LABORATORY OF APPLIED THERMODYNAMICS

Zissis Samaras and Leonidas Ntziachristos

ARISTOTLE UNIVERSITY THESSALONIKI
SCHOOL OF ENGINEERING
DEPT. OF MECHANICAL ENGINEERING

Road transport particle emissions characterization: focus on ultrafine particles

Ultrafine Particles: Science, Technology & Policy Issues, May 1, 2006

Contents

Based on the EU *Particulates* Research project activities, results and database (http://lat.eng.auth.gr/particulates/)

- Development of a measurement protocol to address both semi-volatile and solid particles
- Results from LDVs and HDVs
- Comparison of Diesel particle exhaust emissions from Light Duty vehicles and Heavy Duty engines
- Diesel Particulate Filter Efficiency
- Conclusions and follow-up

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

- David Kittelson (USA)
- Georg Reischl (AUT)

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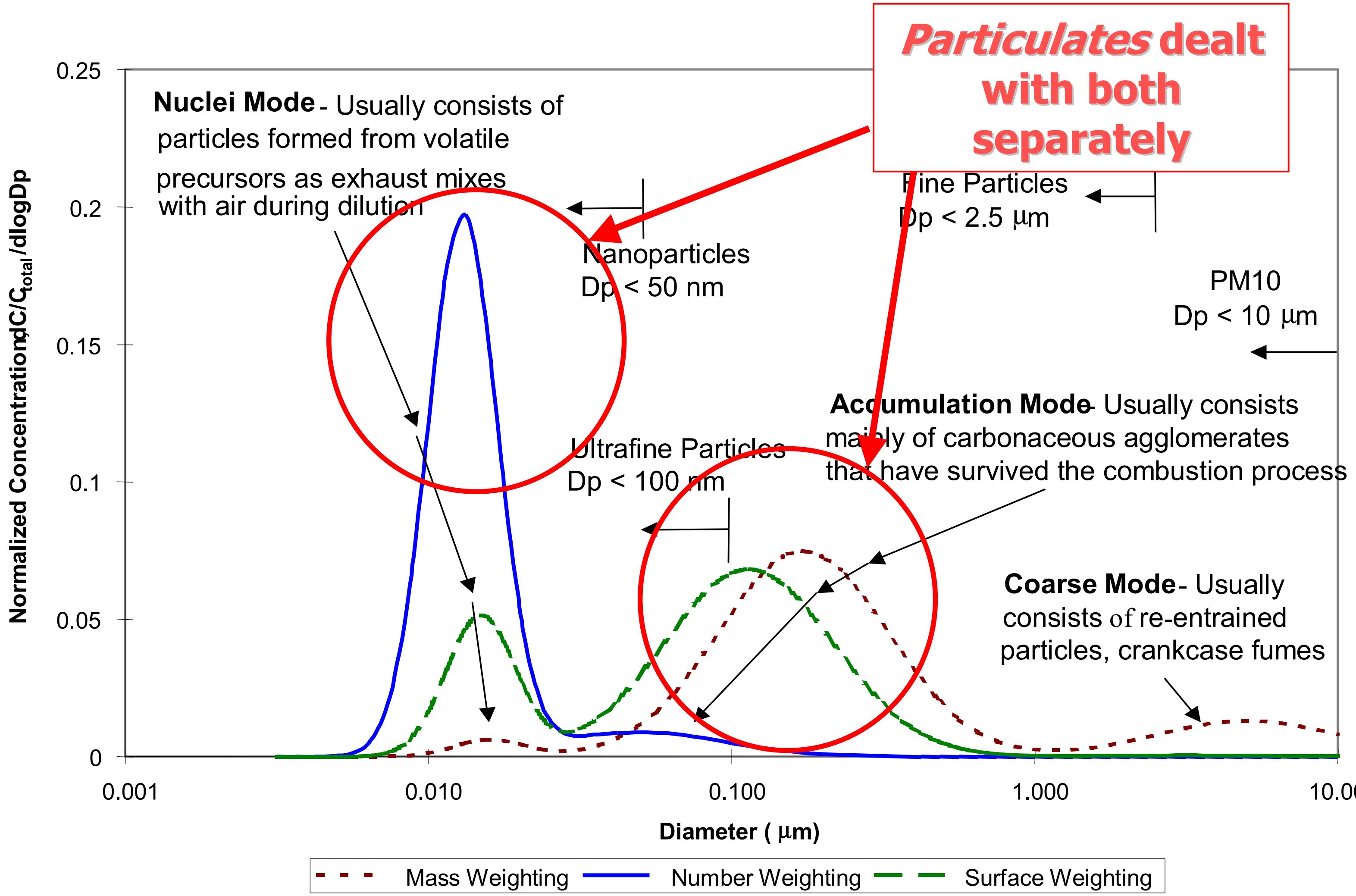
Motivation to Develop a Sampling System

- Primary aim was to develop a database with emission factors of several particle properties from various engine concepts and fuels and aftertreatment systems for evaluation of technology potential.

- Non-solid particles also of interest to understand their origin and occurrence.

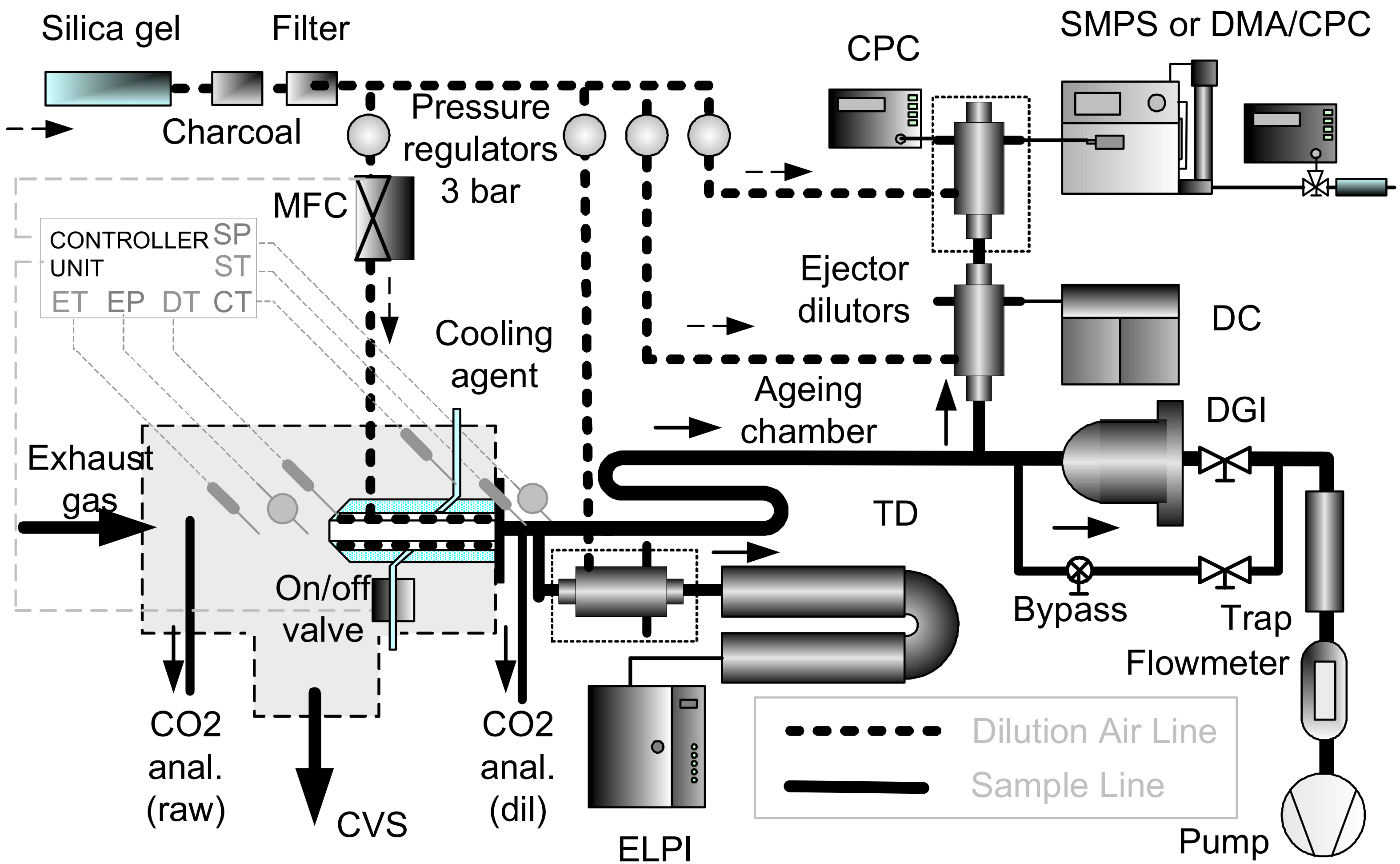
- CVS not practical due to variance in sampling conditions. A dedicated sampling system was developed to establish the same sampling conditions in all laboratories, even over transient tests.

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



Source: David Kittelson

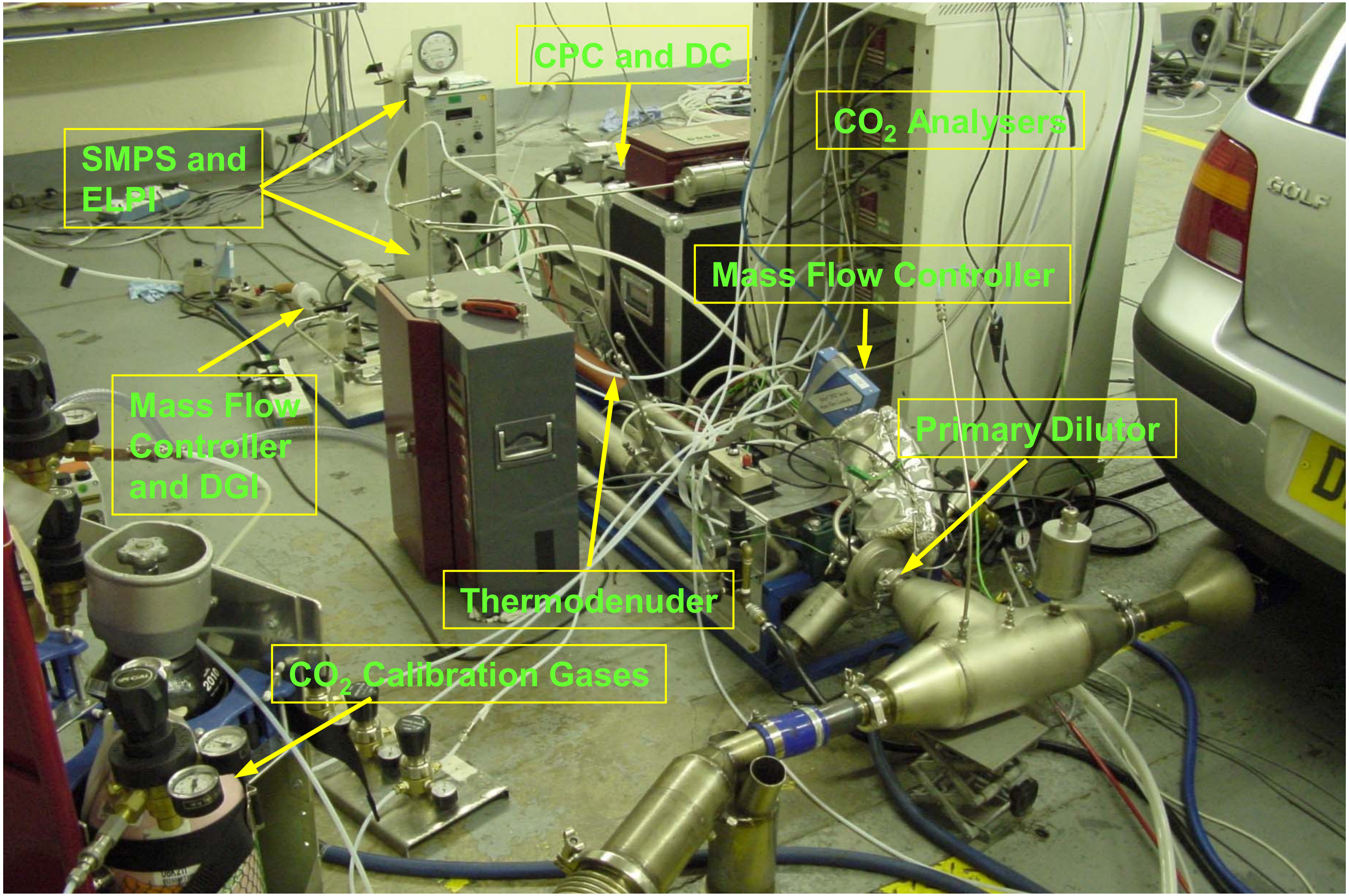
Particulates Sampling System Schematic



Constant sample flowrate, constant sampling conditions regardless of particle source

SAE paper 2004-01-1439

Picture of Sampling System and Instrument Configuration

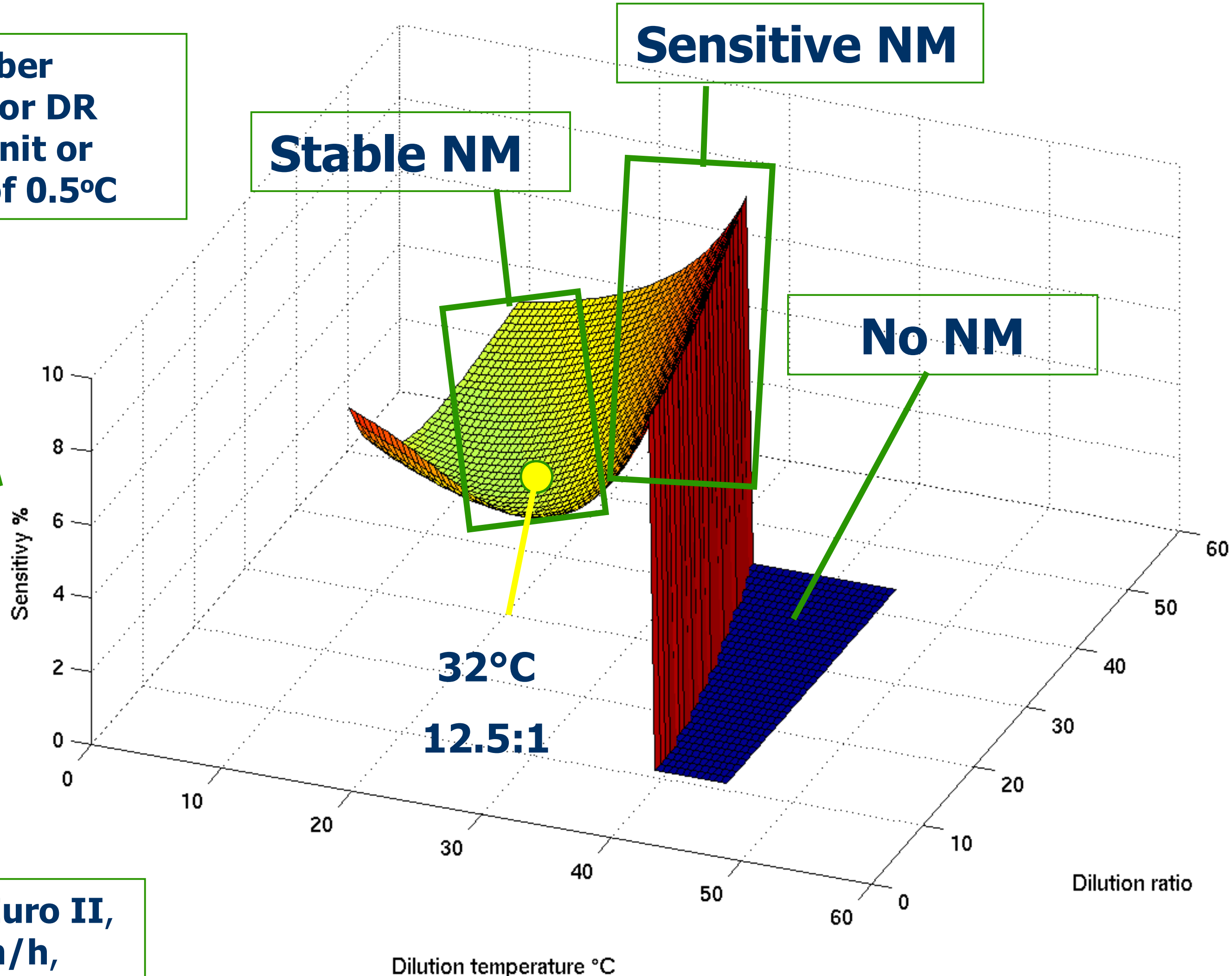


Particle Properties Recorded in *Particulates*

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

Selection of Sampling Conditions
Dilution Ratio (DR) & Dilution Ait Temperature (DAT)

