Overview of the EU DG TREN Particulates Project on the Characterisation of Exhaust Particulate Emissions from Road Vehicles

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In the framework of *Particulates*, a specific particle measurement protocol was developed, which attempts to address as many needs for a multidimensional characterisation of particulates as possible. A small portion of the exhaust gas enters the primary dilutor and is diluted with dehumidified and filtered air. The primary dilution ratio is adjusted to a nominal ratio of 12:1 and is achieved with rapid turbulent mixing (time constant ~1 ms). A constant dilution air temperature is forced at 32°C. The selection of the dilution conditions was rather based on the need to define repeatable and relatively stable conditions, in particular as regards production of 'secondary" (nano-) particle production. The diluted exhaust gas stream is divided into two branches, called "wet" and "dry" branch by convention. In the wet branch, after primary dilution, the aerosol is allowed to stabilise for a couple of seconds before analysis, necessary to equilibrate the concentration and homogenise the diluted sample.

In the wet branch a CPC is used to record total particle concentration above 10 nm. Over steady state tests an SMPS is used to scan particle concentration in the range 10 nm – 1 μm mobility diameter. The current produced by a unipolar corona-type charger is used to monitor the diffusion-active particle surface area. The rest of the high flow of the wet branch is led to high volume flow impactor, used to give information about mass size distribution. In the dry branch, non-volatile (solid) aerosol properties are separated by means of a Thermodenuder. Solid particle size distribution and number concentration in the range 30 nm – 1 μm aerodynamic diameter are monitored downstream of the thermodenuder with an ELPI. Also, the legislated CVS method is used to collect mass of particles on teflon-coated filters.

A large matrix of vehicle technologies and fuel qualities have been measured with this protocol. The results are compared and evaluated on the basis of total particle mass and VOF/NVOF split, total particle number, total active surface equivalent, size segregated solid particle number, mass weighted size distribution and number weighted size distribution. Some of the above are measured in near real time and then integrated over a cycle, some other are measured directly as average values over a cycle, while one is measured over steady states only. As regards the sizes: basically the measurements focus to sizes below 1 micron and emphasis is put on nano particles, i.e. in the range of 10 to 50 nanos. Mass data are also collected from 1 to 10 microns. In summary it is attempted to provide size distribution (continuous) up to ~ 1 micron and then data for 1 - 2,5 and 2,5 to 10 microns. Conventional emission factor expressions are used, such per km, per kWh, but also per hour, per cubic centimeter exhaust etc.

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7th International ETH Conference on Combustion Generated Particles

Zurich 18-08-2003

Contents of the presentation

1. Outline of the "PARTICULATES" project
2. Measurement Protocols and Common Formats
3. Some Results
4. Preliminary Conclusions

A 5 FP European research programme
sponsored by the Directorate General
on TRansport and ENergy

The "PARTICULATES" project team

Partners:
Aristotle University (GR) – Coord.
Concawe (B)
Volvo (S)
Tampere University (FIN)
EMPA (CH)
AEAT (UK)
IFP (F)
AVL (AUT)
AVL- MTC (S)
Graz University (AUT)
Aachen University (D)
JRC Peten (NL)
VTT (FIN)
Ford Forschungszentrum Aachen (D)

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

Consultants
D. Kittelson
G. Reischl

The "PARTICULATES"

relevant info

- Project started April 2000
- 3,5-year duration (ends October 2003)
- Total cost: 3,6 M€, EU contribution: 2,5 M€ (70%)
- http://vergina.eng.auth.gr/mech/lat/particulates

The "PARTICULATES" targets

- Definition of the *exhaust aerosol properties* which will be examined and evaluation of available measurement *instruments* and *techniques*
- Development and introduction of a *harmonised protocol* for the definition of exhaust aerosol sampling conditions
- Examination of the *particulate emissions* of current light duty vehicles and heavy duty engines
- Investigation of the influence of *engine technology, fuel quality* and *after-treatment* on particulate emissions

