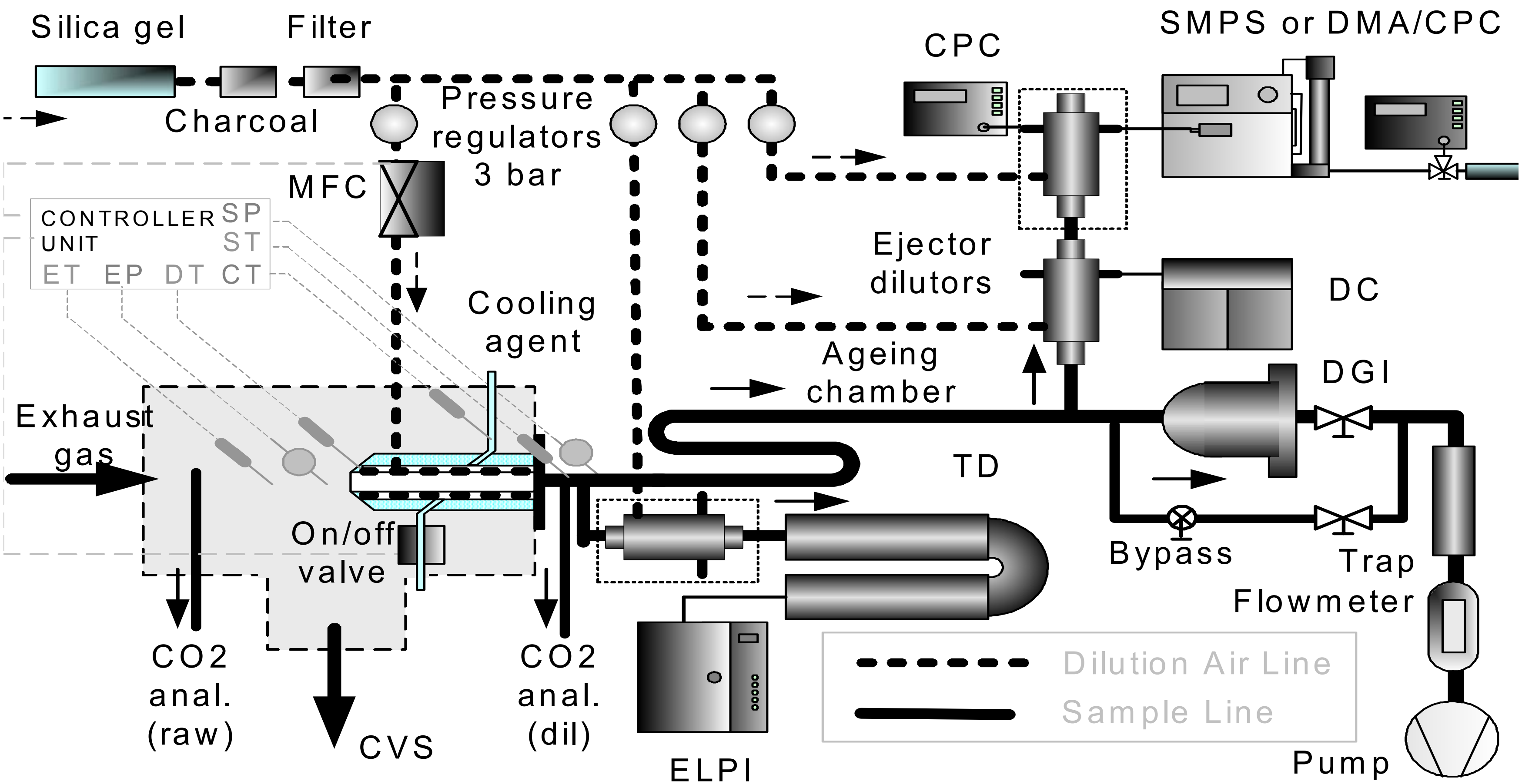
- Research conducted in the framework of the **“Particulates”** project funded by the European Commission, DG TREN (Apr. 2000 – Sep. 2003)
- Scope of the project was to **develop a sampling methodology** for the detailed characterization of exhaust particles and to **apply it** for measurements on a large number of cars and heavy duty engines
- Primary aim was to develop a basis for **emission factors** for several particle properties for various engine technologies, fuels and aftertreatment systems
- Detailed results have been reported in two SAE papers
  - Light duty vehicles: SAE 2004-01-1985
  - Heavy duty engines: SAE 2004-01-1986

Typical Diesel Particle Size Distributions Number, Surface Area, and Mass Weightings



Source: D.Kittelson

Sampling System Used



Experimental: Particle Properties Recorded

Instrument	Property	Size resolution	Temporal resolution
Condensation Particle Counter (CPC)	Particle number concentration	One channel >7 nm	1 s (transients)
Scanning Mobility Particle Sizer (SMPS)	Particle sizing and concentration	64 channels per decade 7-300 nm or 10-450 nm	90 s (steady states)
Electrical Low Pressure Impactor (ELPI) + thermodenuder (TD)	Solid particle sizing and concentration	First 8 channels considered with filter stage 7nm - 1 μm	1 s (transients)
Diffusion Charger (DC)	Active surface	One channel 7nm - 1 μm	1 s (transients)
Gravimetric Impactor (DGI)	Mass-based particle sizing	5 stages <10 μm	Integral over a test