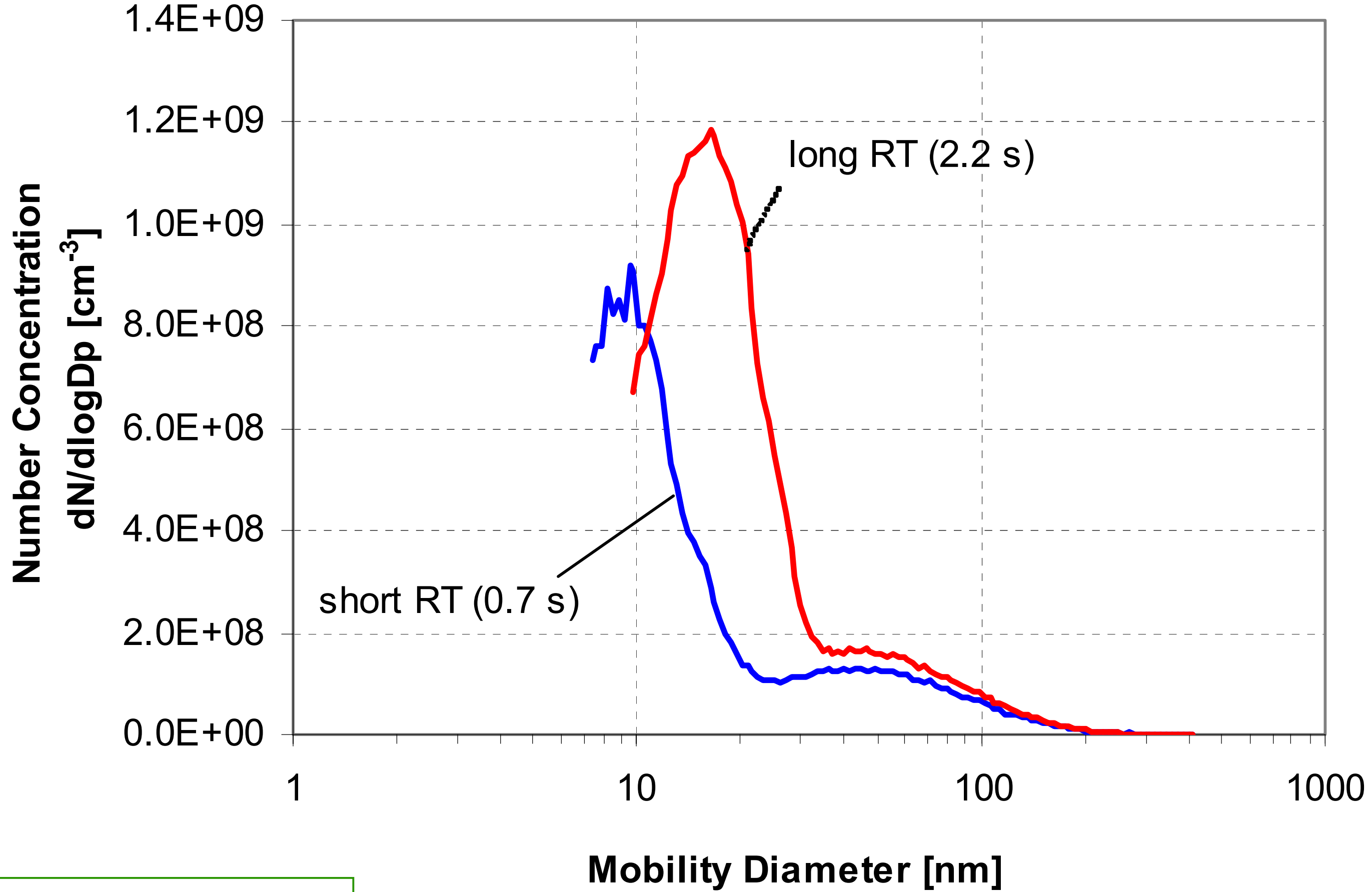
Change in number concentration for DR variation of 1 unit or DAT variation of 0.5°C



Vehicle: **Skoda Euro II**, Condition: **50 km/h**, Load: **7 kW**

Aerosol Science and Technology, 38:1149–1160, 2004

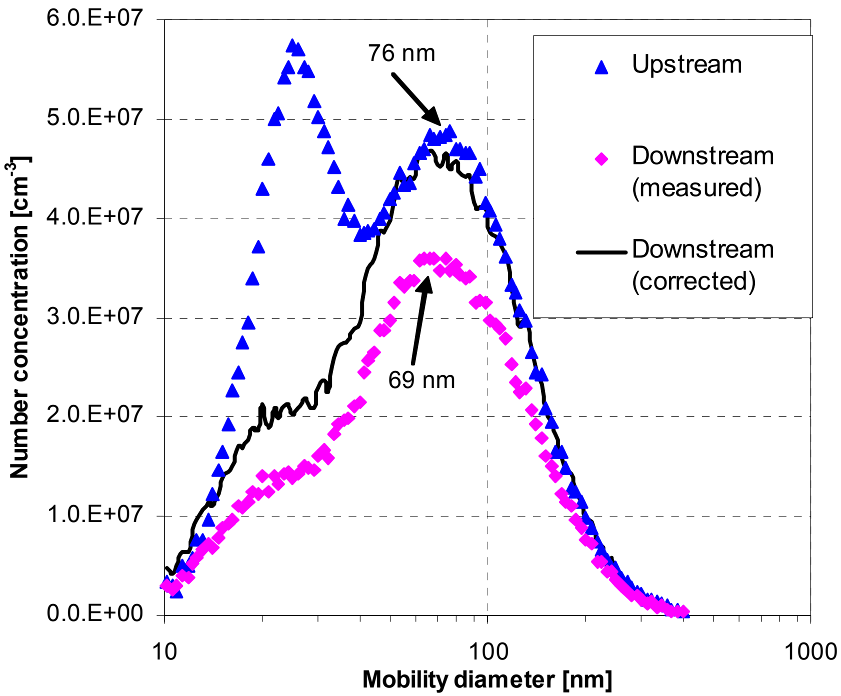
Selection of Sampling Conditions – Residence Time



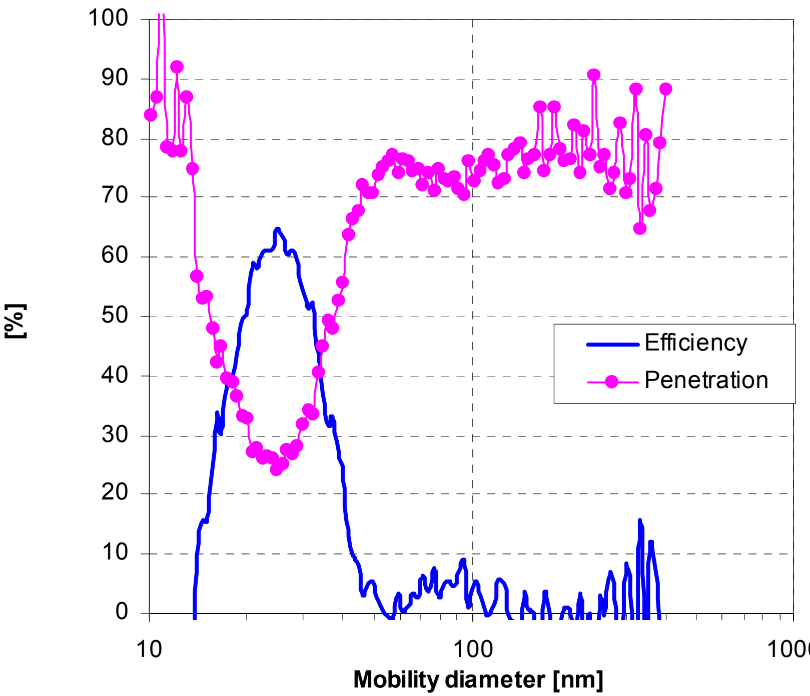
Vehicle: **Euro 1 VW Golf**
Condition: **50 km/h**
Load: **7.6 kW**
DR: **~25:1**, DAT: **22°C**

Thermodenuder Performance

Particle distribution upstream and downstream of the TD

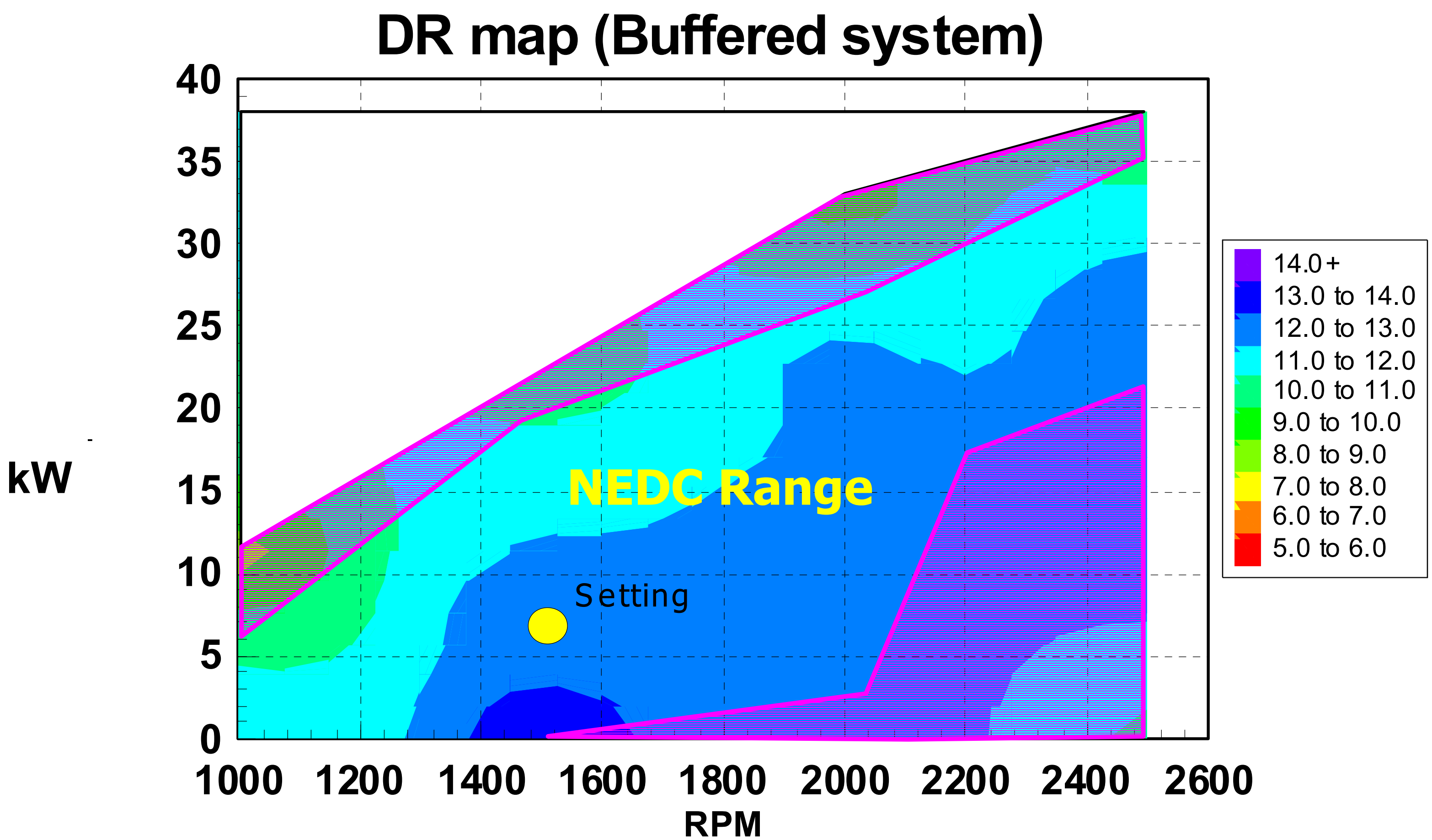


Particle penetration and efficiency of the TD



Engine: **Euro 1 VW TDI**, DR setting: **5:1,** TDR to SMPS: **~1000:1**, Speed: **2000 rpm**, Load: **10%**

Primary Dilution Ratio Variation (Steady states)

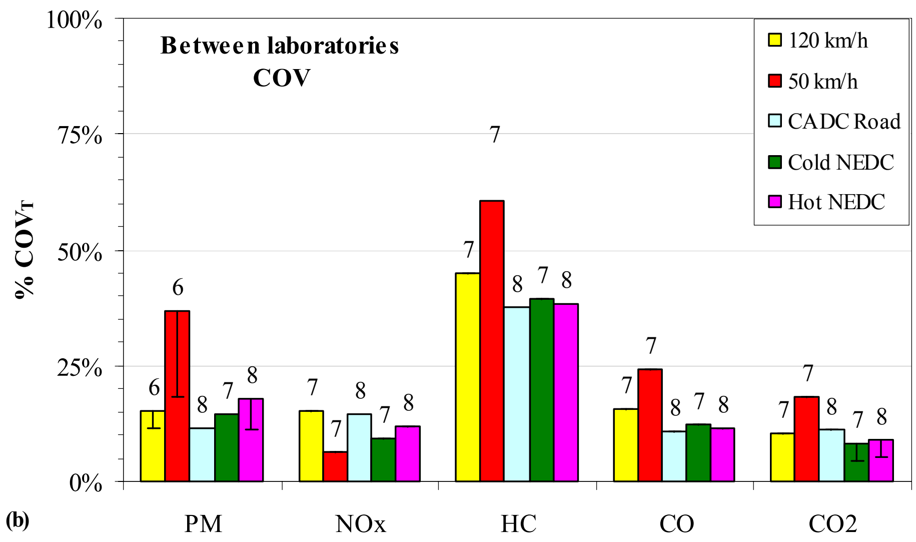


Engine: **Euro 1 VW TDI**
DR setting: **12,95:1** (1500 rpm, 25% load)

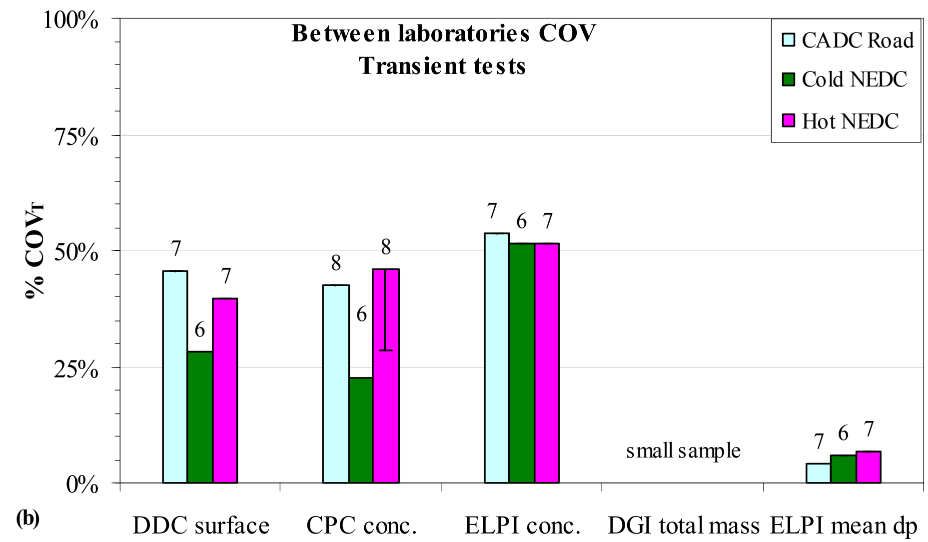
SAE paper 2004-01-1439

Round Robin Results (Between Lab Variability)

Regulated Pollutants & CO_2



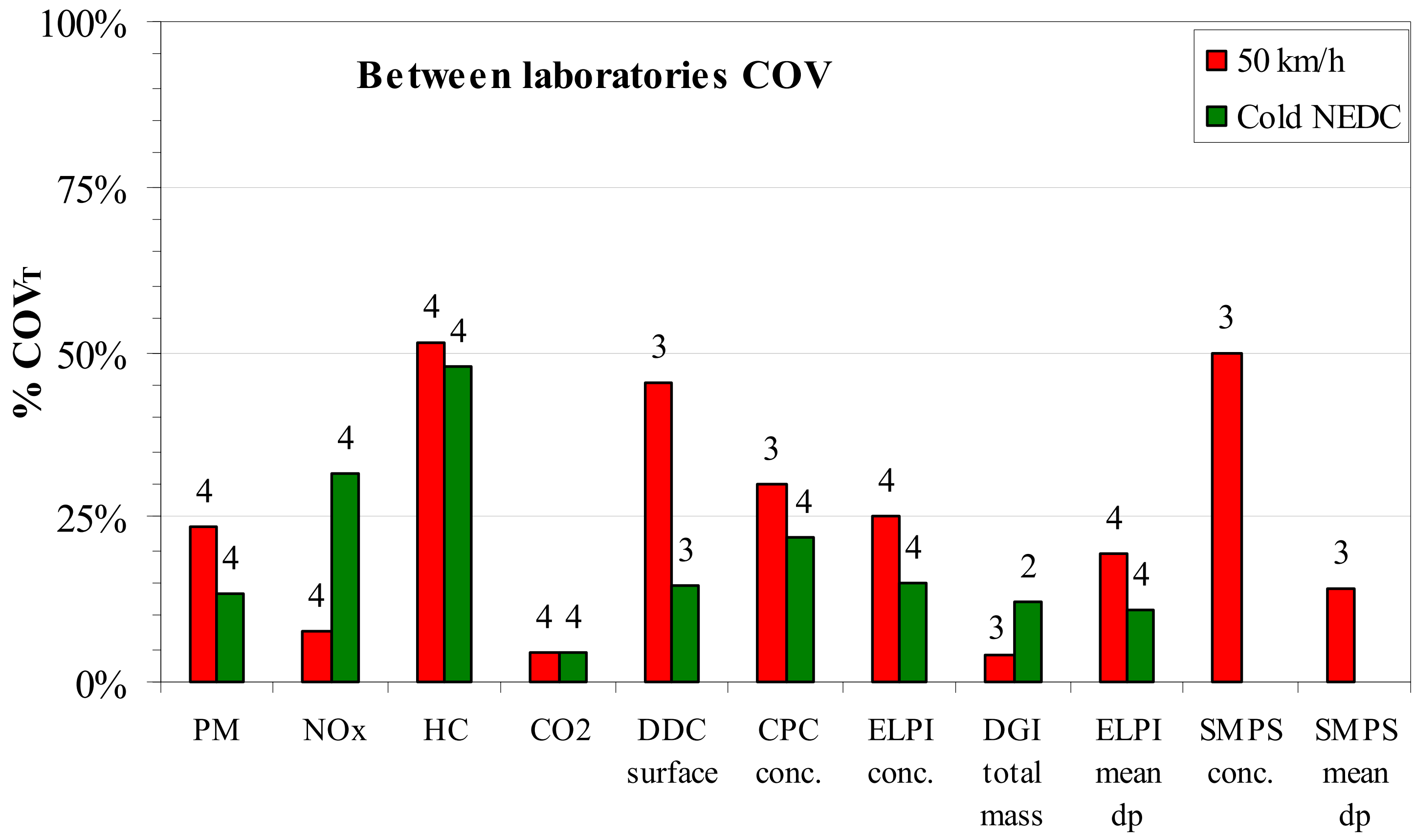
Aerosol Instruments



Round-Robin Tests Conducted Before the Main Measurement Campaign

Measurement Science and Technology 15 (2004) 1855–1866

Comparison of Results during the Main Measurement Campaign



On-Road Chasing of Exhaust Plume

Test vehicle:

VW Golf TDI 1.9 l Euro 3
speed, fuel consumption
EN590 diesel (280 ppm S)

Ford Mobile Lab:

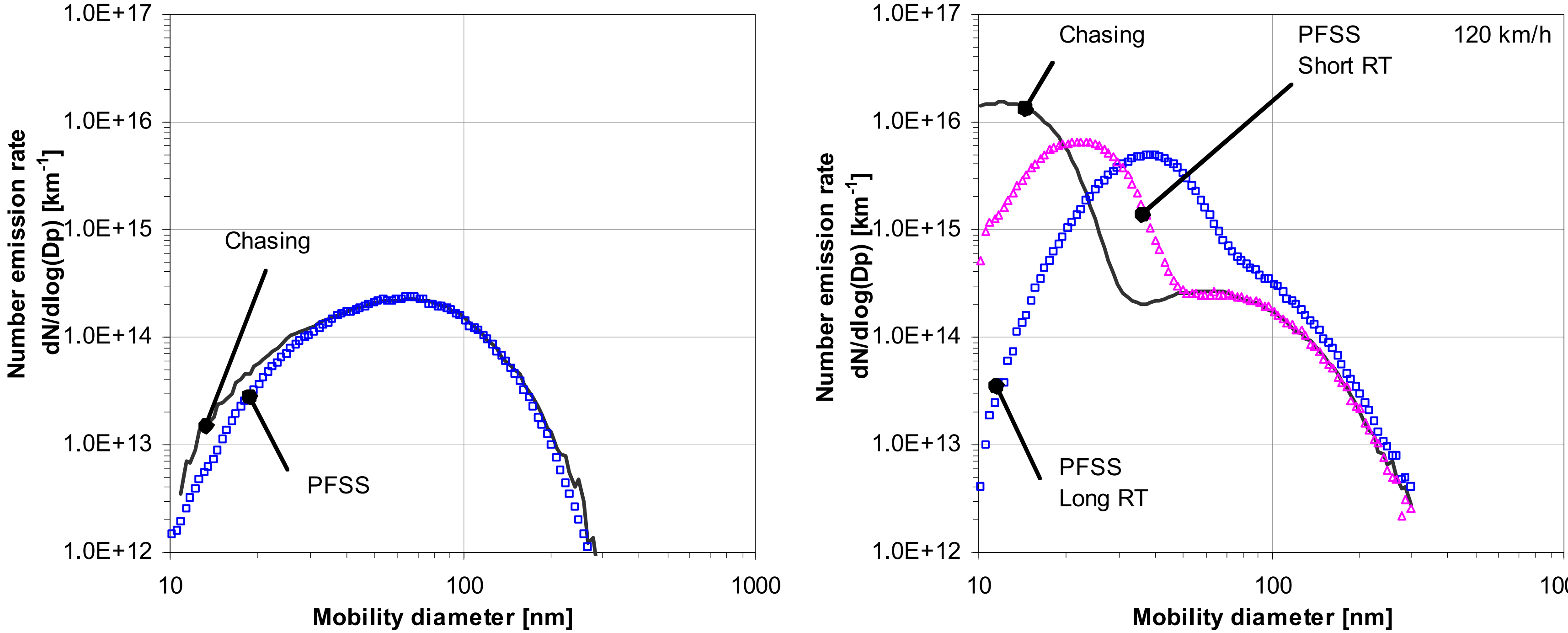
SMPS, CPC, NOx, CO_2
T and RH

Test track:

high speed oval, 4 km/lap
14 m distance: 0.4 s (120 km h^{-1})
1 s (50 km h^{-1})

Atmospheric Environment, Vol. 39/18 (2005) 3191-3198

Validation With Chasing Experiment



Vehicle: **Euro 3 VW Golf**,
Chasing Experiment: DR 2500:1 @ 50 km/h, 7000:1@ 120 km/h, T_{amb}=5ºC, RH=50%
Lab Experiment: PDR: **12,5:1,** TDR: **~1000:1,** DAT: **32ºC,** Residence Time: **0.6-2.5 s**

Atmospheric Environment, Vol. 39/18 (2005) 3191-3198

Vehicle/engine characteristics

Emission Standard	Make	Engine Size [l]	Power @ engine speed [kW/rpm]	After-Treatment
Light Duty Vehicles				
Euro 2	VW Golf TDI	1.9	66/4000	DOC
Euro 2	Peugeot 406 HDI	2.0	79/4000	DOC
Euro 3	Renault Laguna dCi	1.9	78/4000	DOC
Euro 3	VW Golf TDI (3 indiv. vehicles)	1.9	74/4000	DOC
Euro 3+	Peugeot 307 SW	2.0	79/4000	DOC+DPF
Euro 3+	Peugeot 607 HDI	2.2	98/4000	DOC+DPF
Heavy Duty Engines				
Euro 1	Volvo	12.0	247/1900	w/o
Euro 2, Euro 3+	Volvo DH10A	9.6	210/2000	w/o, CRDPF
Euro 3, Euro 4	Scania DC11	10.6	250/1900	w/o, SCR
Euro 3, Euro 3+	Volvo D12C	12.1	247/1900	w/o, CRDPF
Euro 3	Scania DC12	11.7	300/1800	w/o
Euro 4	AVL Prototype	10.6	300/1900	CRDPF
Euro 5	AVL Prototype	11.7	300/1800	SCR
Medium/Heavy Duty Vehicles				
Euro 3	IVECO Eurocargo	3.9	125/2700	w/o
Euro 3	Mercedes Citaro	12.0	185/2000	w/o, PM Cat

Experimental: Gasoline Vehicle Sample

- **Port injection SI (G)**
  - four Euro 3
  - one Euro 1
  - one Californian 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.

Experimental: Fuel Matrix

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

Only tested on some engines/vehicles

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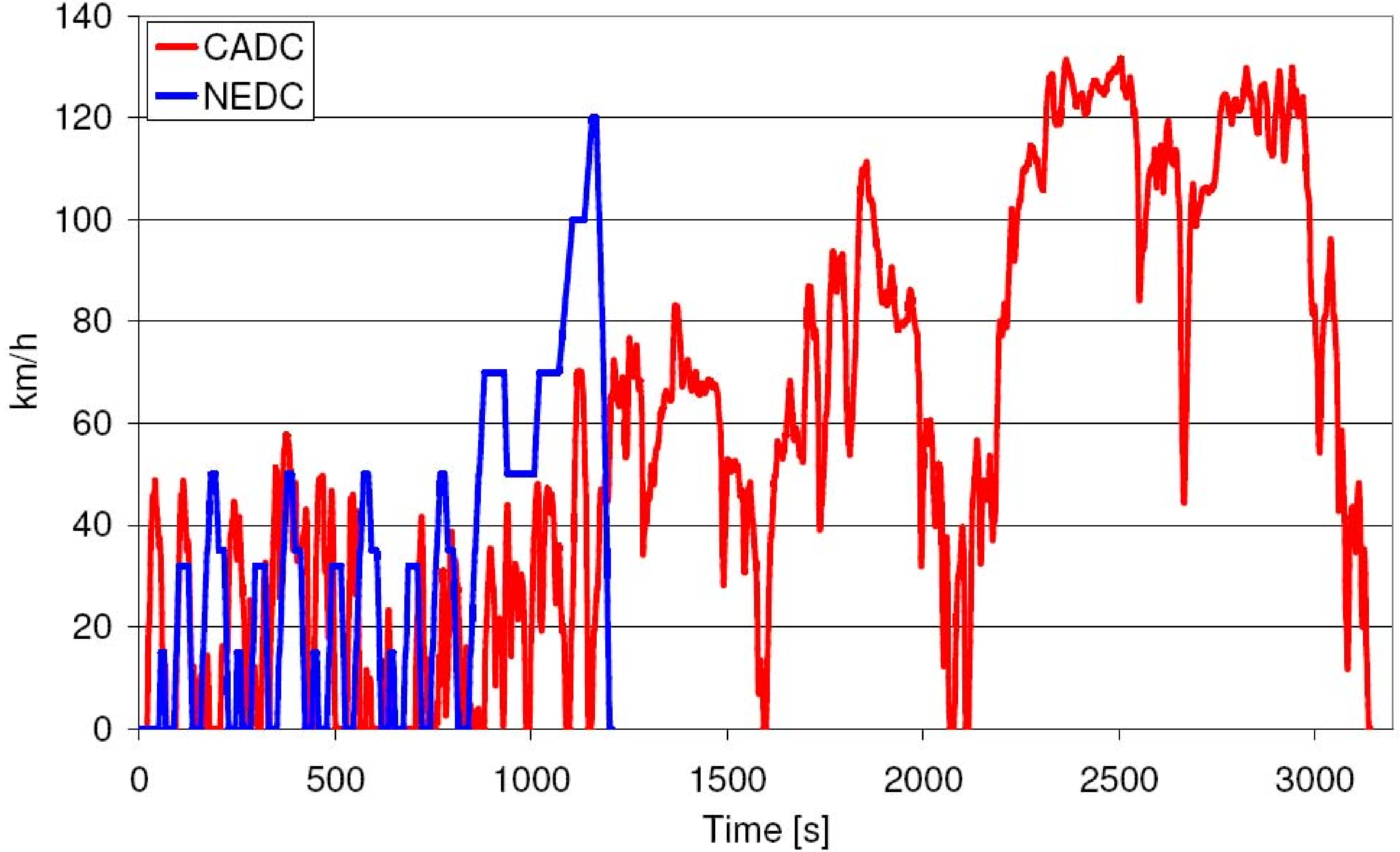
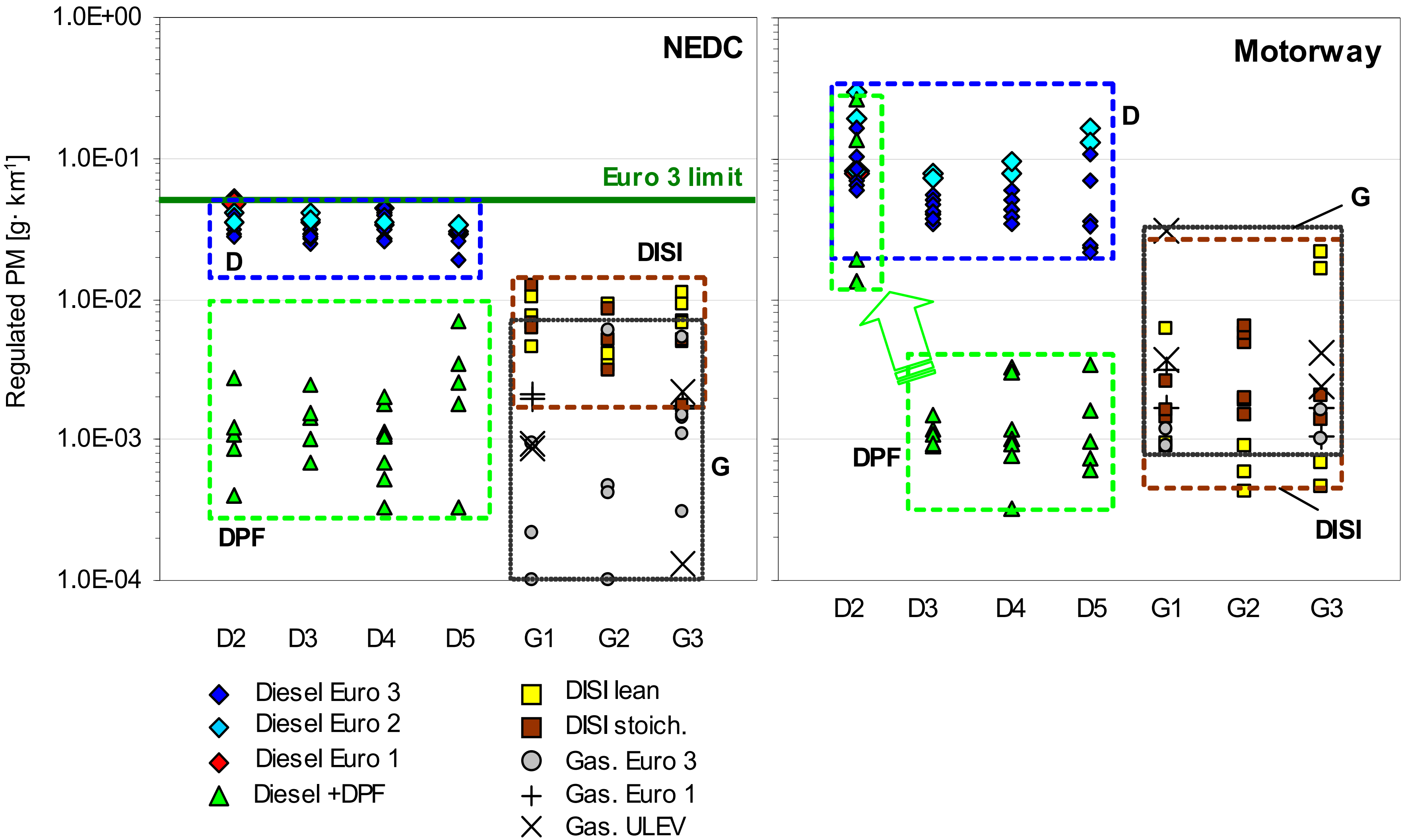
LDV Test Cycles: Regulatory NEDC and Real World Driving Cycles (Common Artemis Driving Cycles = CADC)