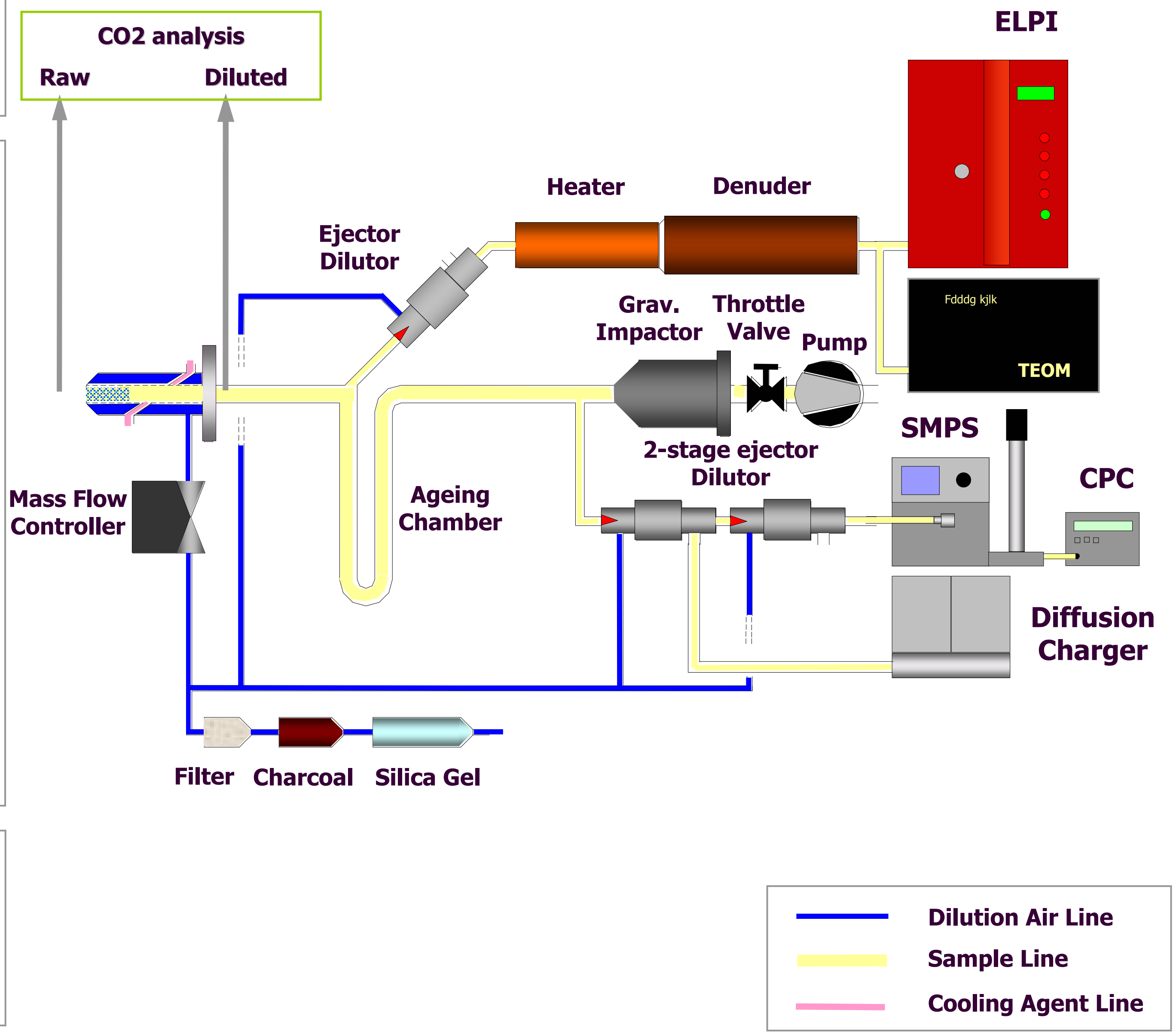
Status and outlook

- A commonly agreed test procedure was developed, addressing sampling and dilution conditions
- A test protocol was developed based on the selected instruments
- The test conditions were evaluated with a round robin exercise
- A car chasing study was conducted to check the relevance of the test protocol
- Testing of a large number of vehicles and fuels is completed
- Collection of all test results is centrally conducted using common formats and methodologies
- Final results are expected October 2003