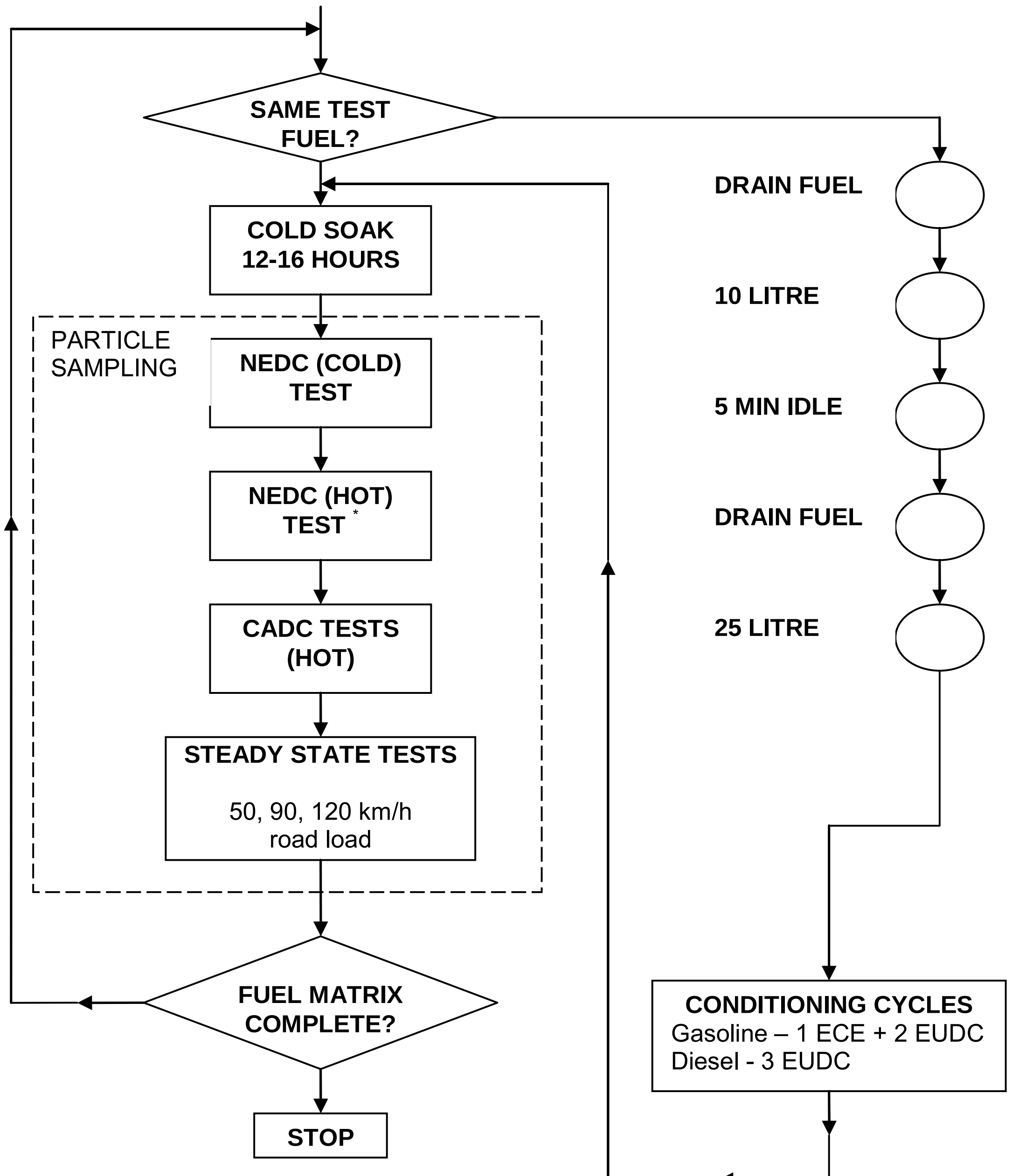
Fuels used

Fuel Code	Sulphur mg/kg	Remarks
D1	1550	*Historic* diesel
D2	280	2000 diesel
D3	38	2005 diesel
D4	8	2009 diesel
D5	3	Swedish Class 1
D6	307	pre 2000 fuel
D7	7	D4 + 5% RME
G1	143	2000 gasoline
G2	45	2005 gasoline
G3	6	2009 gasoline

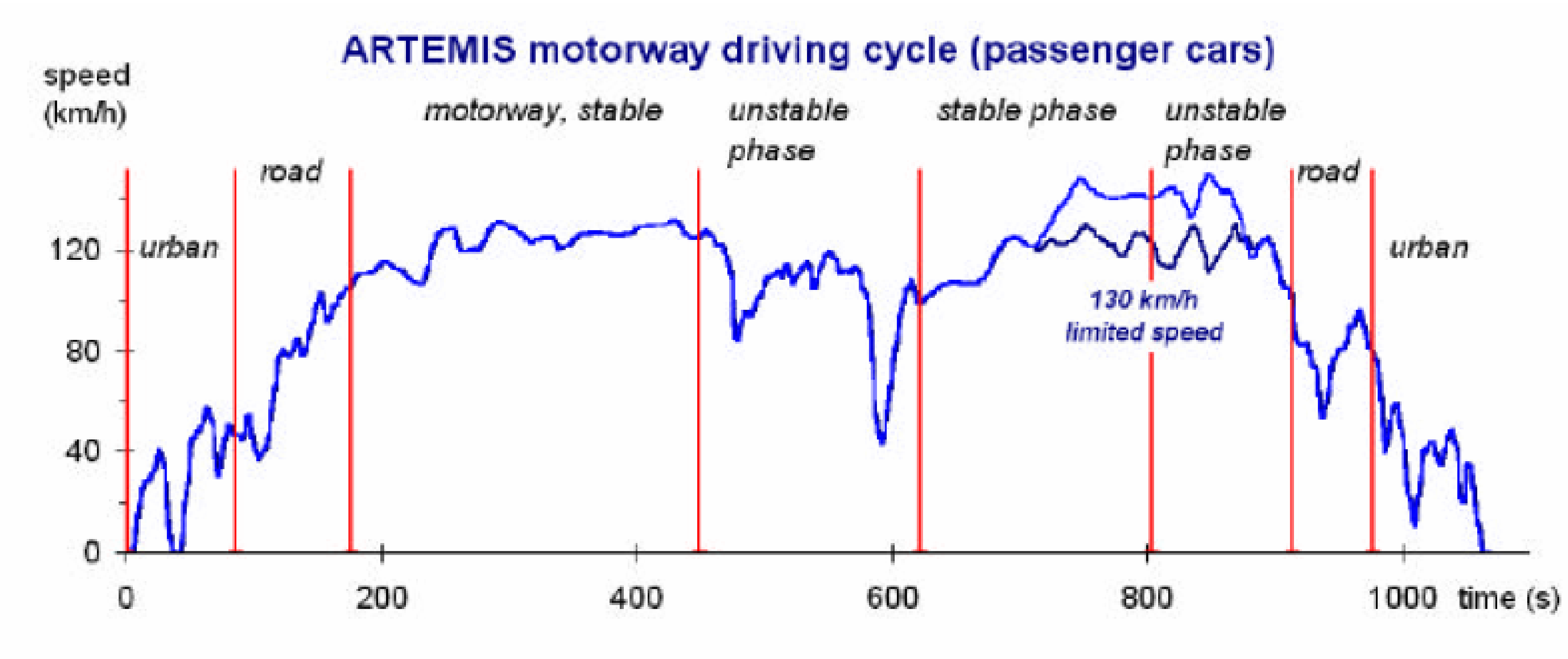
(Shaded rows:) Only tested on some engines/vehicles

Light Duty Vehicles

Daily test sequence



NEDC and Real World Driving Cycles Used Example: *Artemis Motorway*



ETH conference, Zurich, 16-08-2004

Particulates Project

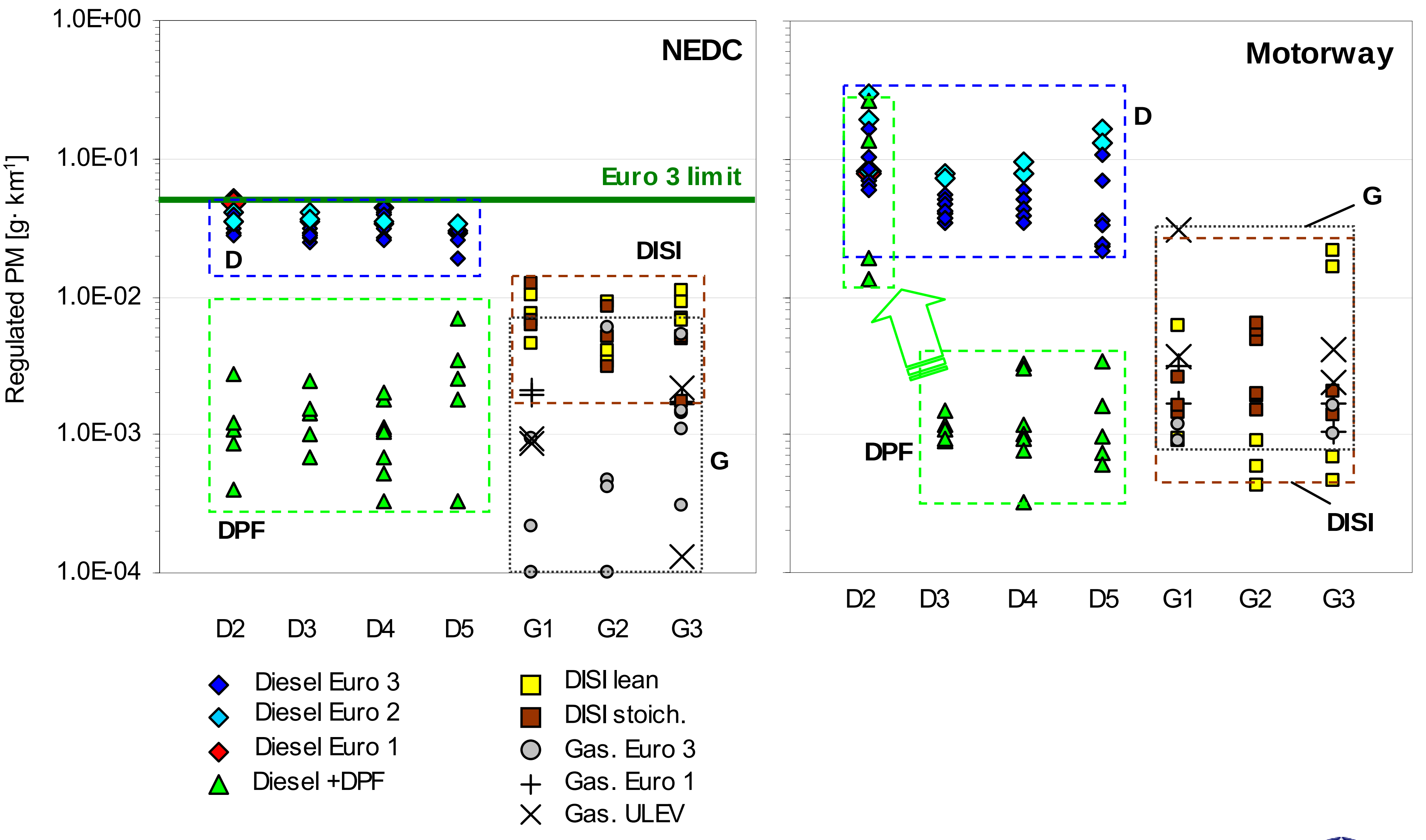
24 Passenger Cars

- Conventional Diesels (D)
  - five Euro 3
  - two Euro 2
  - one “simulated” Euro 1
- DPF equipped (DPF)
  - four OEM equipped
  - one retrofitted