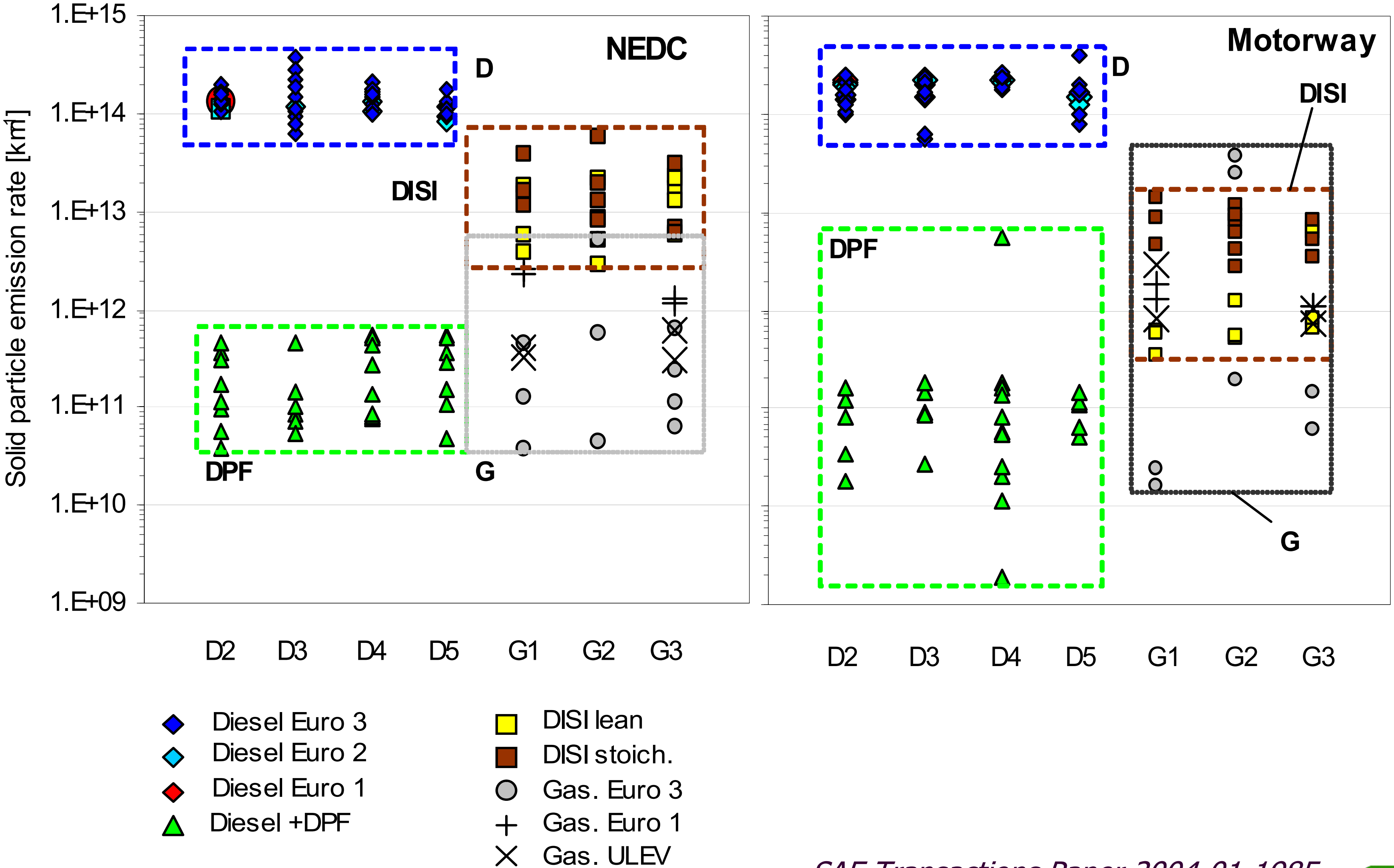


LDV Results: Regulated PM



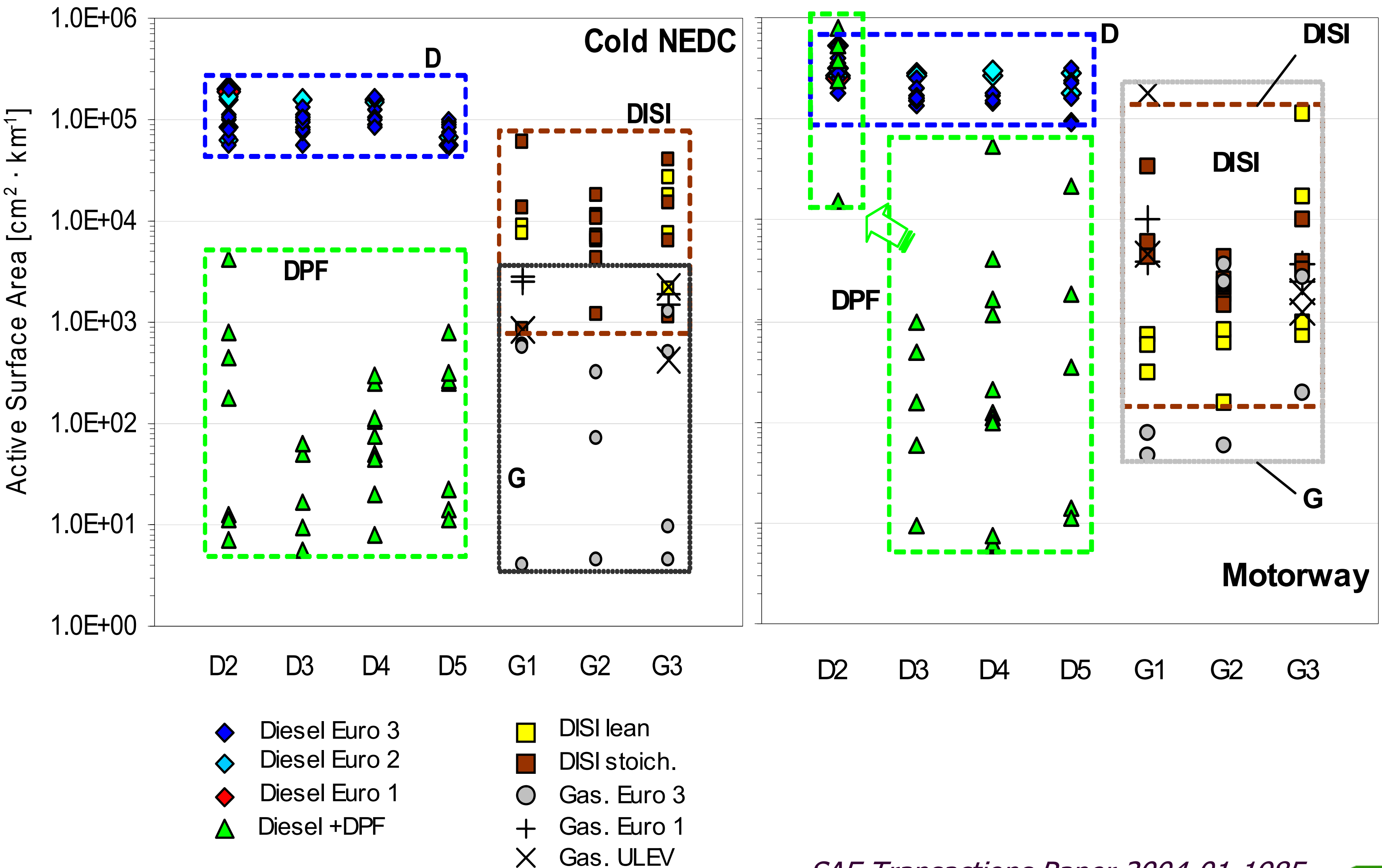
SAE Transactions Paper 2004-01-1985

LDV Results: Solid Particle Number (TD+ELPI)



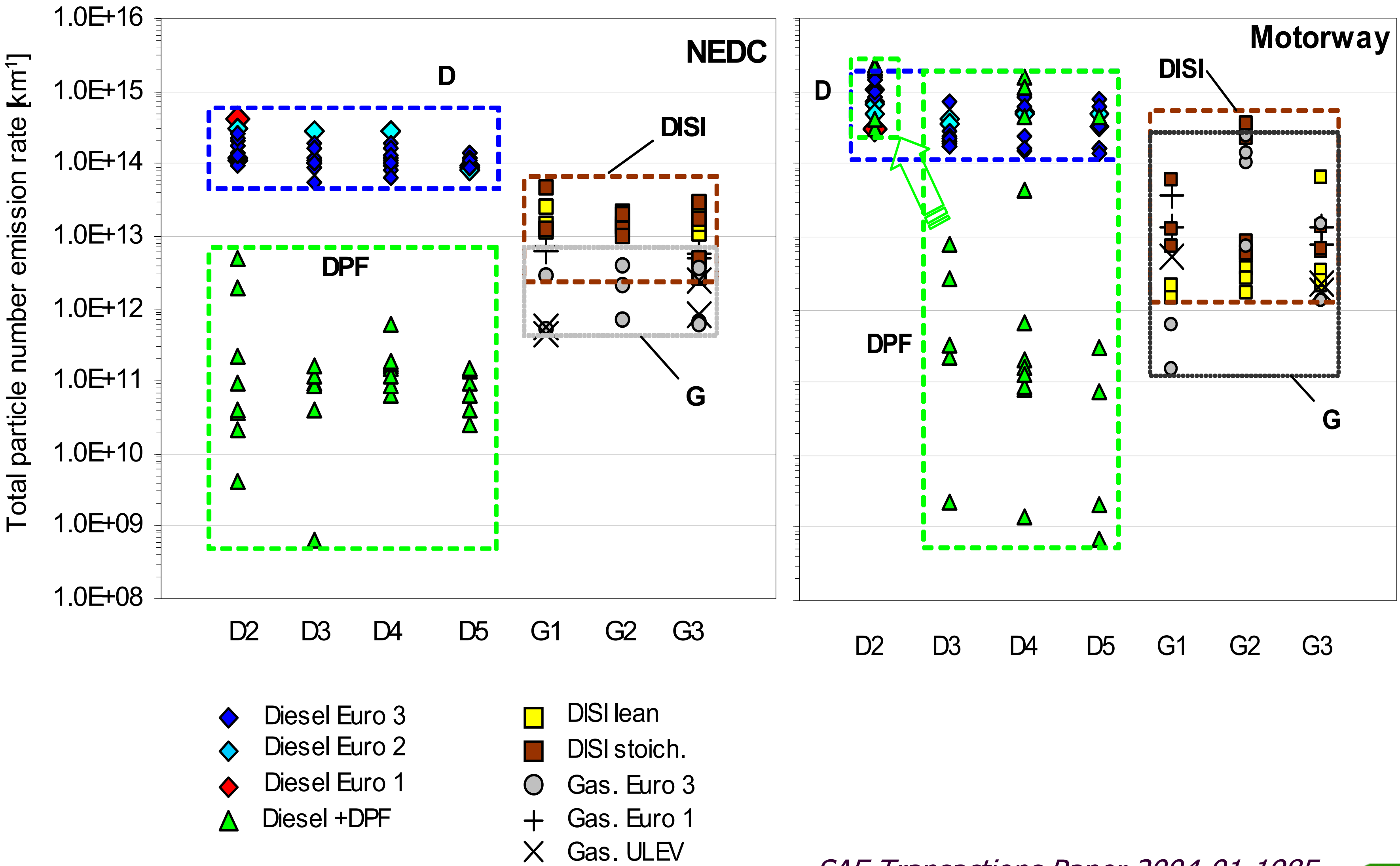
SAE Transactions Paper 2004-01-1985

Results: Active Surface (Diff. Charger)



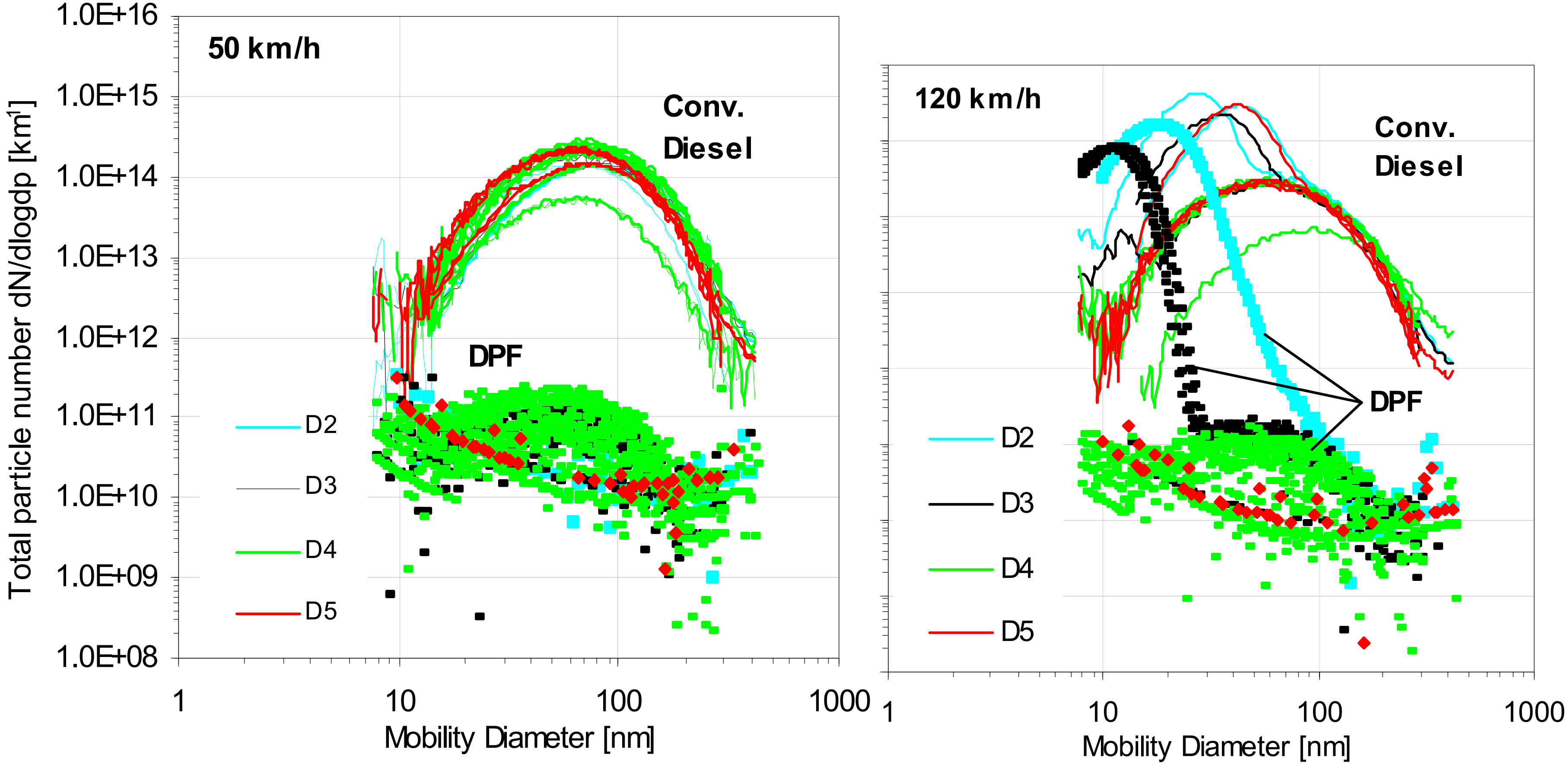
SAE Transactions Paper 2004-01-1985

LDV Results: Total Particle Number (CPC)



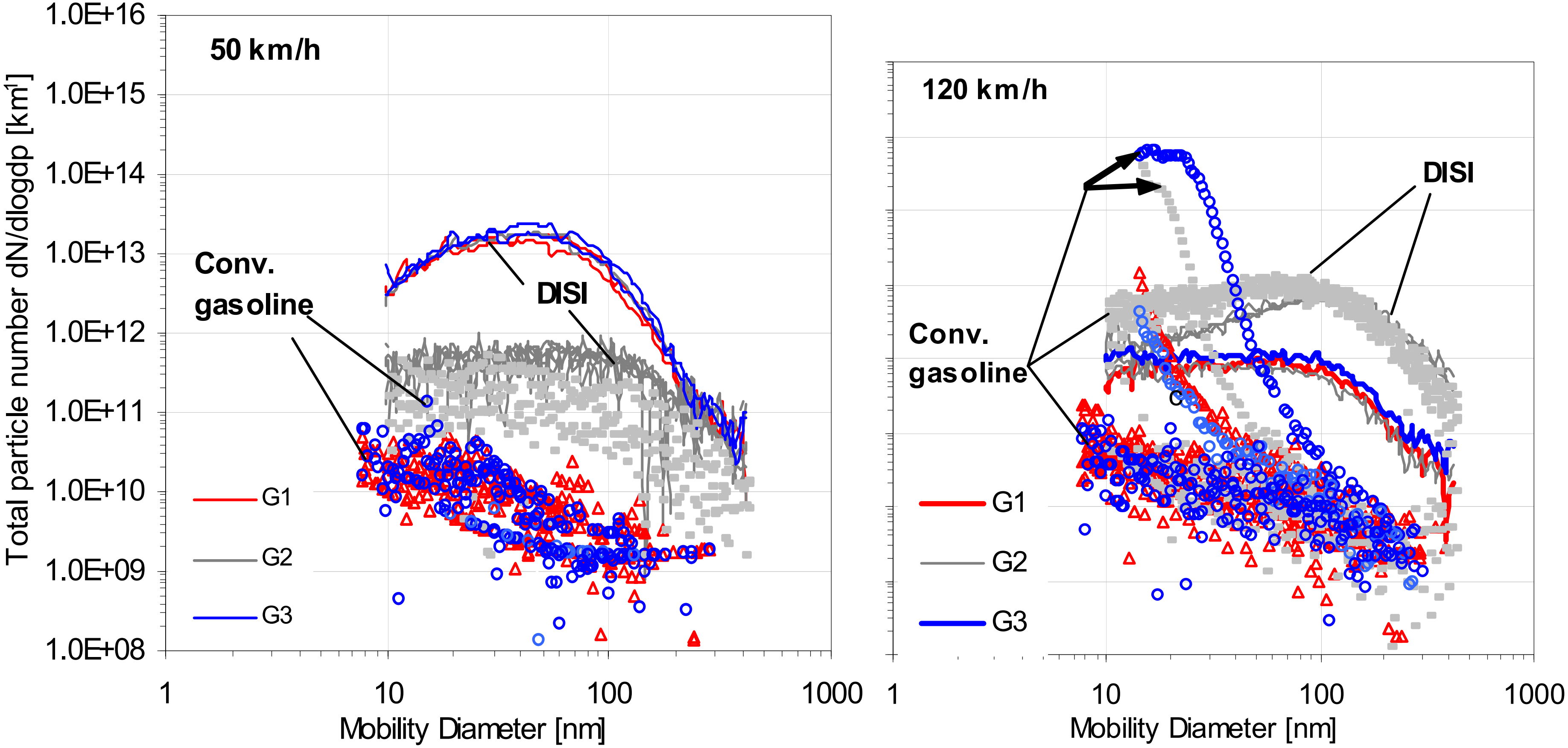
SAE Transactions Paper 2004-01-1985

LDV Results: Total Particle Size Distribution (SMPS) - Diesel



SAE Transactions Paper 2004-01-1985

LDV Results: Total Particle Size Distribution (SMPS) - Gasoline



SAE Transactions Paper 2004-01-1985

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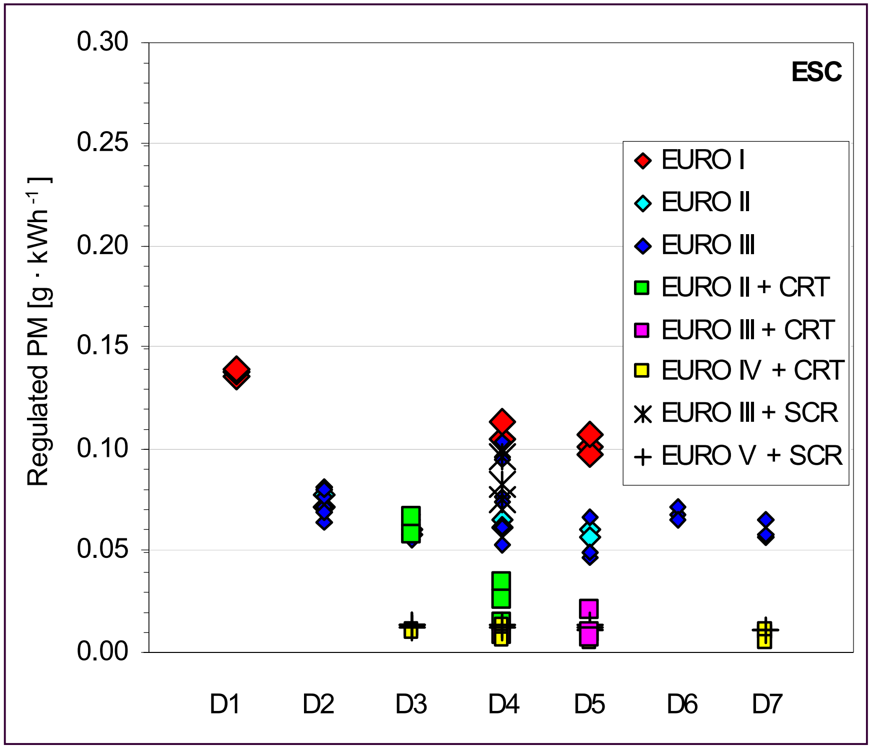
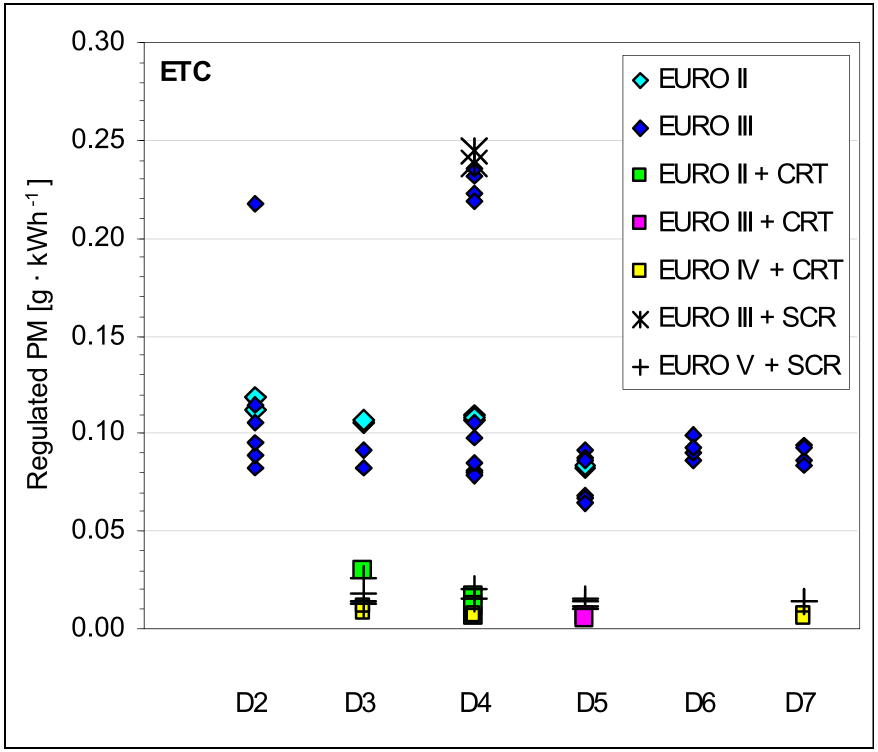
HDV Results: Regulated PM