Main Issues in Particle Analysis

- **Issue 1**: What to measure? … instrument
  - Particle property
  - Size range
  - Resolution (time, size)
  - Applicability / cost
- **Issue 2**: How to measure? … sampling method
  - Dilution factor
  - Residence time
  - Temperature
  - RH
- **Decisions** were taken accounting for:
  - Requirements from health and environment experts
  - Potential for evaluation of technology measures

Sampling system used



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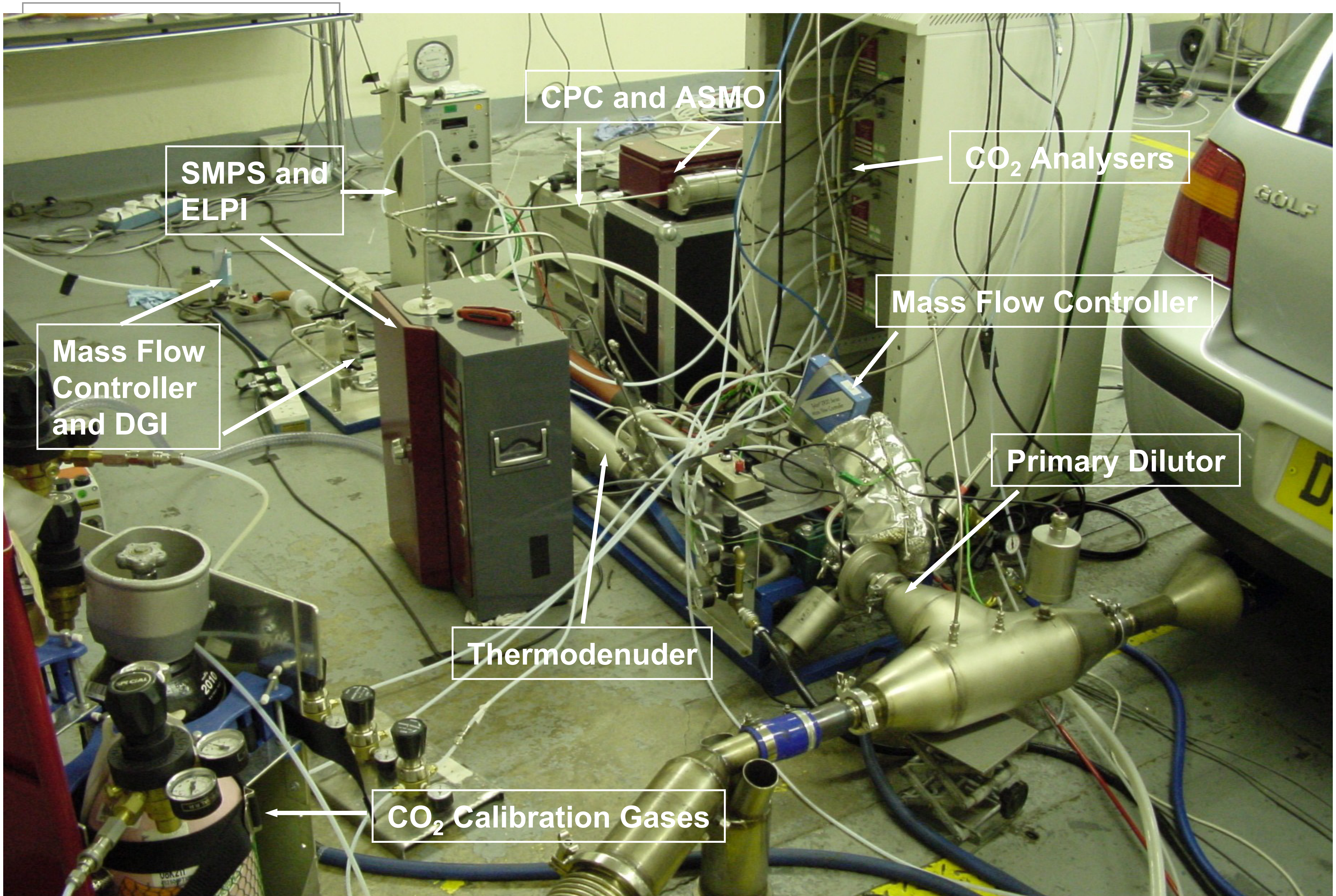
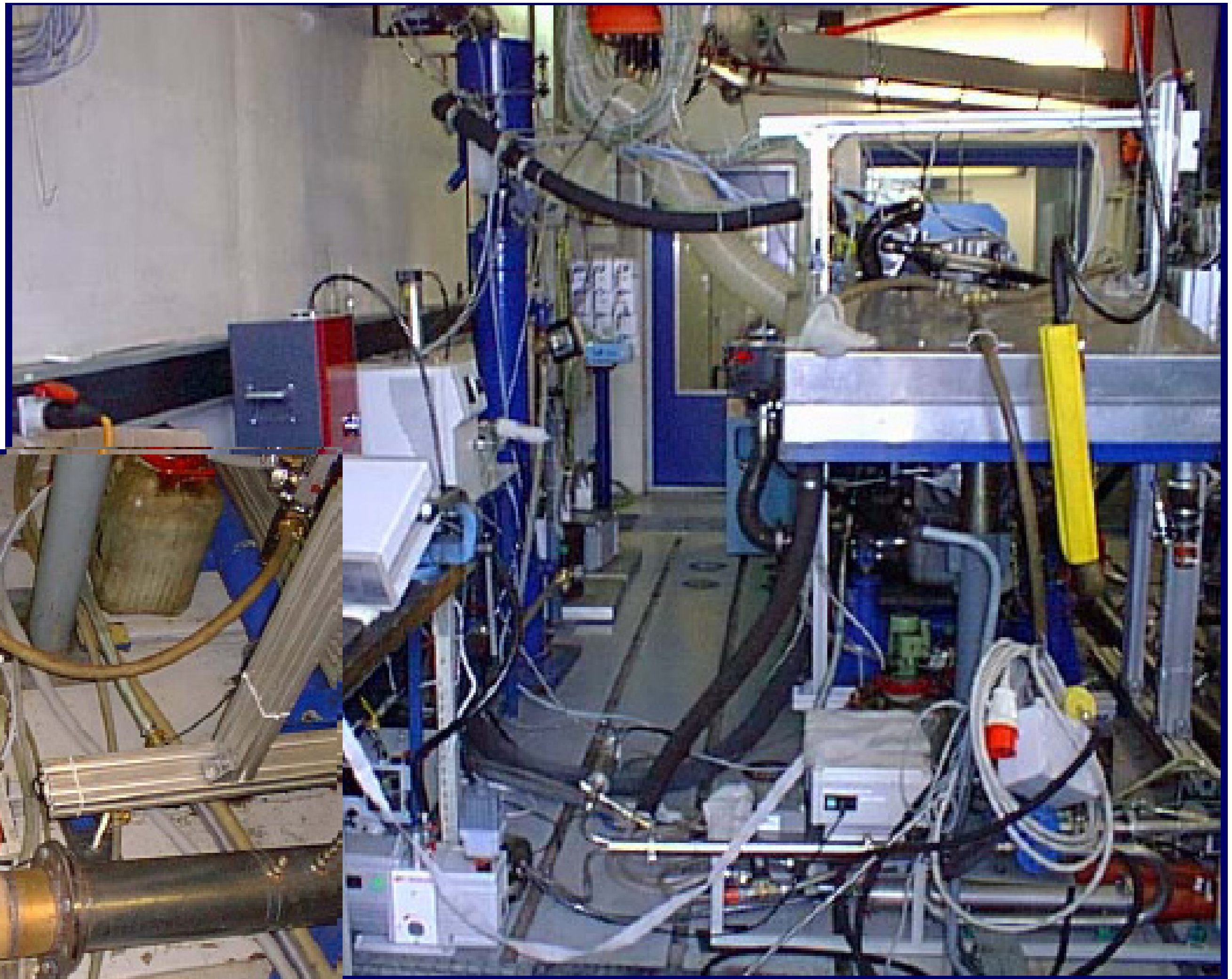
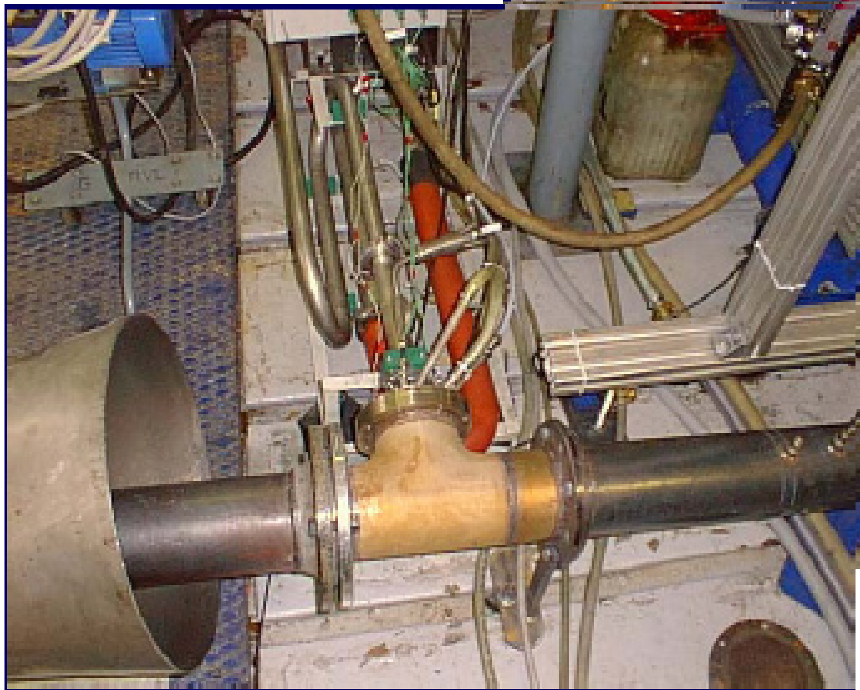