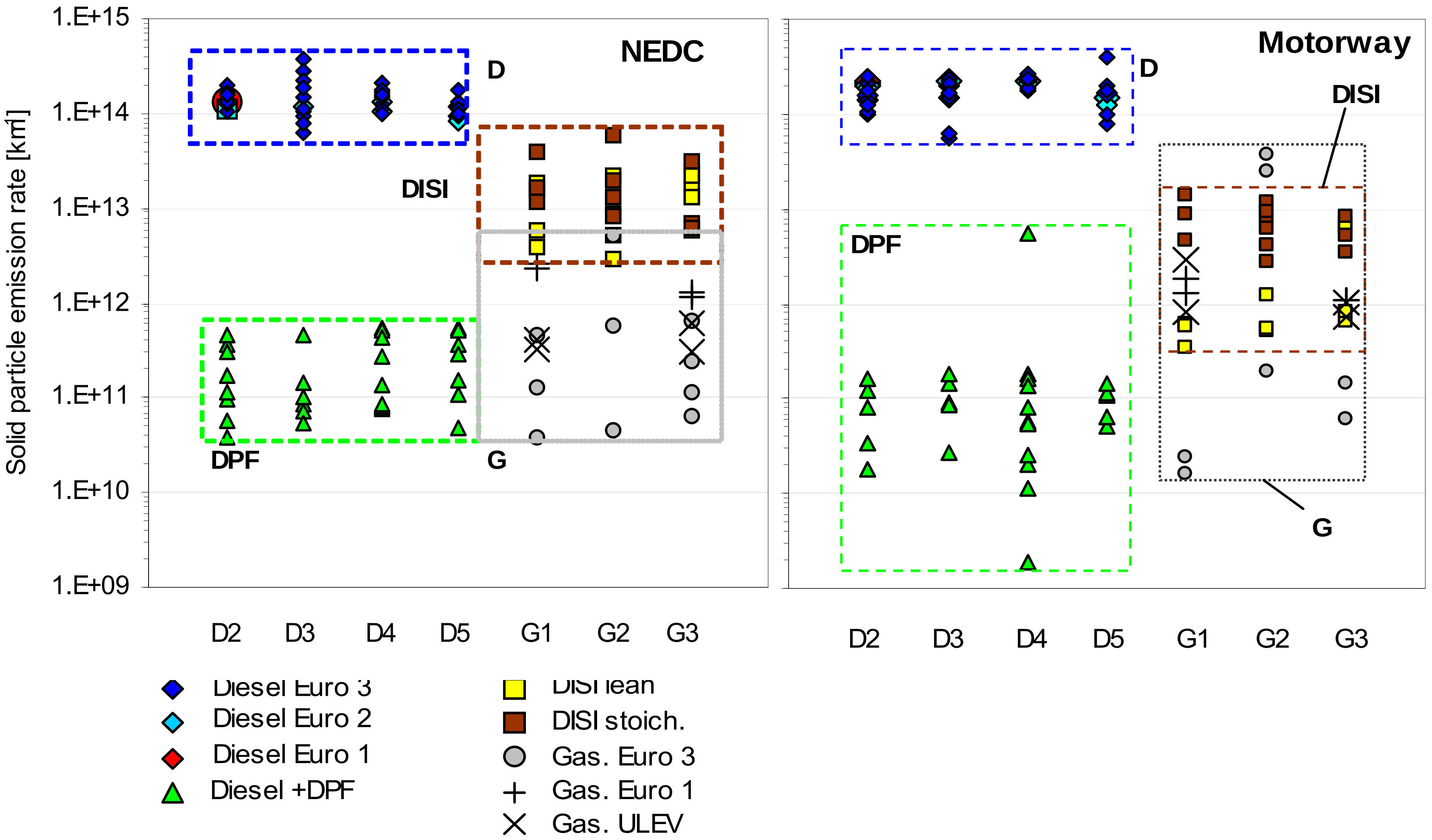
- Port injection SI (G)
  - four Euro 3
  - one Euro 1
  - one California ULEV
- Direct injection SI (DISI)
  - Two stoich. with TWCs
  - three lean with NOx adsorber and TWC

All well maintained and <50 000 km mileage.
Only ULEV and Euro 1 gasoline cars had > 100 000 km.