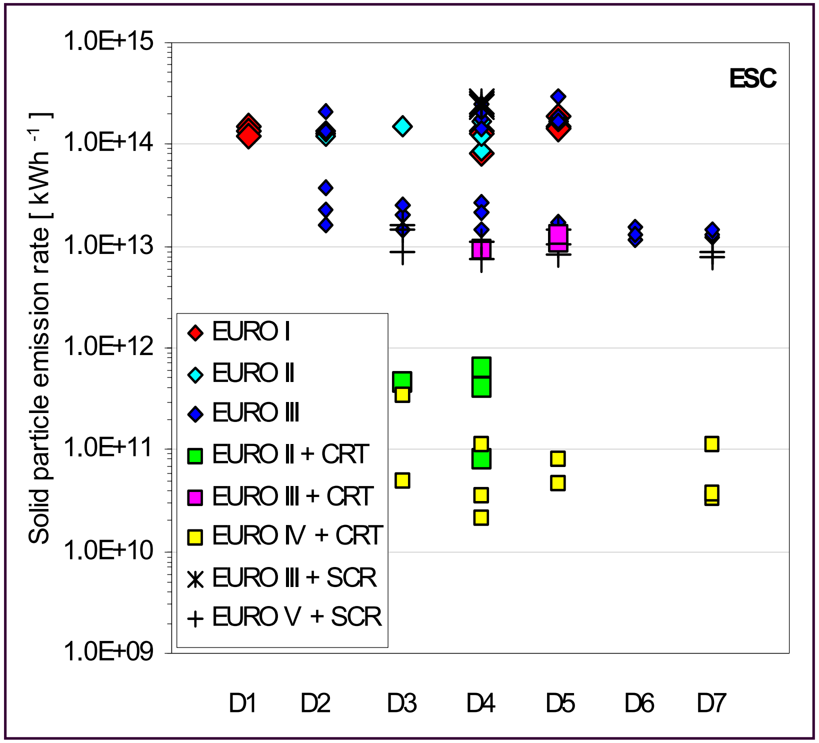


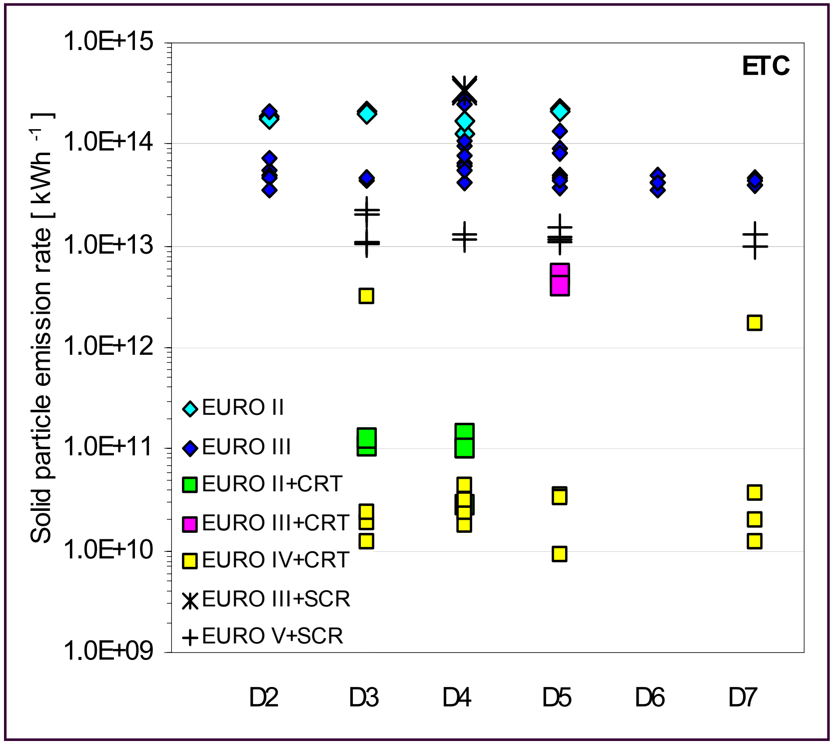


- **Very low PM emissions achieved with CRT equipped systems on low sulphur fuels, & with Euro-V SCR/urea prototype without DPF**
- **Benefits of fuel sulphur reduction also evident**

SAE Transactions Paper 2004-01-1986

HDV Results: Solid Particle Number (ELPI +TD)

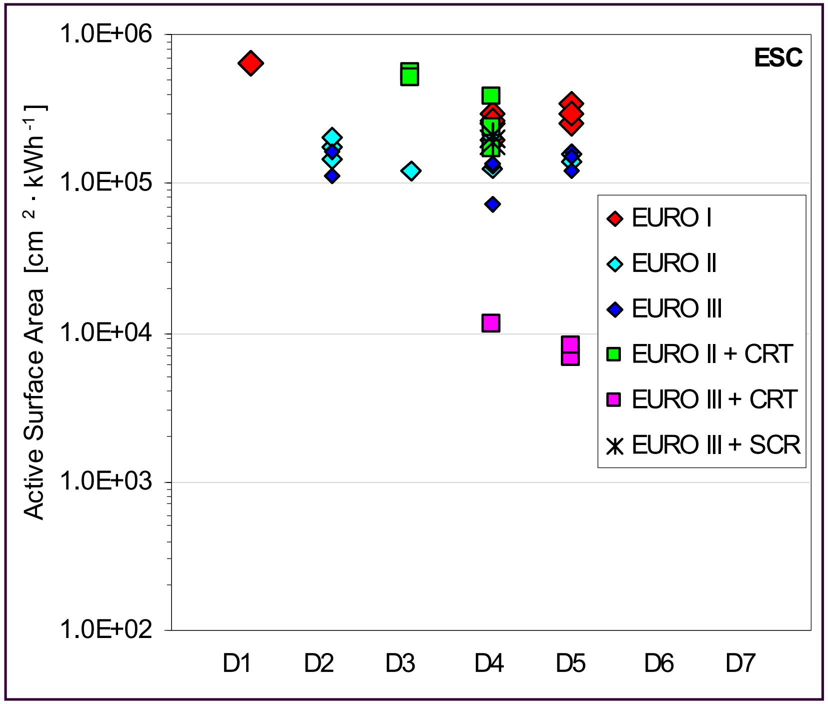


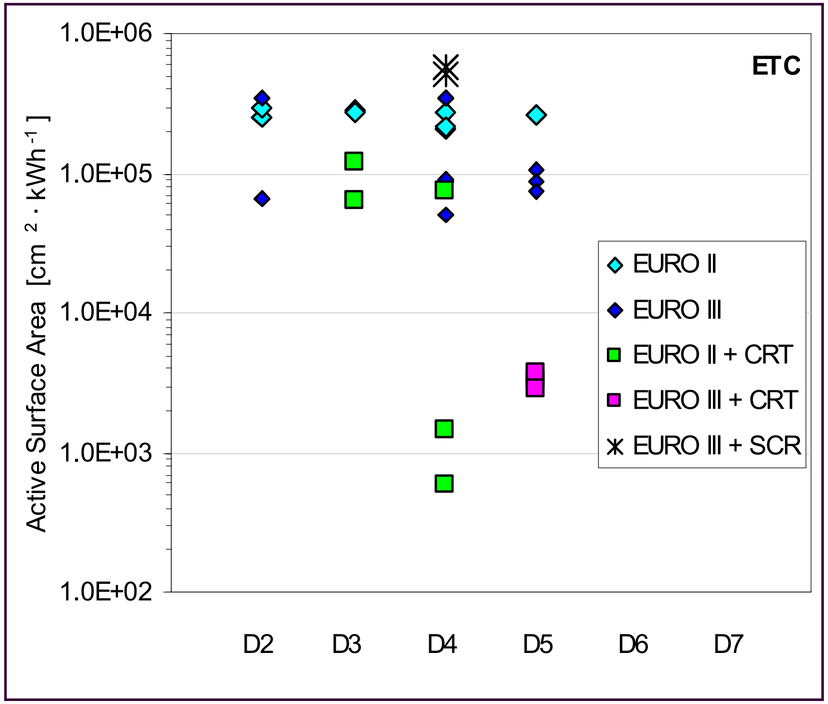


- Conventional Euro-I to Euro-III engine technologies produced total solid particle number emissions in the range of 10^{14} particles/kWh
  - Results for one Euro-III engine ca. an order of magnitude lower, needs further explanation
- DPF systems offer the potential to reduce solid particle numbers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

SAE Transactions Paper 2004-01-1986

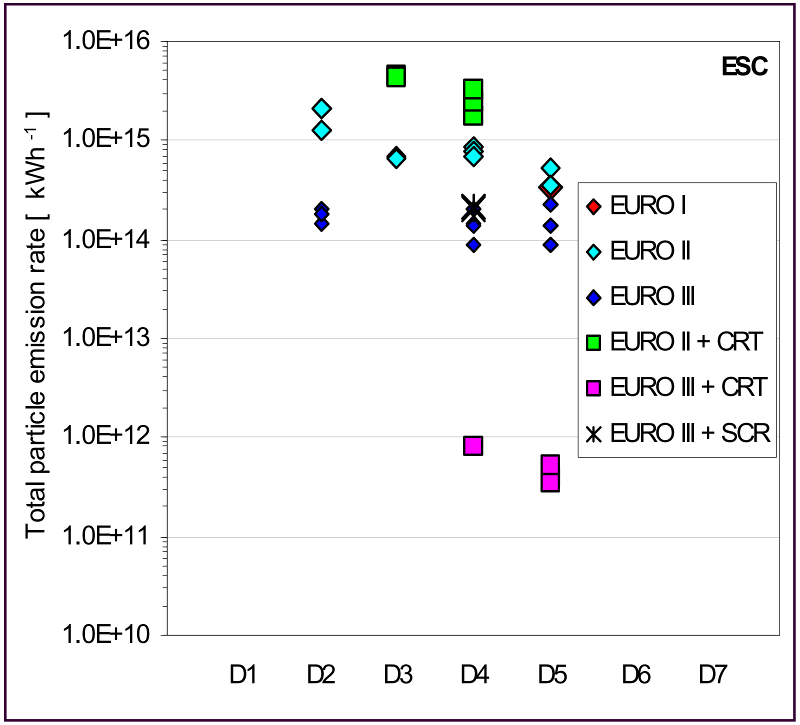
Results: Active Surface (DC)

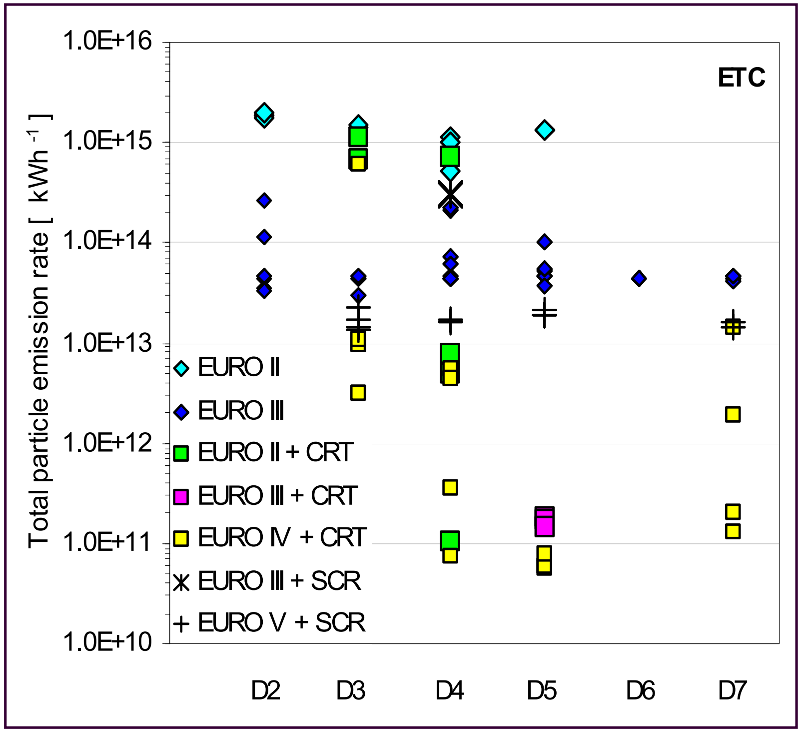




- **Euro-I to Euro-III engines produced active surface values in the range 10^5 to 10^6 cm^2/kWh. The Euro-III engine with CRT gave 1-2 orders of magnitude reduction, broadly in-line with its ELPI performance.**
- **The Euro-II engine with CRT gave active surface values in the same range as the Euro-I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

HDV Results: 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**

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Based on the EU *Particulates* Research project activities, results and database (http://lat.eng.auth.gr/particulates/)

Comparison of Diesel particle exhaust emissions from Light Duty vehicles and Heavy Duty engines

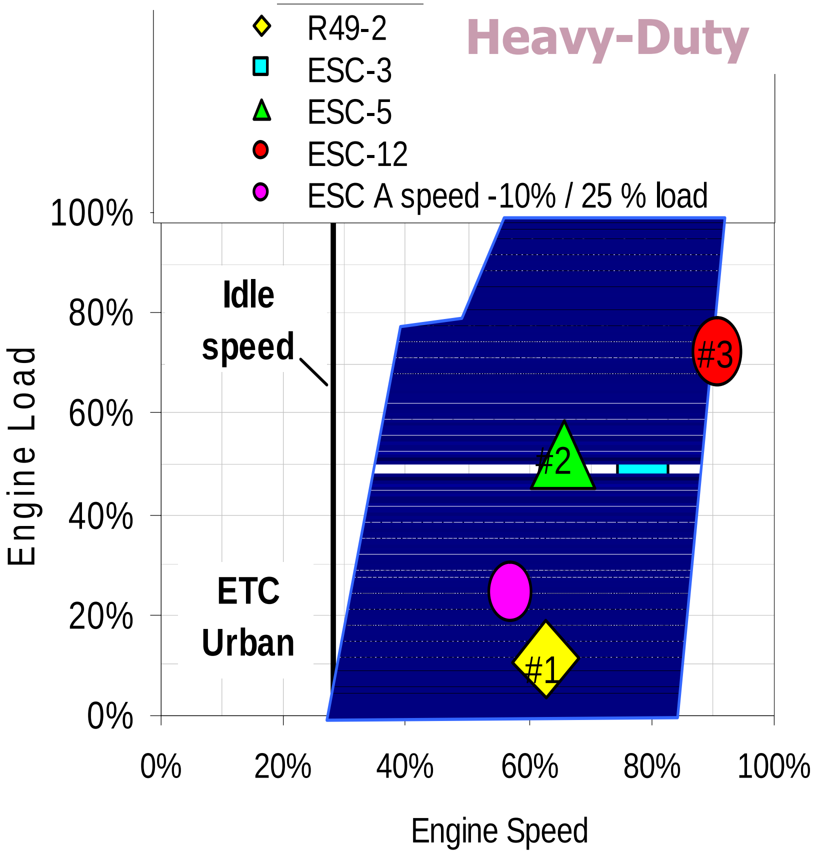
- Due to the different regulatory steps and definitions, there is no clear view on how diesel **LD** vehicle emissions compare to **HD** and results on diesel emissions that appear in the literature may contradict.
- Target is to present particle emission rates and size distributions from HD and LD vehicles, expressed on a per distance traveled and on a per unit of fuel consumed basis to enable a straightforward comparison.
- This information can be used to estimate the contribution of trucks, busses and cars to ambient concentrations and to understand differences in their emission behavior.