Test set up for LDV - Shell





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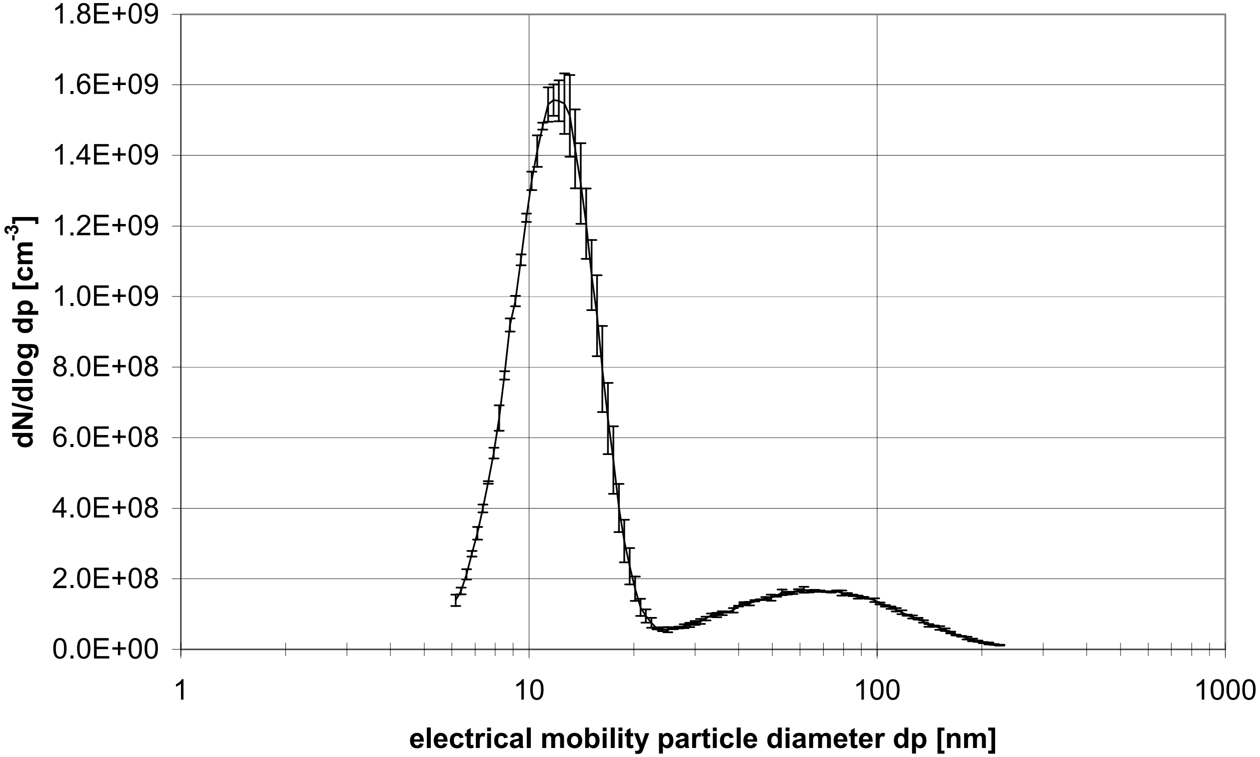
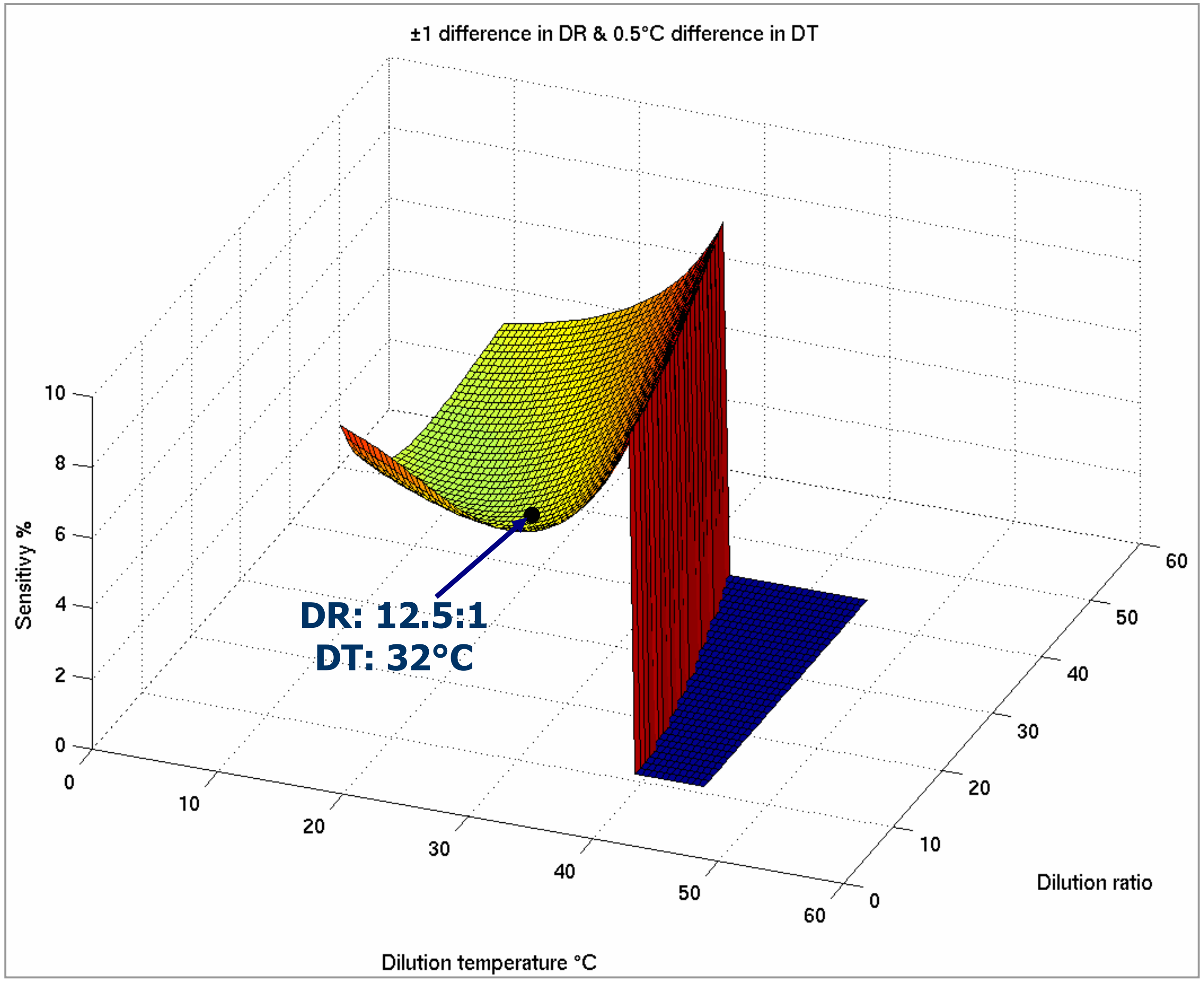
Test set up for HDV - AVL