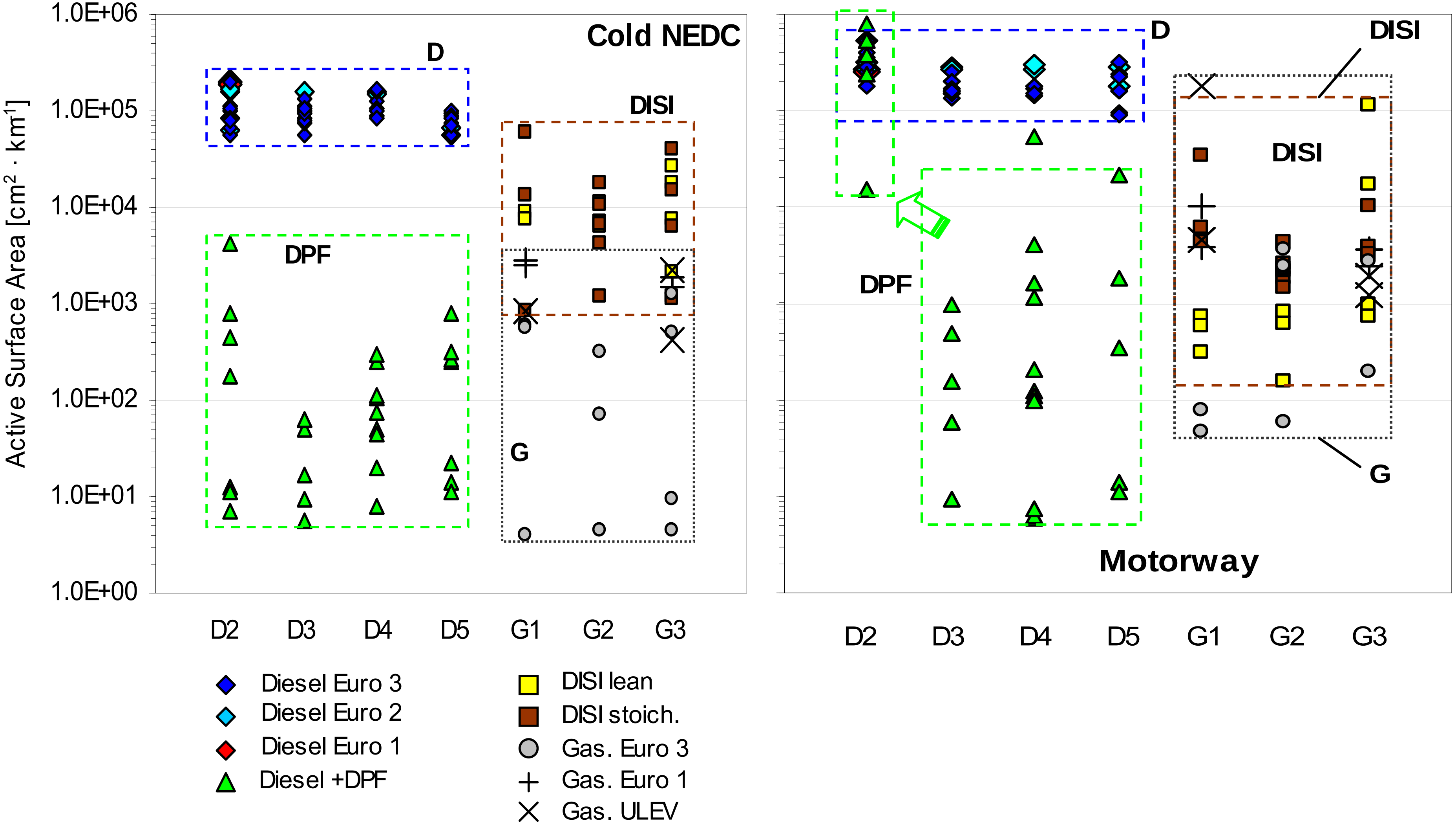
Regulated PM



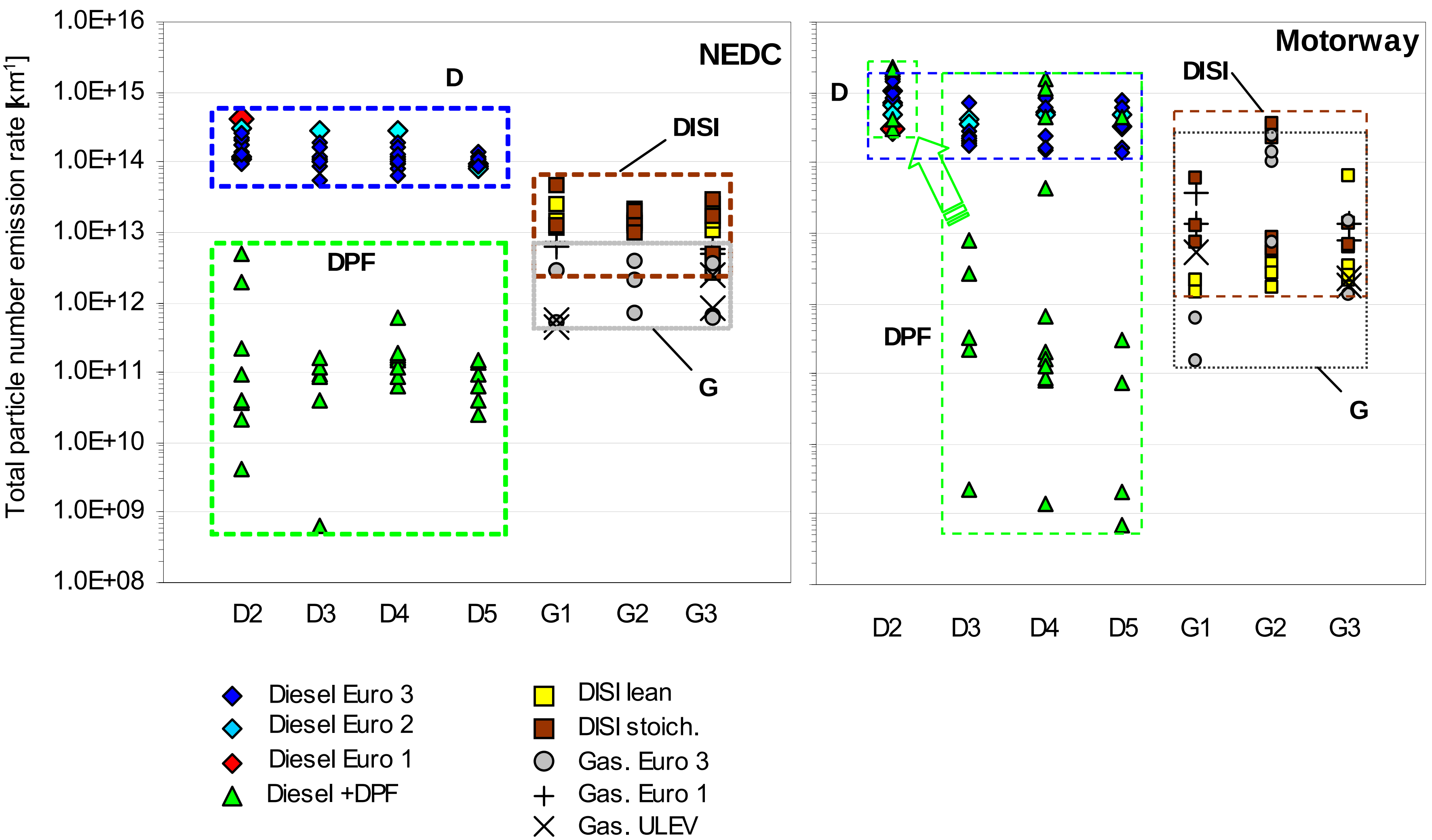
Solid Particle Number (TD+ELPI)



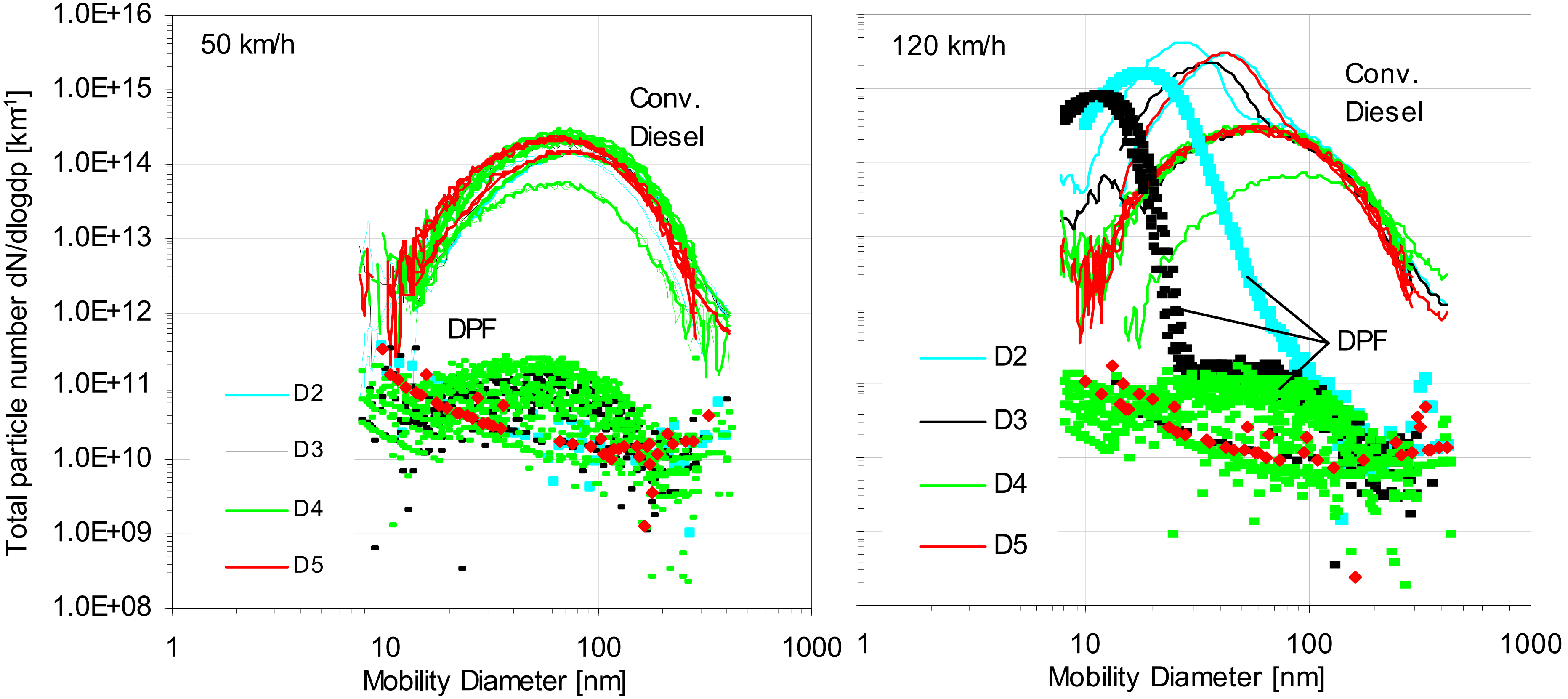
Active Surface (Diffusion Charger)