SAE Transactions Paper 2006-01-0866

LAT

Driving Cycles / Operation modes

Urban



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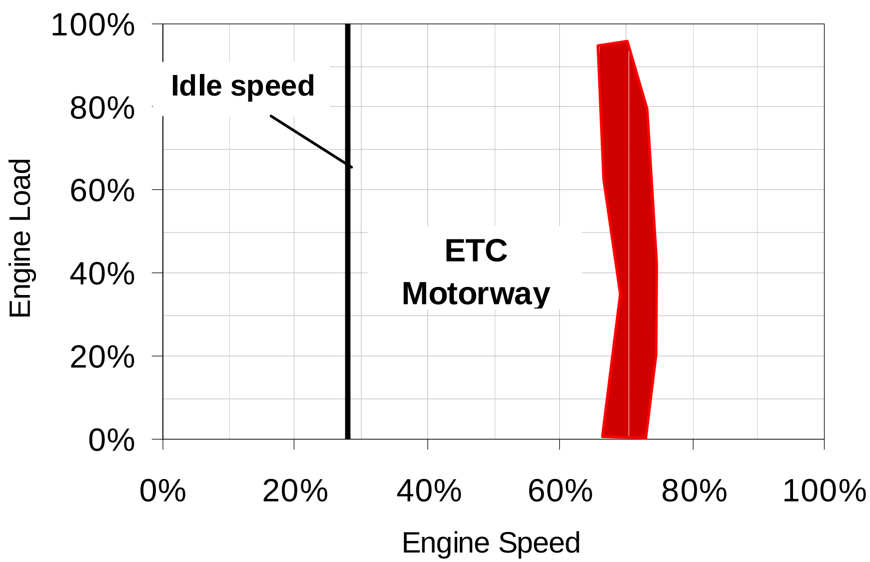
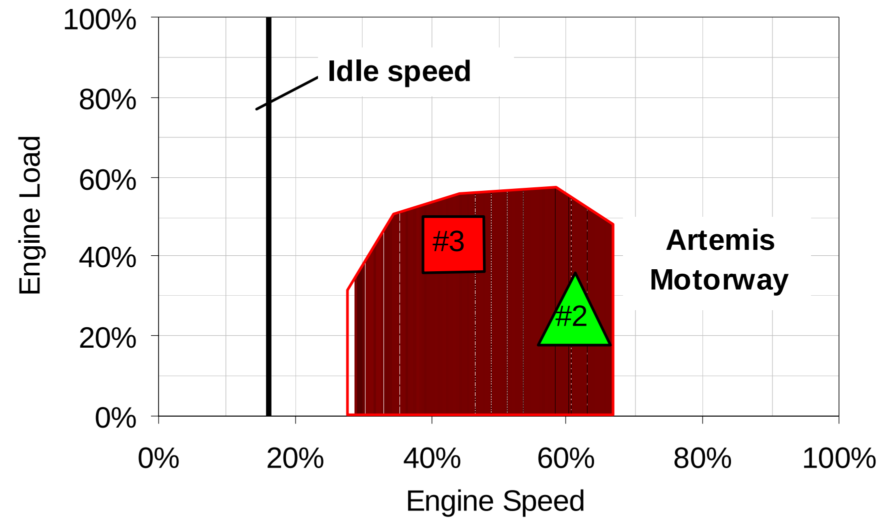
Driving Cycles / Operation modes

Motorway

Heavy-Duty



Light-Duty



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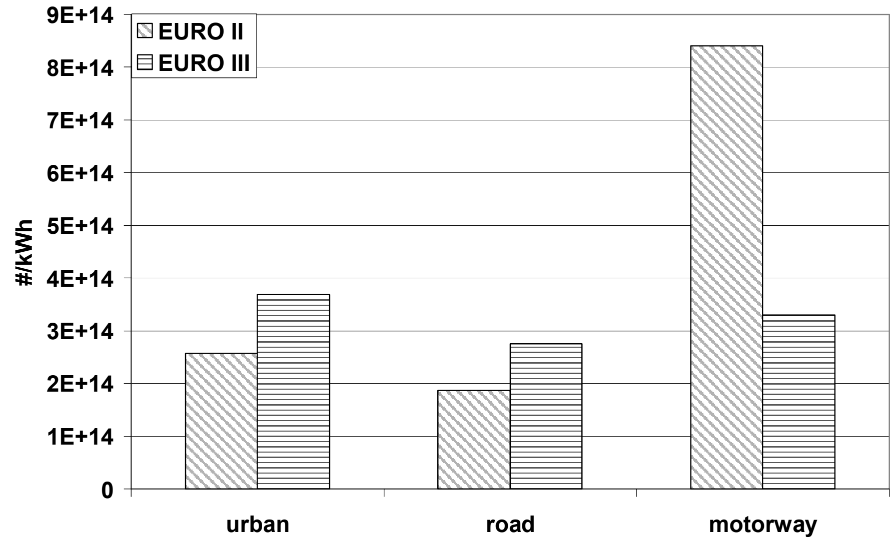
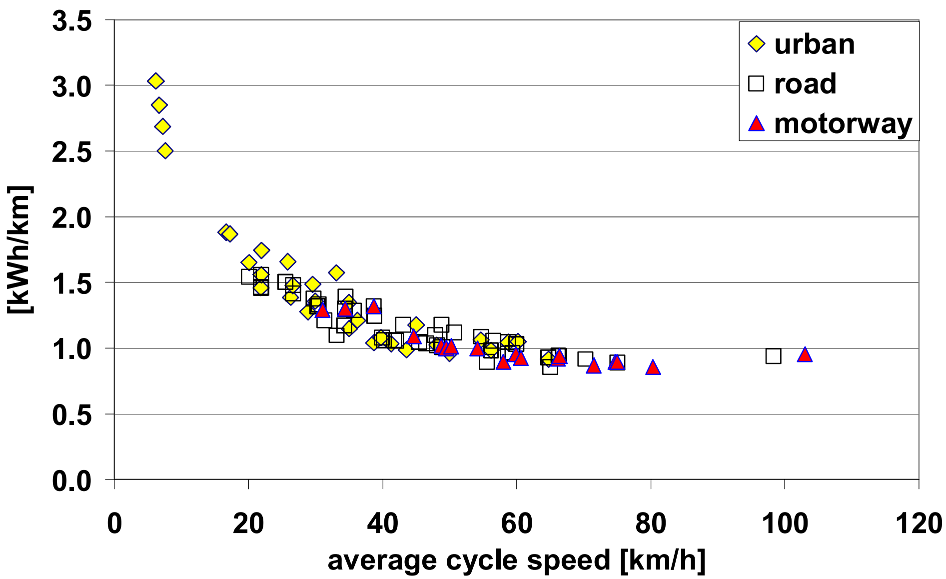
Calculation steps for distance specific emissions of HDVs

(1) Work specific solid particle number emissions for HDEs





(2) Mean positive cycle work per kilometer driven

Example for average-sized 2-axle coaches (50% loaded, 0% road gradient) in real world driving cycles

Calculated by the model PHEM

SAE Transactions Paper 2006-01-0866

Typical particle emission values and ranges for different vehicle categories in urban and highway driving, using low sulfur fuel (<10 ppm wt.)

Category	Emission Standard	PM [g/km]	Nsol ×10^{14} [#/km]	Act. Surf. [m^2/km]
Urban Driving				
Passenger Car	Euro 3	0.06	1.8	10-15
Pass Car + DPF	Euro 3+	0.002	<2×10^{11}	<0.0024
Urban Bus	Euro 3	0.20	5.2	28-88
Truck (7.5 tn)	Euro 3	0.15	3.4	18-58
Truck (16 tn)	Euro 3	0.33	8.7	47-146
Truck (16 tn) + CRDPF	Euro 4	0.06	~10^{11}	n.a.
Truck (16 tn) + SCR	Euro 5	0.06	0.48	n.a.
Highway Driving				
Passenger Car	Euro 3	0.04	1.9	12-15
Passenger Car + DPF	Euro 3+	0.002	<2×10^{11}	<0.0036
Coach	Euro 3	0.11	2.0	11-26
Truck (7.5 tn)	Euro 3	0.08	1.4	8-19
Truck (16 tn)	Euro 3	0.18	2.4	14-32
Truck (16 tn) + CRDPF	Euro 4	0.02	~10^{11}	n.a.
Truck (16 tn) + SCR	Euro 5	0.02	0.03	n.a.

Emissions proportional to engine size

No visible association with engine size

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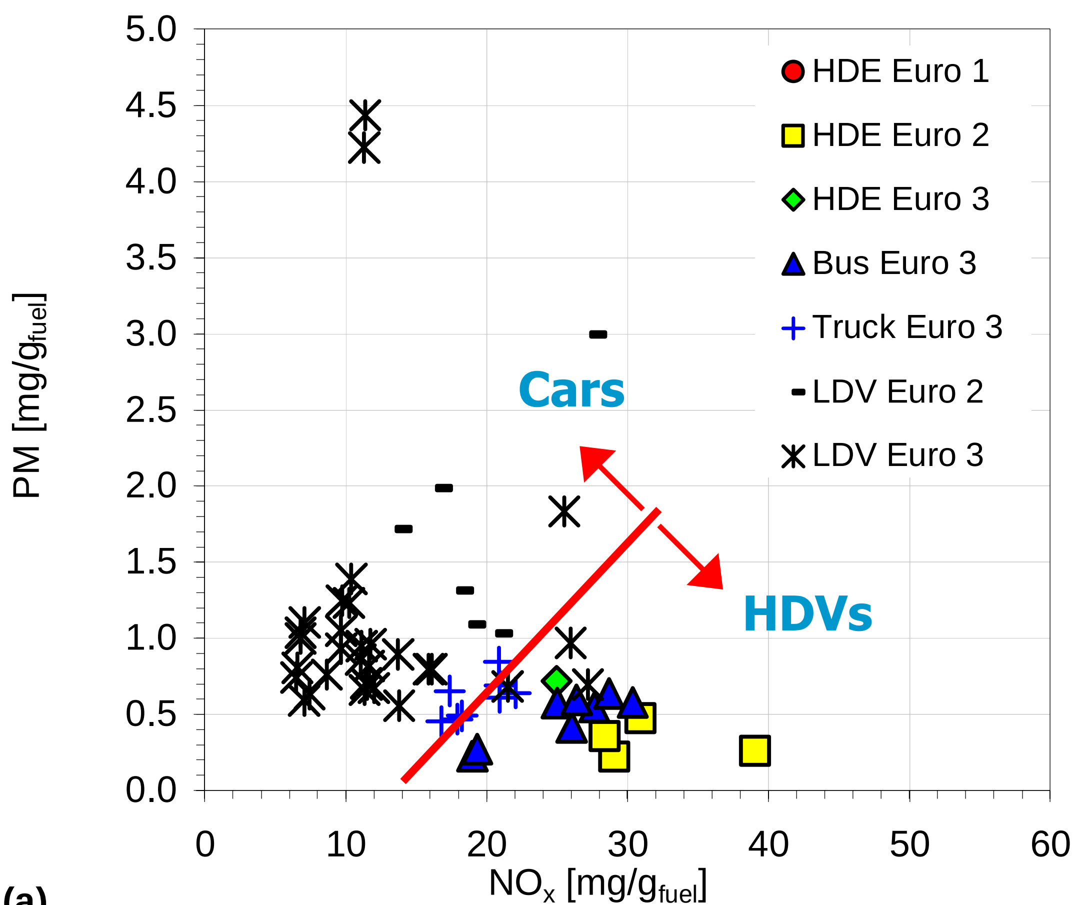
Results: Emissions per unit fuel consumed - PM



(a)

- Cars tuned towards low NOx / high PM emissions
- HDVs tuned towards high NOx, high efficiency

Euro Level	NOx [g/kWh]		PM [g/kWh]	
	LDV	HDE	LDV	HDE
Euro 2	4.1	7.0	0.56	0.15
Euro 3	3.5	5.0	0.35	0.10
Euro 4	1.7	3.5	0.17	0.02
Euro 5	1.4	2.0	0.03	0.02

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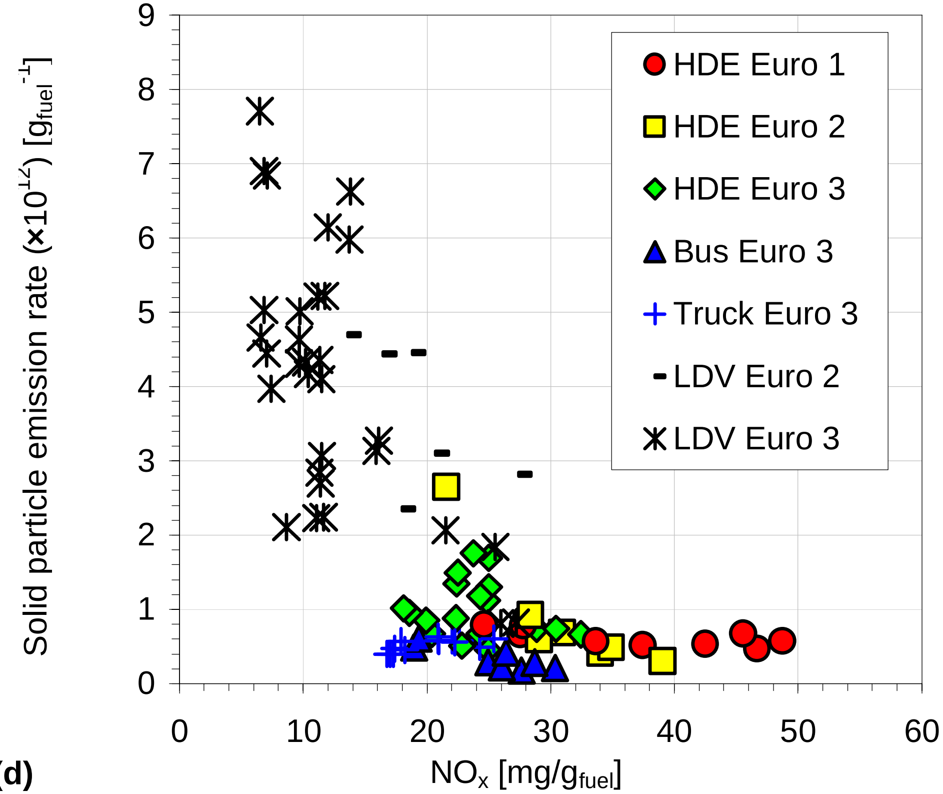
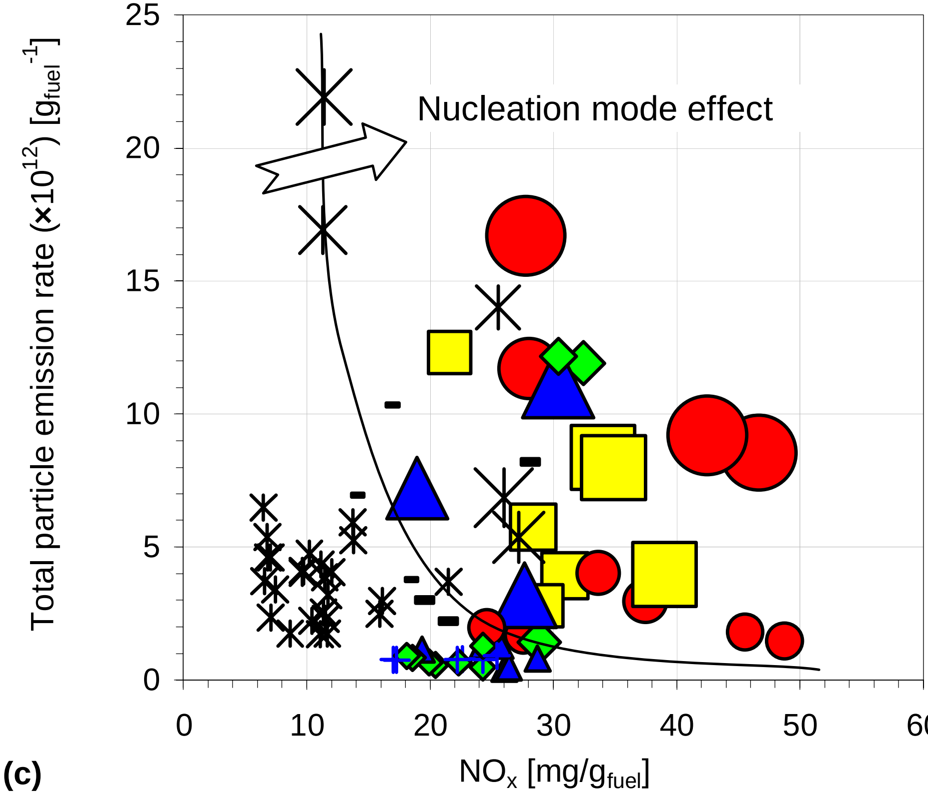
Results: Emissions per unit fuel consumed
Particle Number

Solid



(d)

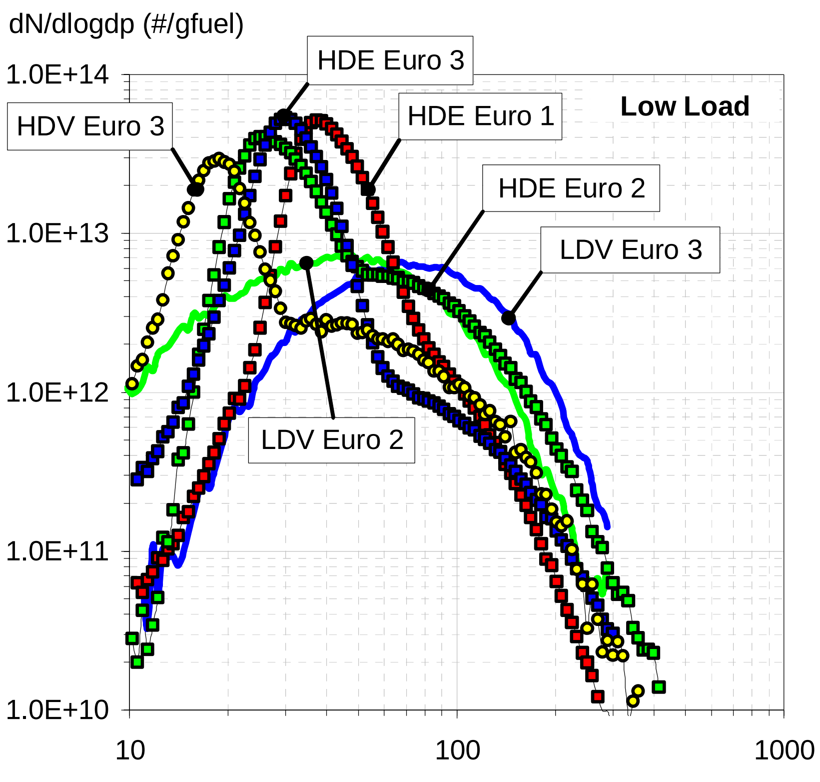
Total



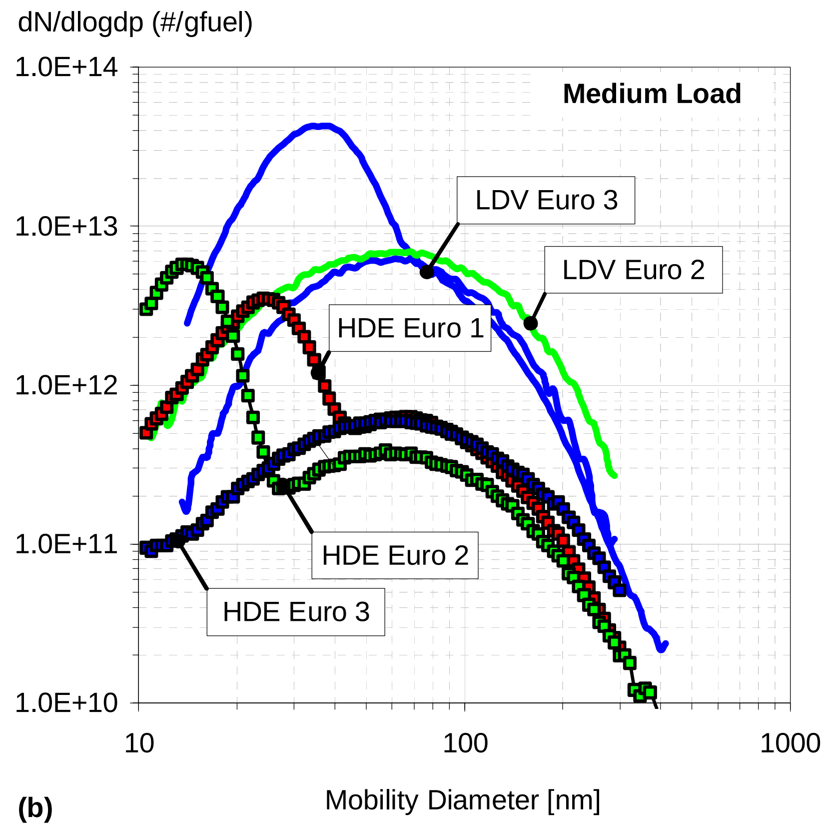
(c)

Nucleation mode is associated with the low solid particle number emissions of HDVs .