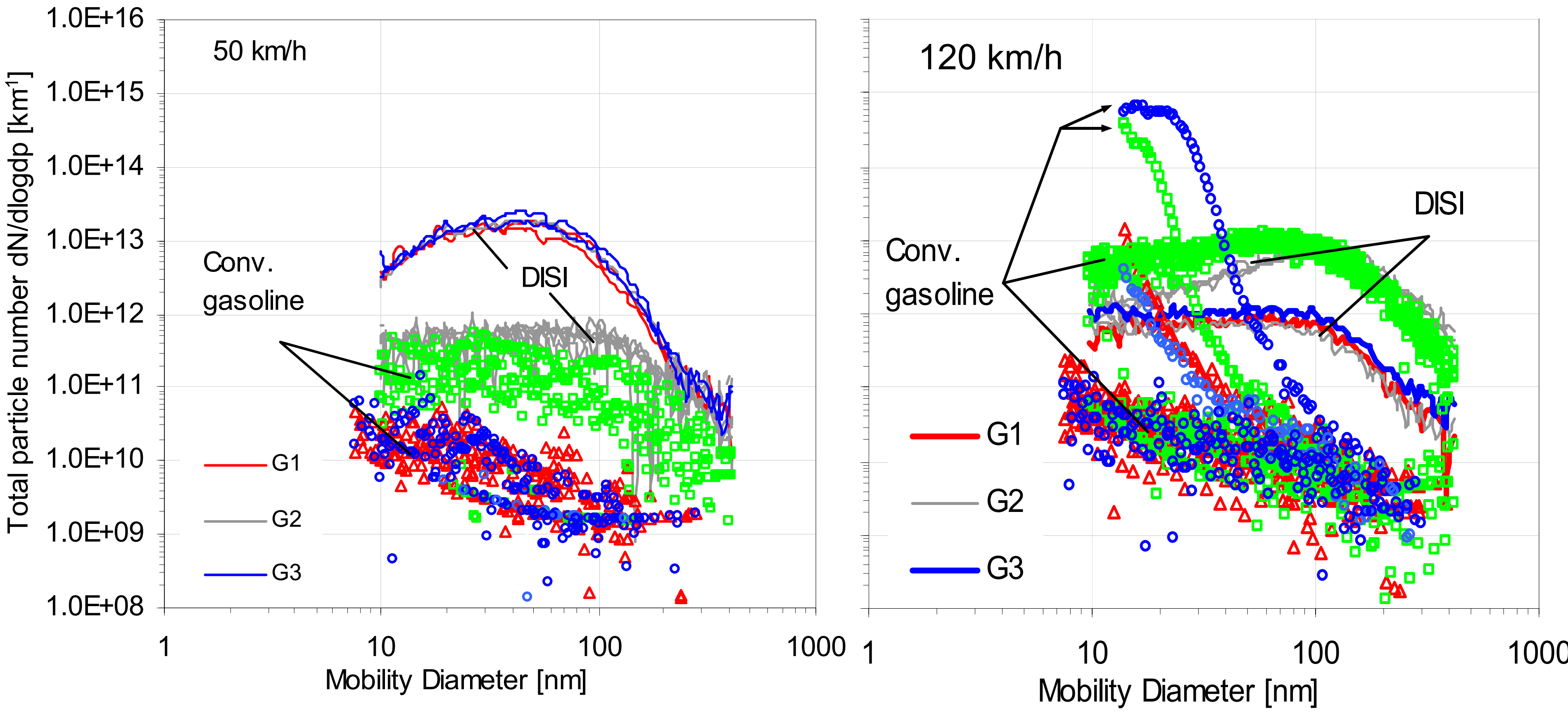
Total Particle Number (CPC)



Particle Size Distributions (SMPS) - Diesel



Particle Size Distributions (SMPS) - Gasoline



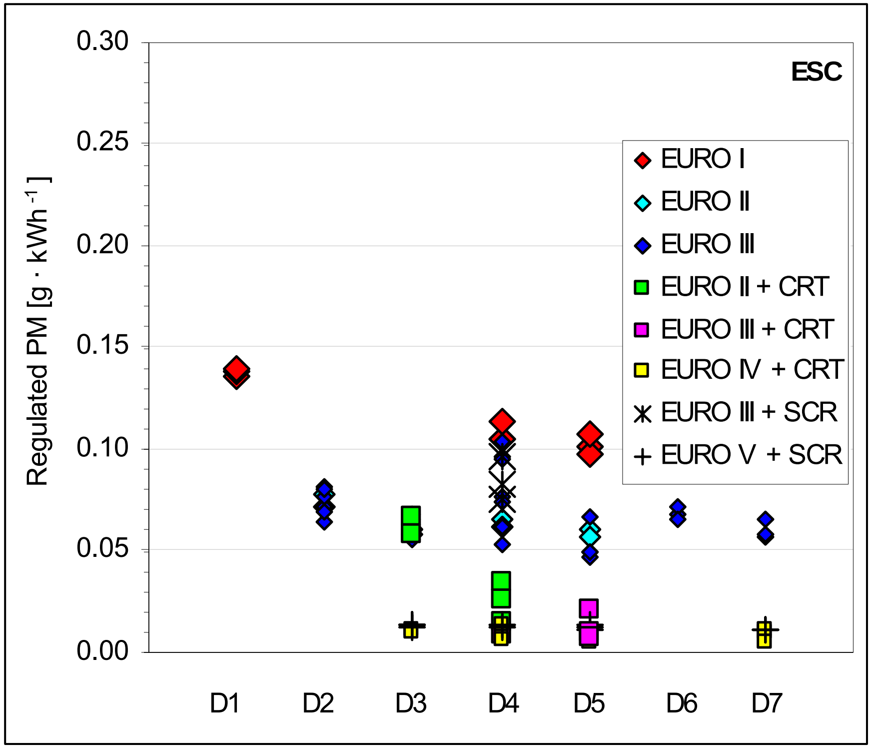
Heavy Duty Engines

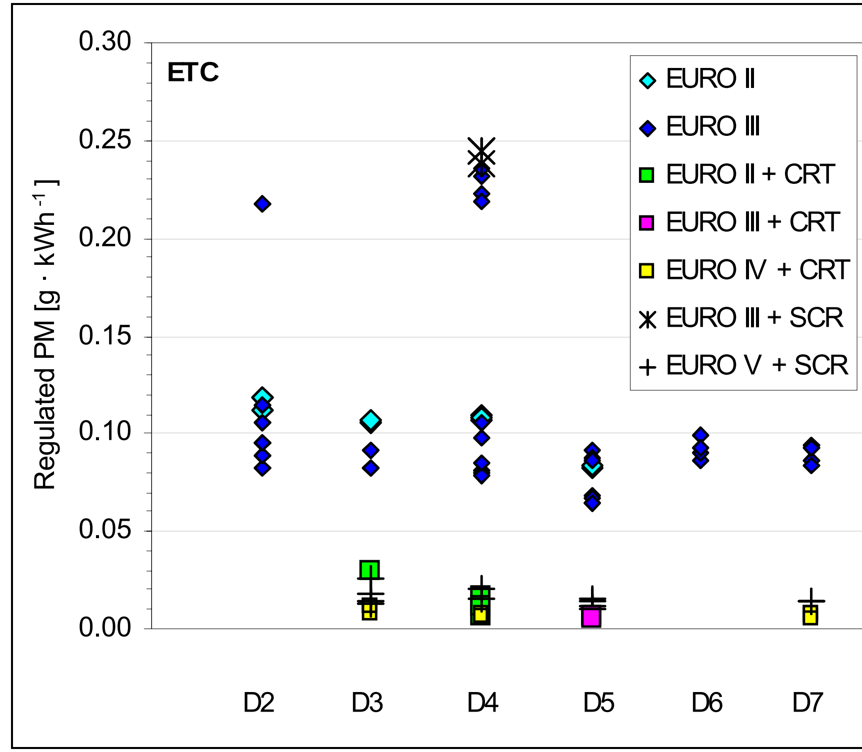
10 Heavy Duty Engines

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.