Particle size distributions from LDVs, HDEs and HDVs



(a)



(b)

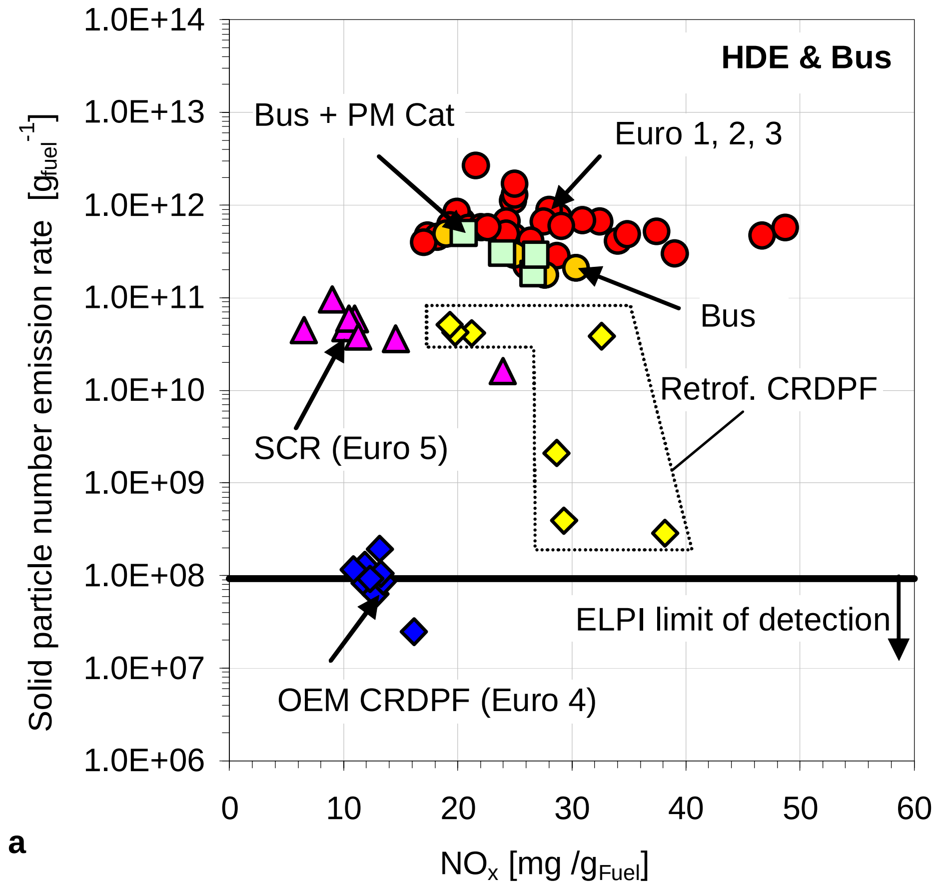
HDE tend to produce nucleation particles at low loads probably due to high SOF

LDV tend to produce nucleation particles at high loads probably due to sulphates

SAE Transactions Paper 2006-01-0866

Results: Effect of aftertreatment - HD

Solid



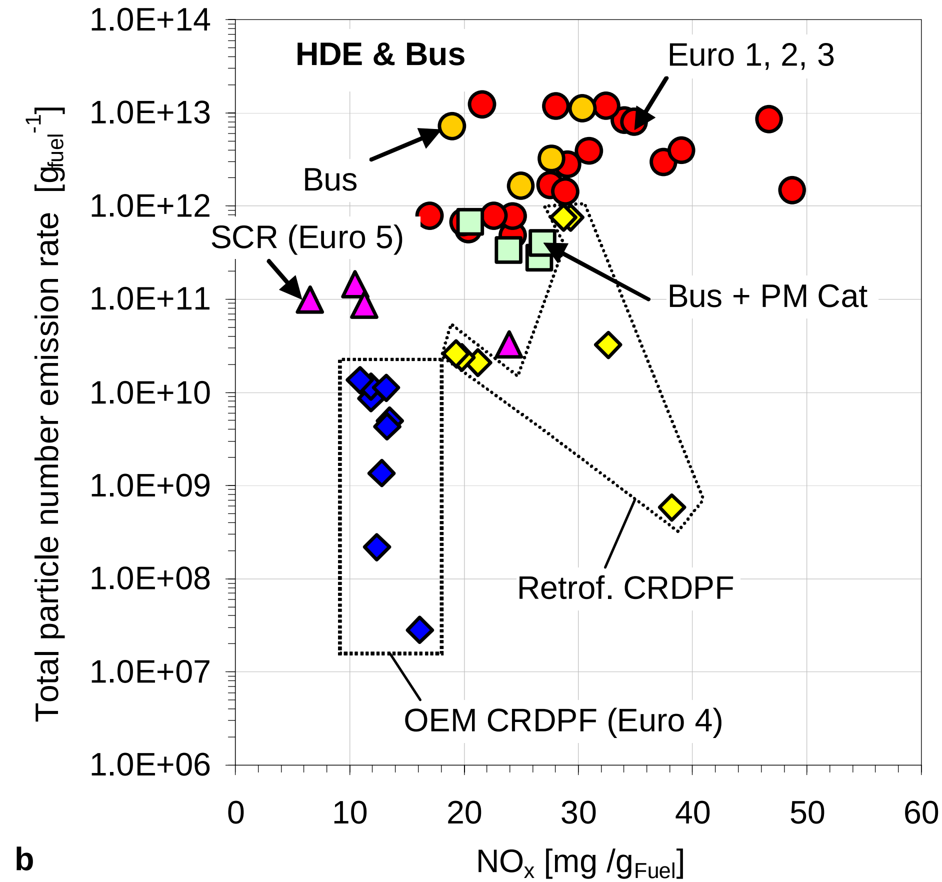
- OEM DPF reduces solid particle number by more than 3 orders of magnitude
- Engine tuning for SCR application reduces particle number by 1 order of magnitude and leads to highest NOx reductions
- DPF retrofitting has a positive but variable effect. All reductions beyond one order of magnitude
- The PM catalyst has a negligible overall effect

Results: Effect of aftertreatment - HD

- Results are more difficult to interpret due to the NM formation

- SCR reduces particle number without inducing NM formation

Total



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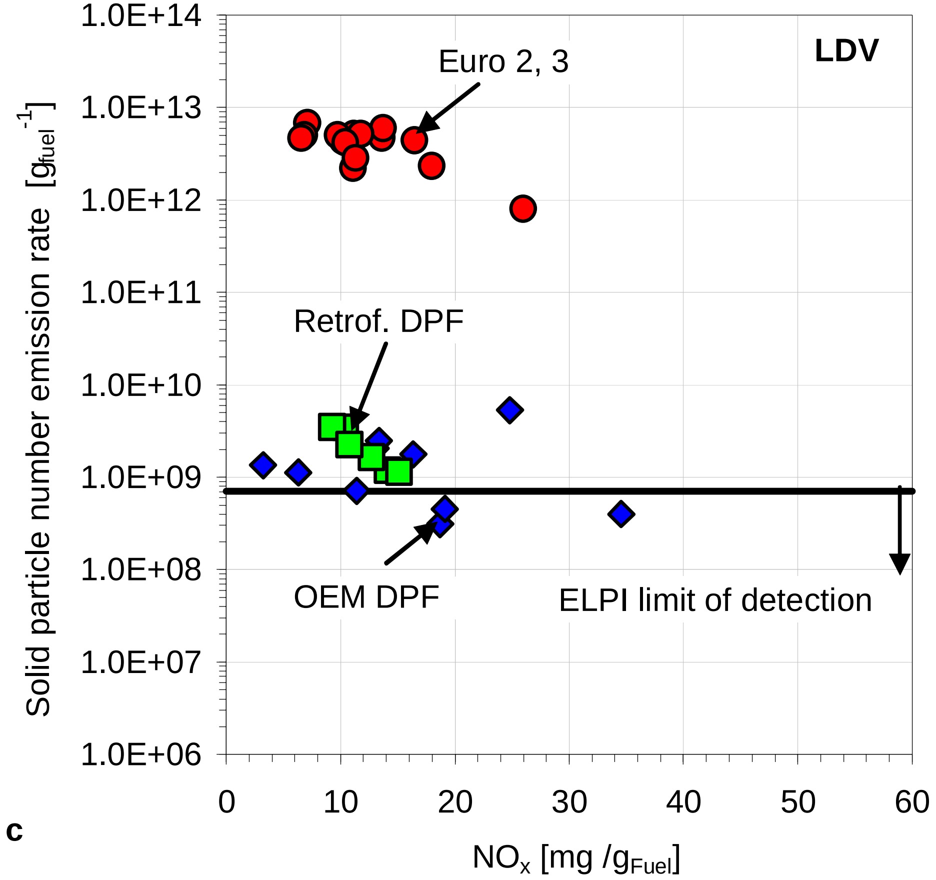
Results: Effect of aftertreatment - LD

Solid

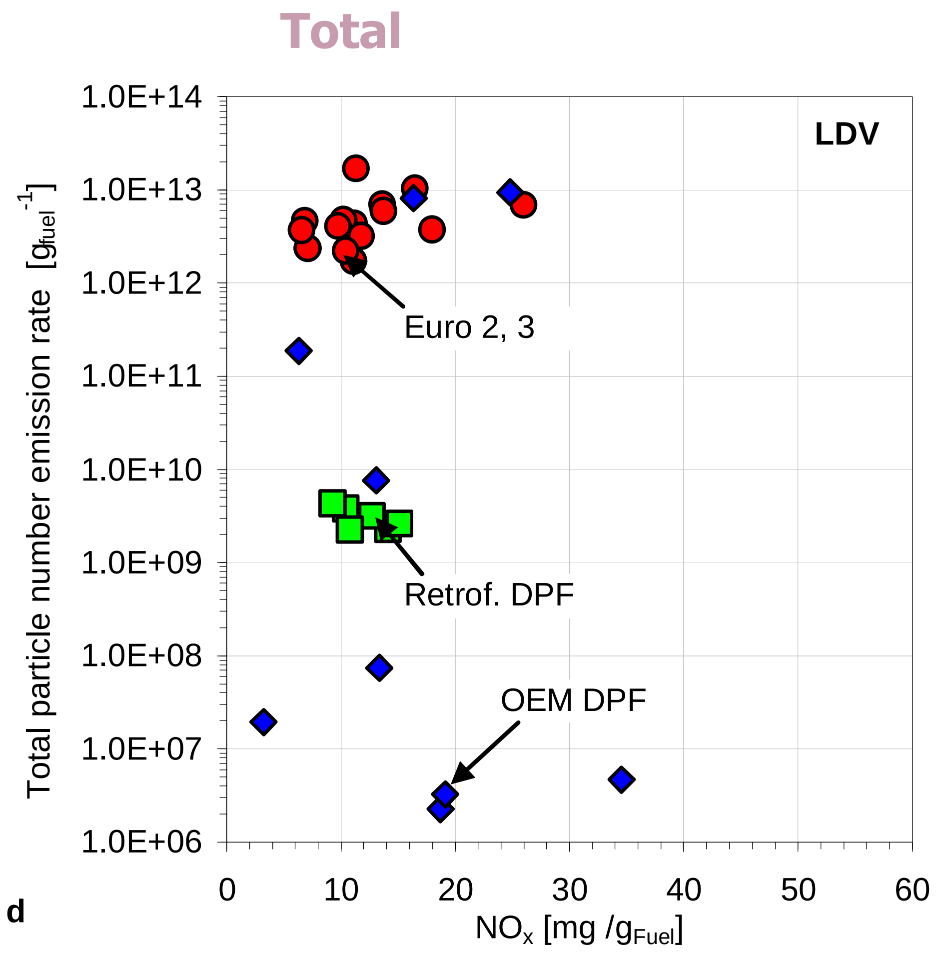


- Both retrofitted and OEM DPF seem to reduce solid particle number by at least 3 orders of (ELPI limit of detection)

Results: Effect of aftertreatment - LD

- Particle reduction by OEM DPF may reach up to 6 orders of magnitude
- Total particle number may reach conventional levels during regeneration

⑤ there is room for more rigorous control of condensable species in the exhaust gas



Contents

Based on the EU *Particulates* Research project activities, results and database (http://lat.eng.auth.gr/particulates/)

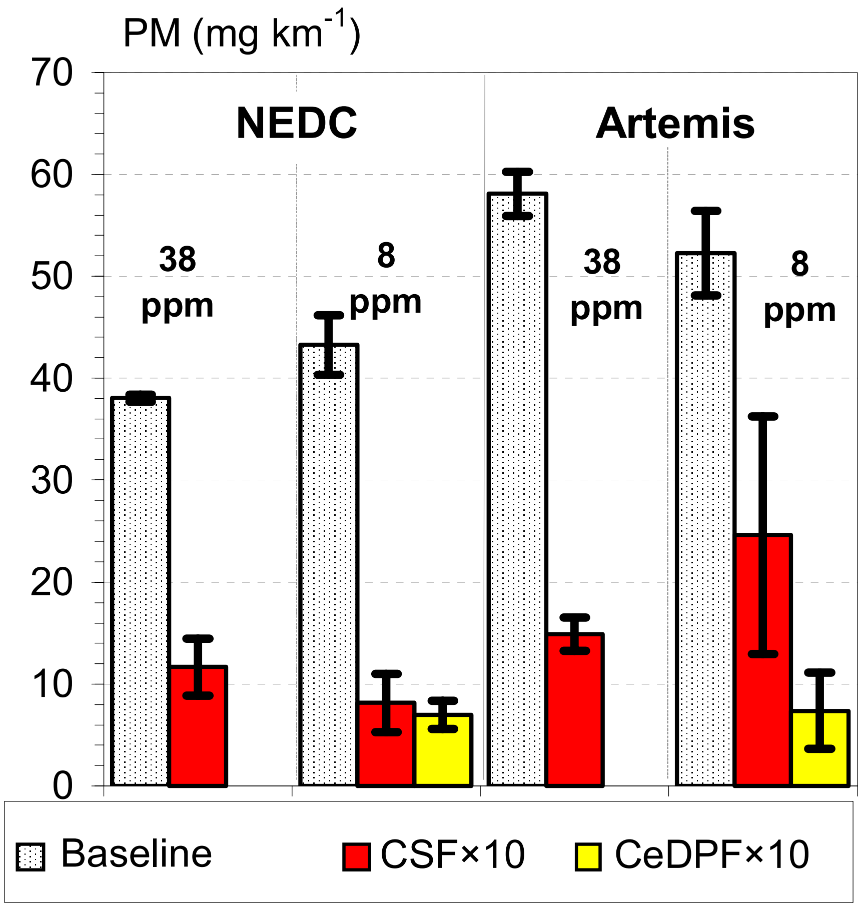
- Development of a measurement protocol to address both semi-volatile and solid particles
- Results from LDVs and HDVs
- Comparison of Diesel particle exhaust emissions from Light Duty vehicles and Heavy Duty engines
- Diesel Particulate Filter Efficiency
- Conclusions and follow-up

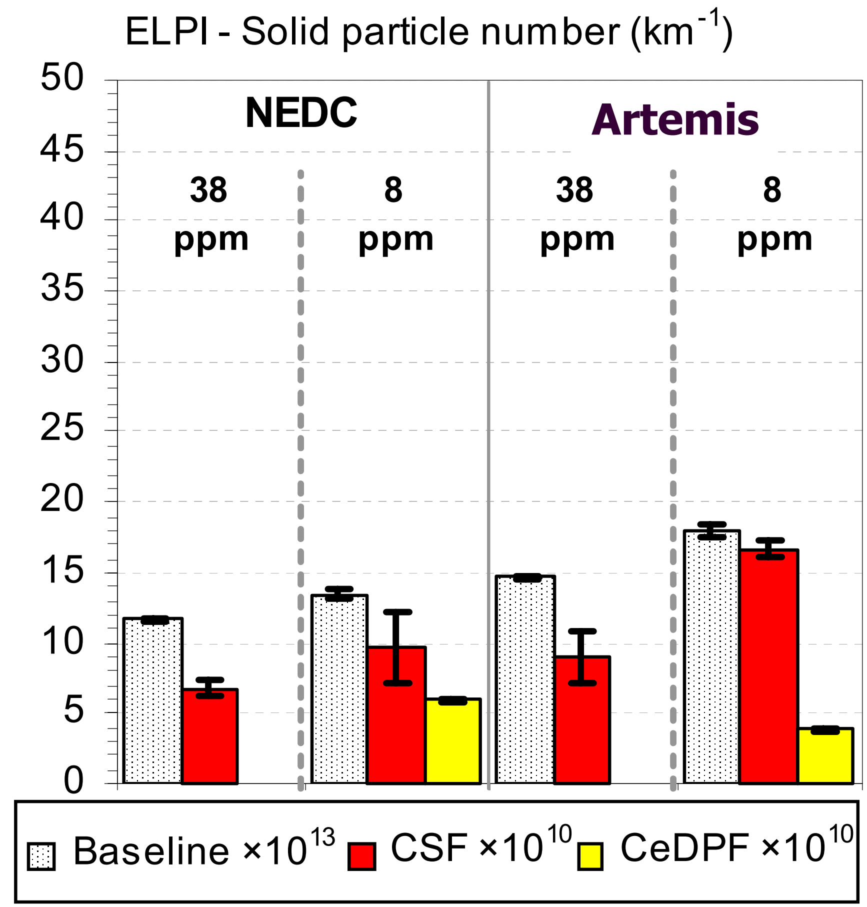
Diesel Particle Filters – Test Vehicle - Fuels

- Ce-based additive (CeDPF) at 25 ppm
  - NGK SiC ∅144 mm×L 152.4 mm (5.66"×6"),
  - cell density of 200 cpsi and wall thickness of 0.38 mm.
- Catalyzed soot filter (CSF) with Pt-based catalyst
  - NGK SiC ∅144 mm×L 152.4 mm (5.66"×6"),
  - cell density of 300 cpsi and a wall thickness of 0.30 mm
  - material porosity and mean pore size were also larger than the CeDPF (before the washcoat application).
- Test Vehicle
  - 2001 model year Renault Laguna 1.9 dCi meeting Euro 3 emission standards
- Two fuels complying with EN590 specifications were used
  - A higher sulphur fuel (HSF) 38 ppm wt.
  - A lower sulphur fuel (LSF) 8 ppm wt.
- Lubrication oil
  - 15W-40 grade (ACEA A3/B3) with ~6000 ppm wt. sulphur

Atmospheric Environment, Vol. 39/27 (2005) 4925-4936.

Particle mass (PM) and particle properties for the fuel and vehicle configurations studied (1/2)

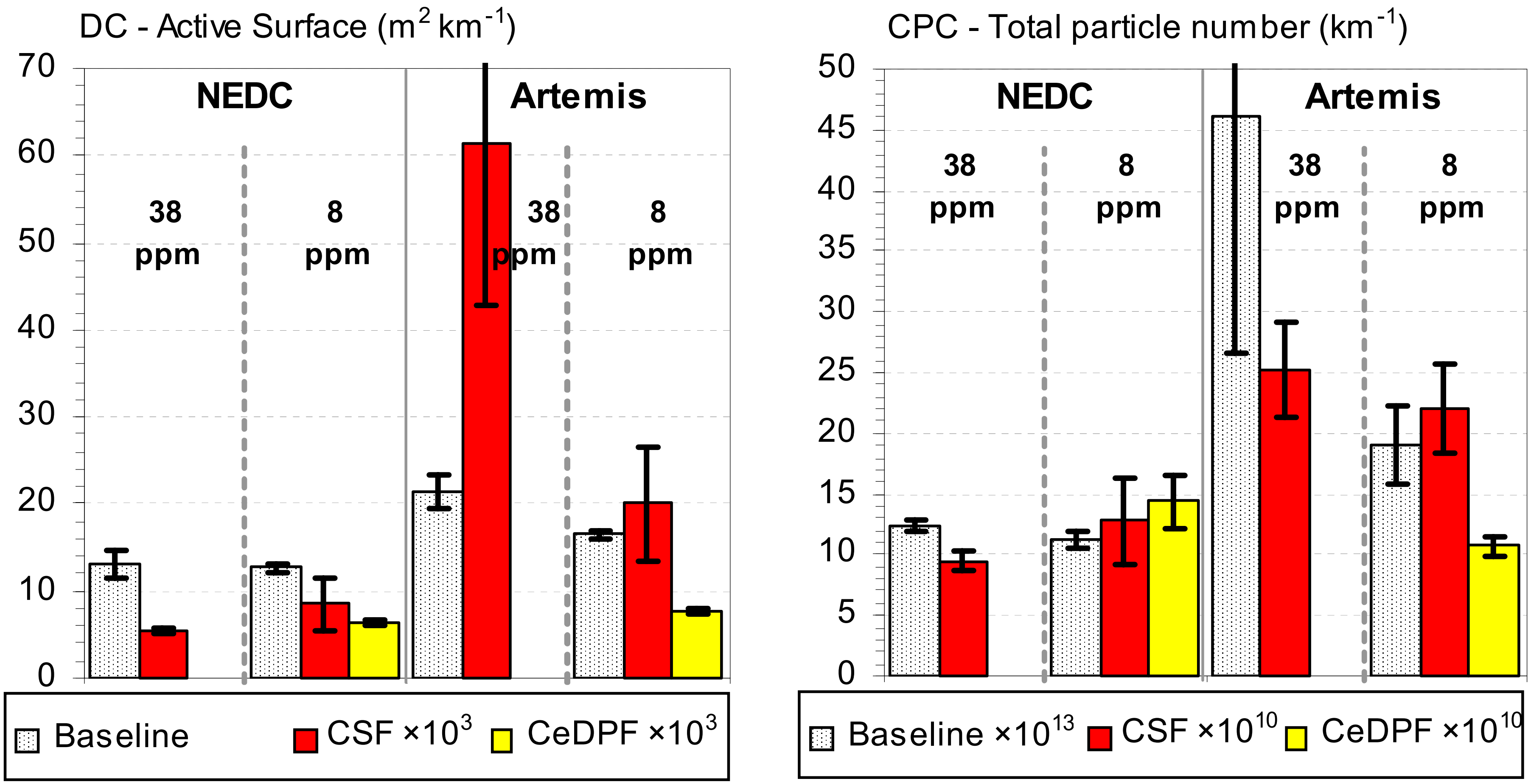




Error bars correspond to min-max of two measurements conducted at different days.

Atmospheric Environment, Vol. 39/27 (2005) 4925-4936.

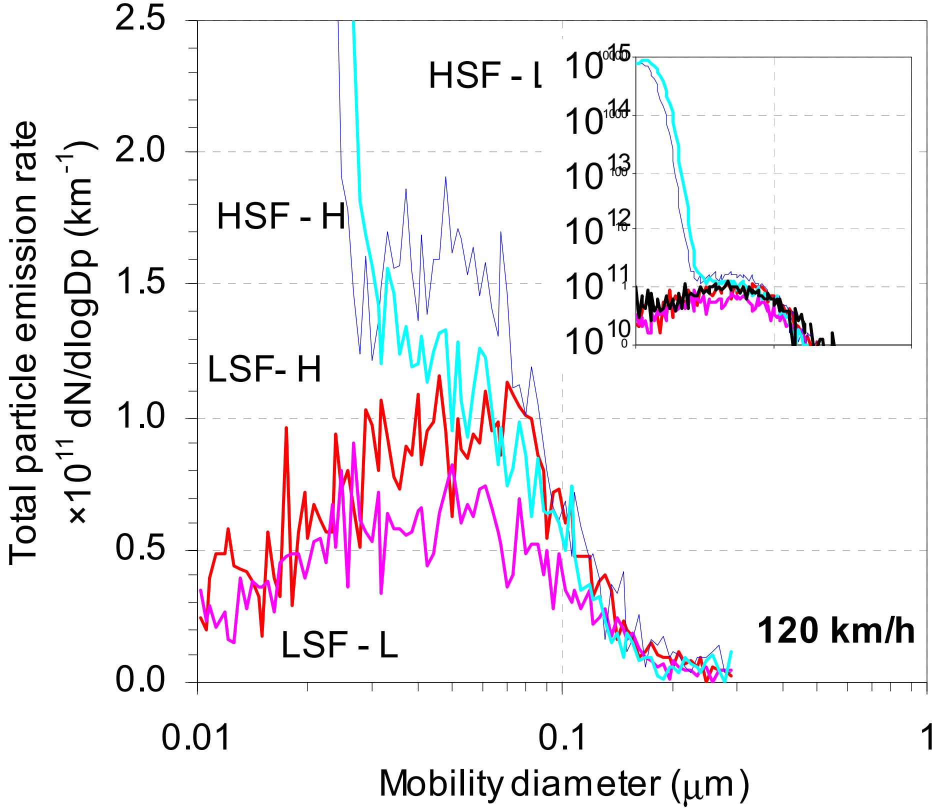
Particle mass (PM) and different airborne particle properties for the fuel and vehicle configurations studied (2/2)

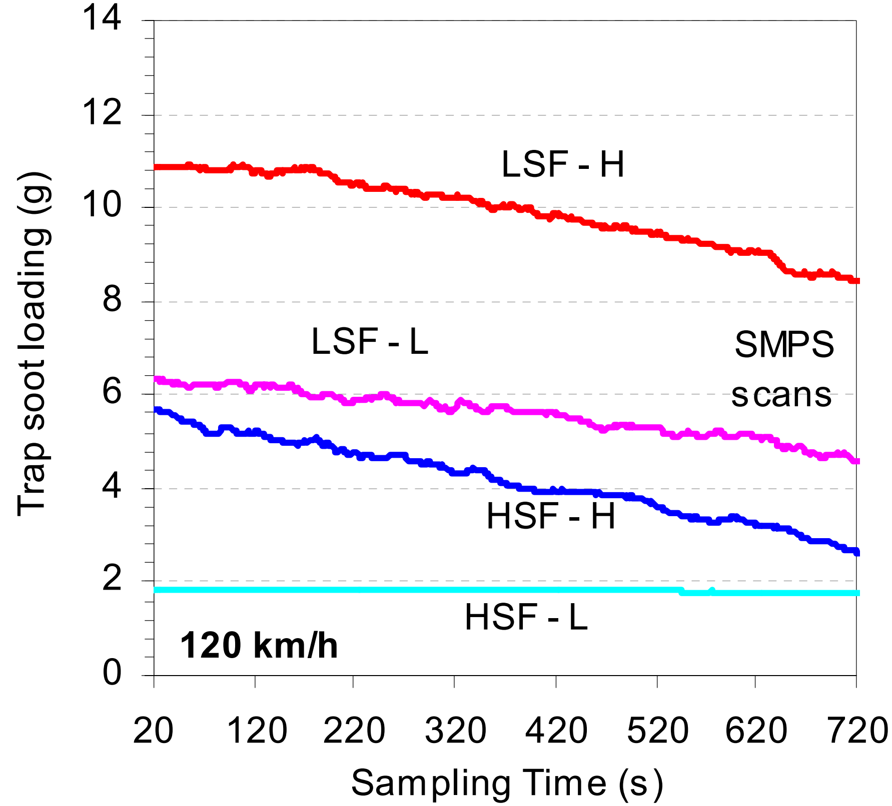


Error bars correspond to min-max of two measurements conducted at different days.

Atmospheric Environment, Vol. 39/27 (2005) 4925-4936.

Effect of CSF soot loading level on particle size distributions 120 km/h





H, L correspond to "higher" and "lower" loadings respectively.

Atmospheric Environment, Vol. 39/27 (2005) 4925-4936.

Filtration efficiency (expressed in %) of DPFs, based on different particle properties

Measure	Driving Cycle	CSF		CeDPF
		38 ppm S	8 ppm S	8 ppm S
PM	NEDC	96.94	98.12	98.39
	Artemis	97.44	95.30	98.59
Active Surface (DC)	NEDC	99.96	99.93	99.95
	Artemis	99.71	99.88	99.95
Solids Number (ELPI)	NEDC	99.94	99.93	99.96
	Artemis	99.93	99.91	99.98
Total Number (CPC)	NEDC	99.92	99.89	99.87
	Artemis	99.95	99.88	99.94
Total Number (SMPS)	50 km/h	99.94	99.95	99.87
	90 km/h	99.94	99.96	99.92
	120 km/h	35.67	99.96	99.94

Due to nucleation

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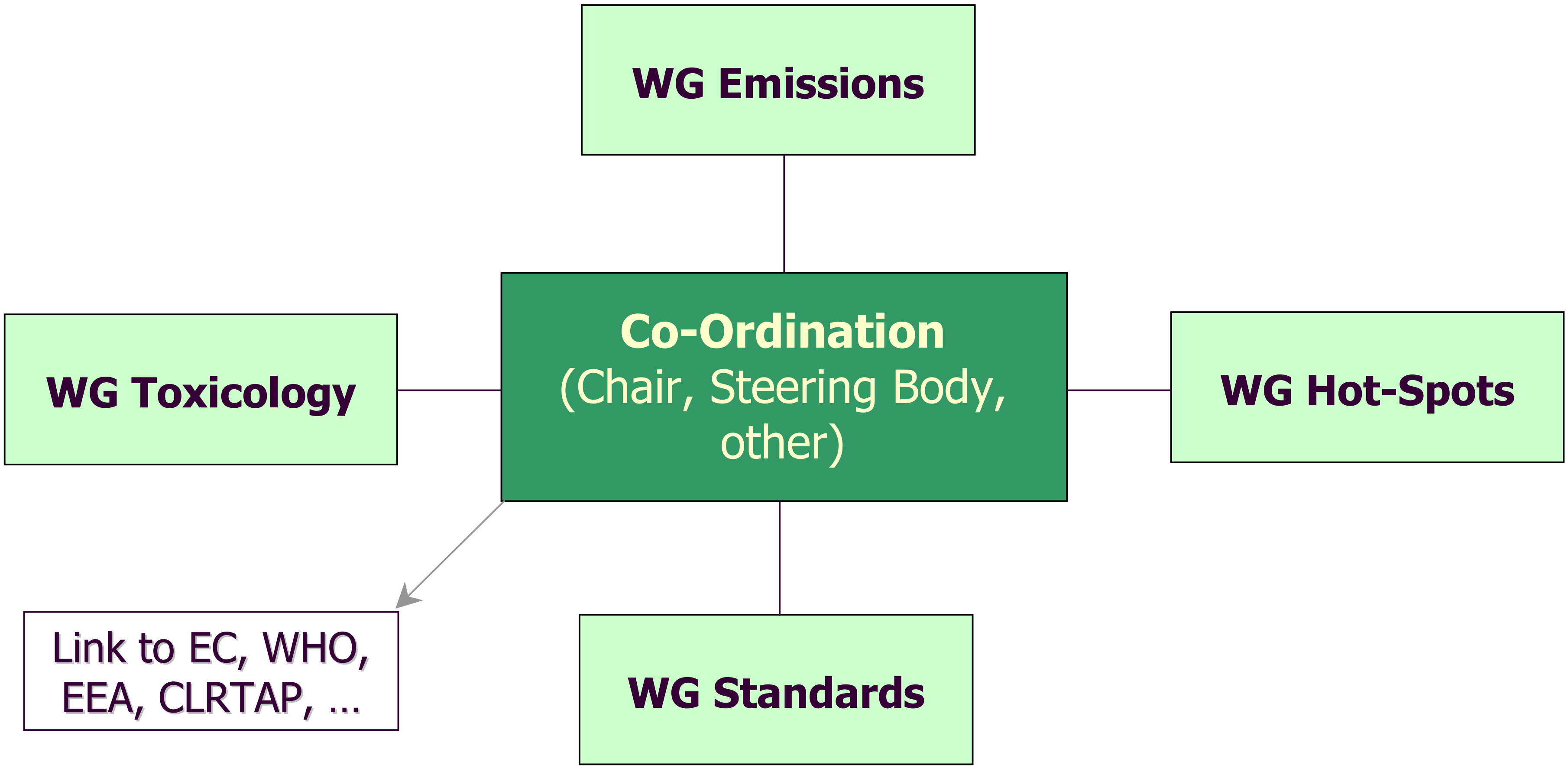
Conclusions - 1

- Semi-volatile (or Nucleation Mode – NM) nanoparticles can be measured in a reliable and repeatable manner, at both LDVs and HDVs
- **Nucleation mode formation in HDVs**:
  - Frequent due to low specific solid particle number
  - More prominent at low loads (higher SOF emissions)
  - Decreases at high loads
  - Decreases with oxidation catalysts
- **Nucleation mode formation in LDVs:**
  - Not present at low loads due to efficient oxidation catalysts
  - Possibility to form at high load, due to sulfate formation, even with sub 10 ppm S fuel and medium S lube oil

Conclusions - 2

- **Aftertreatment systems:**
  - DPFs are most effective for solid particle number (reductions up to 6 orders of magnitude). NM particles may form in some configurations.
  - SCR+advanced engine tuning leads to one order of magnitude less solid particle numbers with no NM formation appearing (+NOx reduction)
  - A "PM-Catalyst" reduced NM particles more effectively than a DOC but had little effect on solid particle number over transient tests.
- 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

Proposal for a European Centre of Expertise on Road Transport Related PM (ECERT-PM)



Thank you for your attention