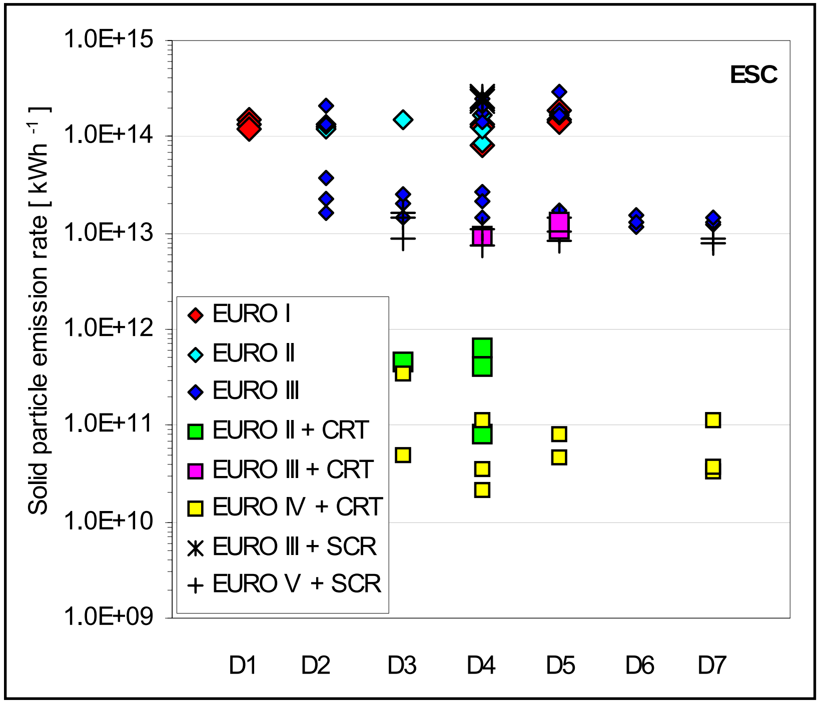
Regulated PM

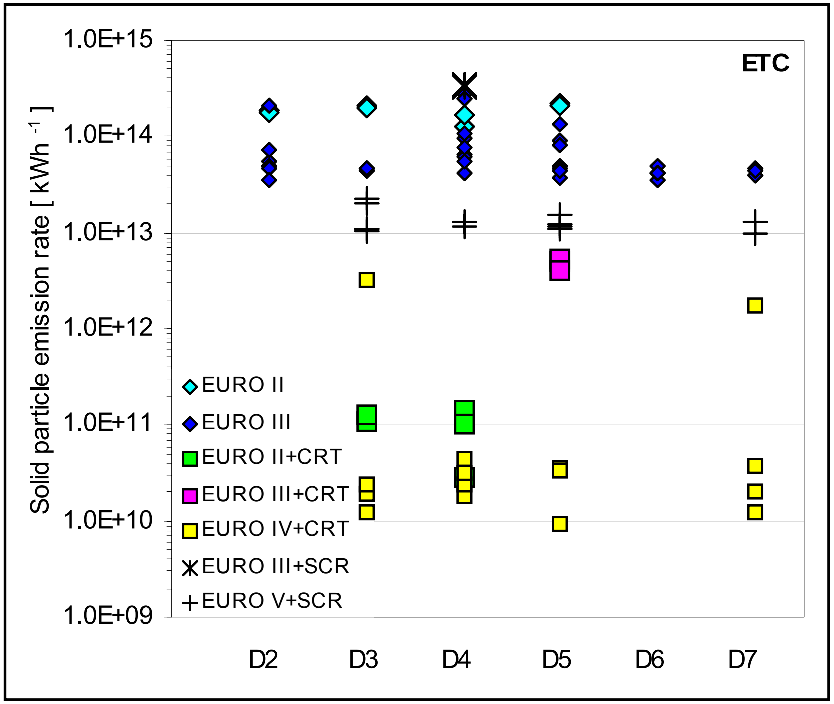




- Very low PM emissions achieved with CRT equipped systems on low sulphur fuels, & with Euro-V SCR/urea prototype without DPF
- Benefits of fuel sulphur reduction also evident

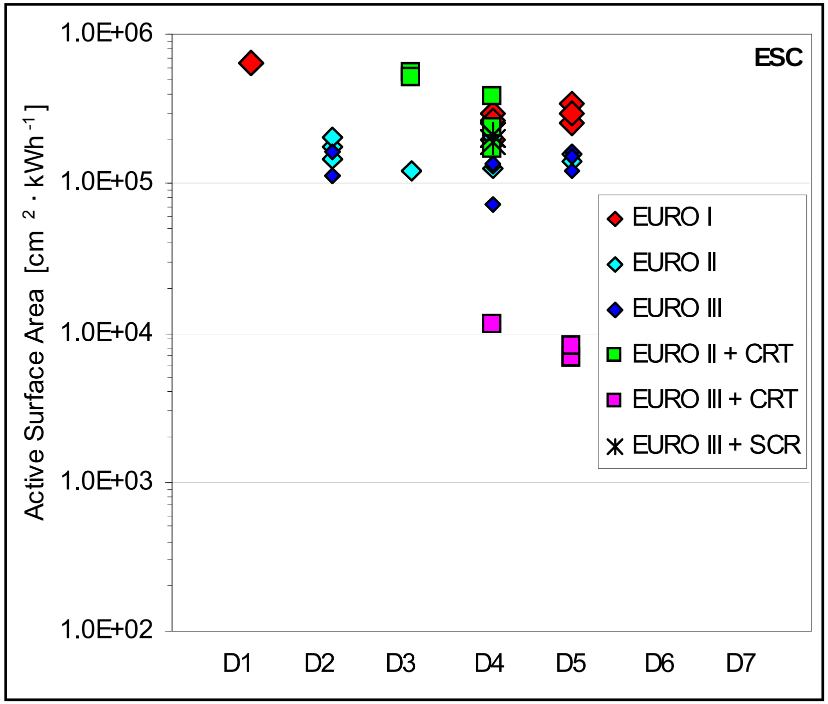
Solid Particle Number (TD + ELPI)

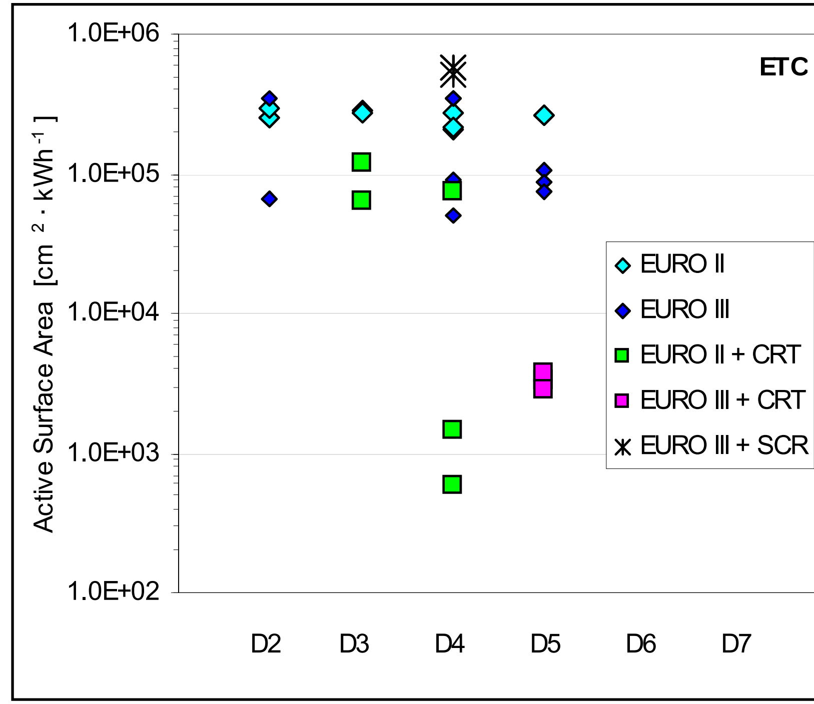




- Conventional Euro-I to Euro-III engine technologies produced total solid particle number emissions in the range of 10^{14} particles/kWh
  - Results for one Euro-III engine ca. an order of magnitude lower, needs further explanation
- DPF systems offer the potential to reduce solid particle numbers 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

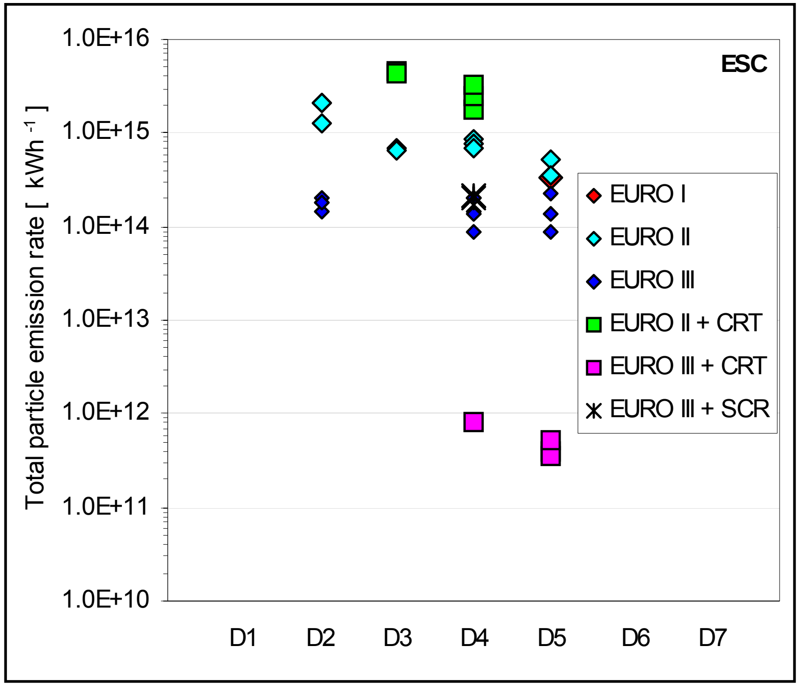
Active Surface (Diffusion Charger)

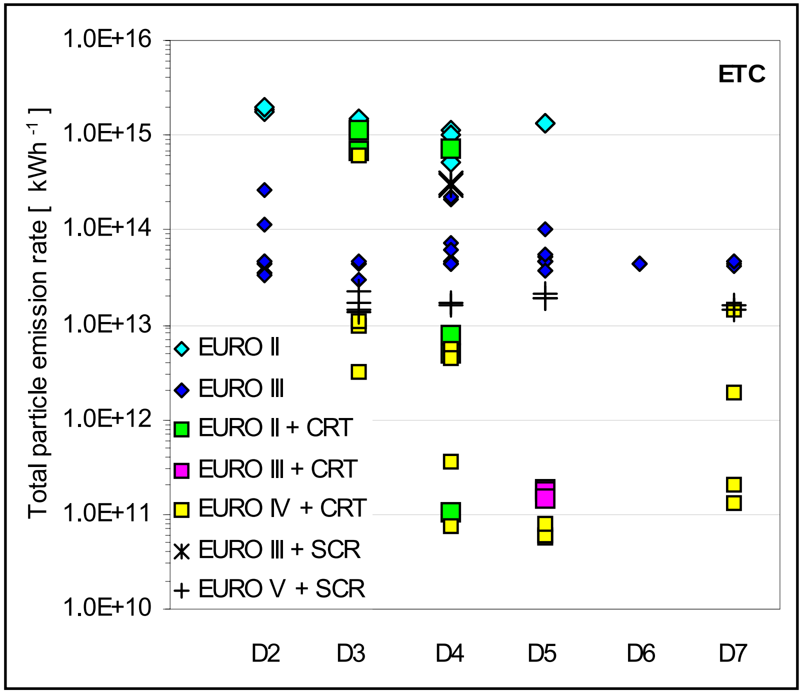




- Euro-I to Euro-III engines produced active surface values in the range 10^5 to 10^6 cm²/kWh. The Euro-III engine with CRT gave 1-2 orders of magnitude reduction, broadly in-line with its ELPI performance.
- The Euro-II engine with CRT gave active surface values in the same range as the Euro-I to Euro-III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

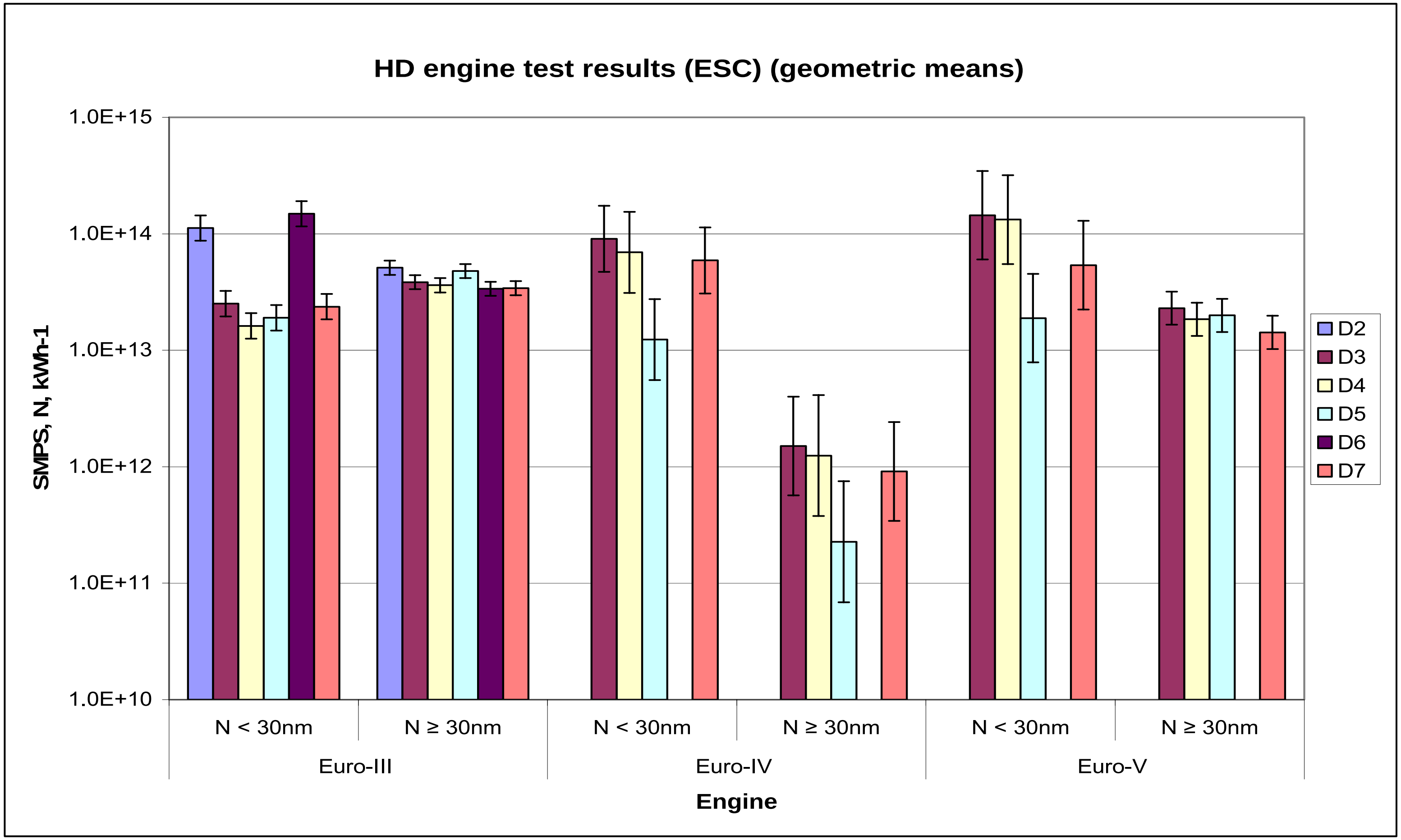
Total Particle Number (CPC)





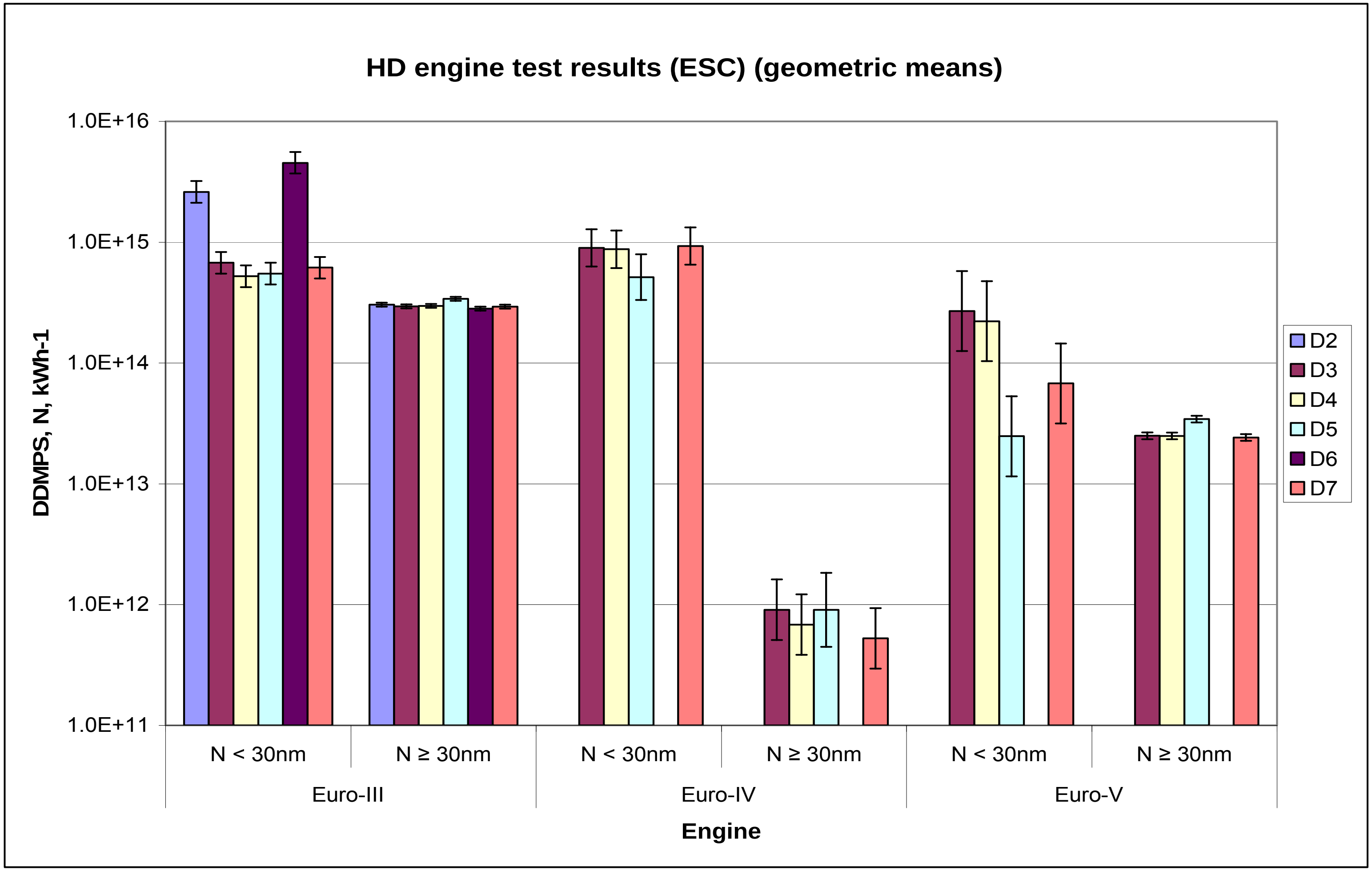
- Total particle number (CPC) emissions of conventional Euro-I to Euro-III heavy duty diesel engines were in the range 10^{14} to 10^{16} particles/kWh
- DPF systems operating on low sulphur fuels have the capability to reduce the total number count by ca. 3 orders of magnitude. However, some cases showed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

Particle Size Distributions (SMPS)



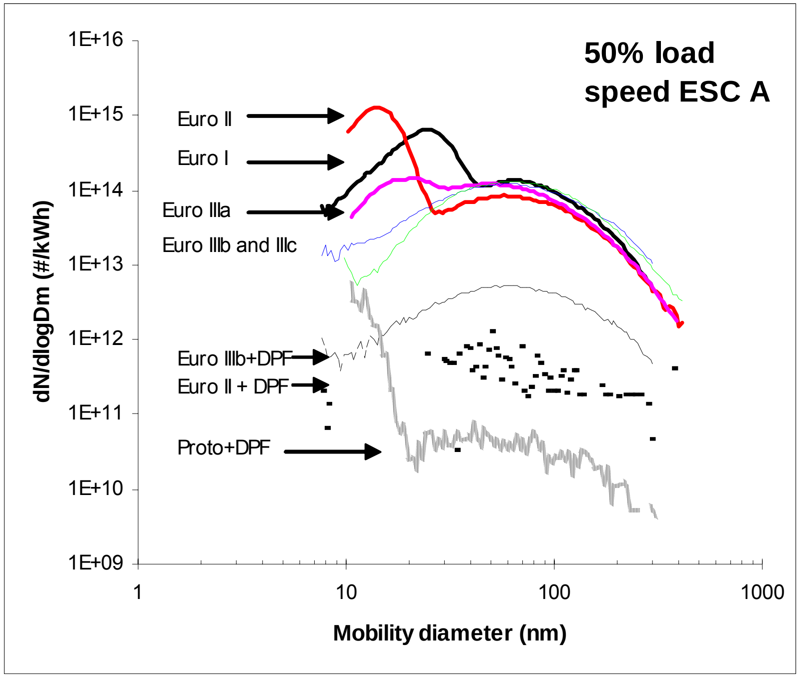
- Clear benefit from sulphur reduction on nucleation mode particles
- Lowest number of accumulation mode particles with Euro-IV DPF system

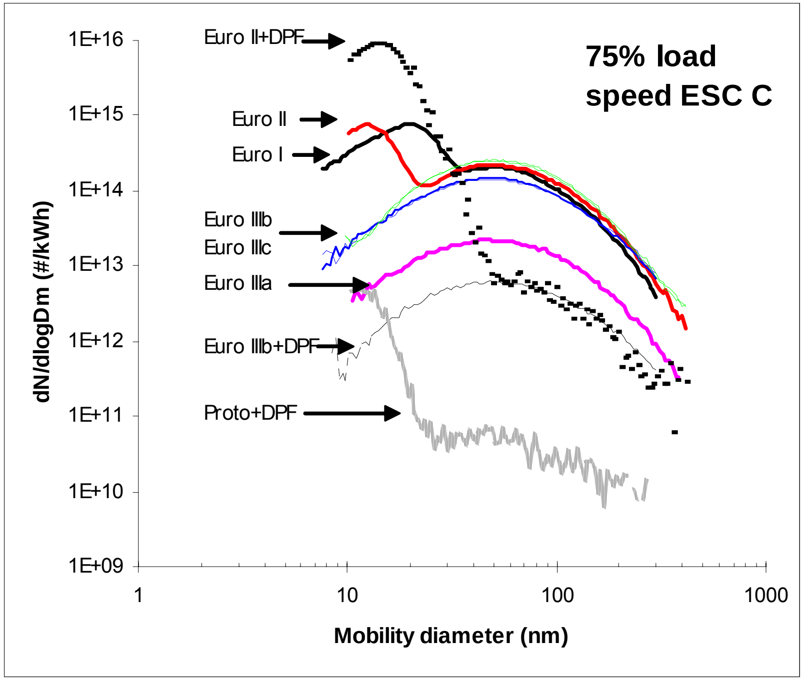
Particle Size Distributions (DDMPS)



- 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 CRT-equipped Euro-II engine
- Some lab-lab differences highlight calibration issues

Conclusions (1)

- The "Particulates" measurement protocol has been successfully applied in multiple labs to evaluate both LDVs and HDEs on a number of fuels
  - A database for development of emissions factors for a wide range of technologies and particulate properties has been generated
- DPF-equipped diesel engines produced very low particulate mass emissions, low numbers of solid particles and low total numbers of particles when operating on sulphur-free fuels
  - a much larger step than Euro-I to Euro-III
  - comparable to conventional gasoline vehicles
- DI gasoline vehicles gave measurable emissions in most particle properties, though particulate mass emissions were well below Euro-4 diesel limits
- A heavy duty prototype Euro-V engine with SCR/urea, without a DPF, gave very low particulate mass, but number emissions remained higher than the DPF-option
- The effect of diesel fuel sulphur was greatest under high temperature operation
  - Under these conditions, lower sulphur fuels reduced particle mass and number emissions
- In the 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 valuable for further research into cleaner vehicles and fuels
- There is some evidence that the number of “solid” particles does not always correlate with mass. However, further methodology development, incl. definition of suitable instrument calibration procedures and multi-lab validation, would be required prior to use of “solid” particle number measurements 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.

Acknowledgments

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Thank you for your Attention!