Typical size distribution of a Euro II car at 50 km/h high load

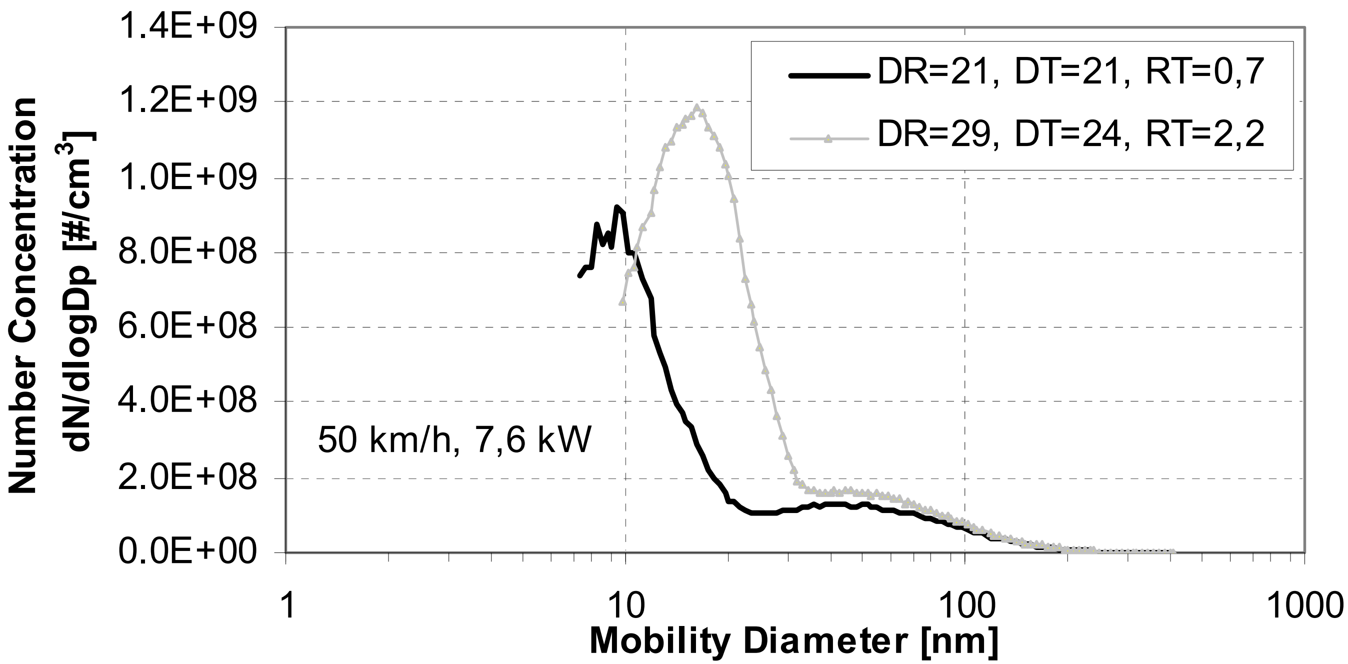


Selection of sampling parameters



- **Similarity to atmospheric dilution**
- **Potential to form nucleation mode**
- **Small sensitivity to change of parameters**
- **Feasibility to reach at the lab**

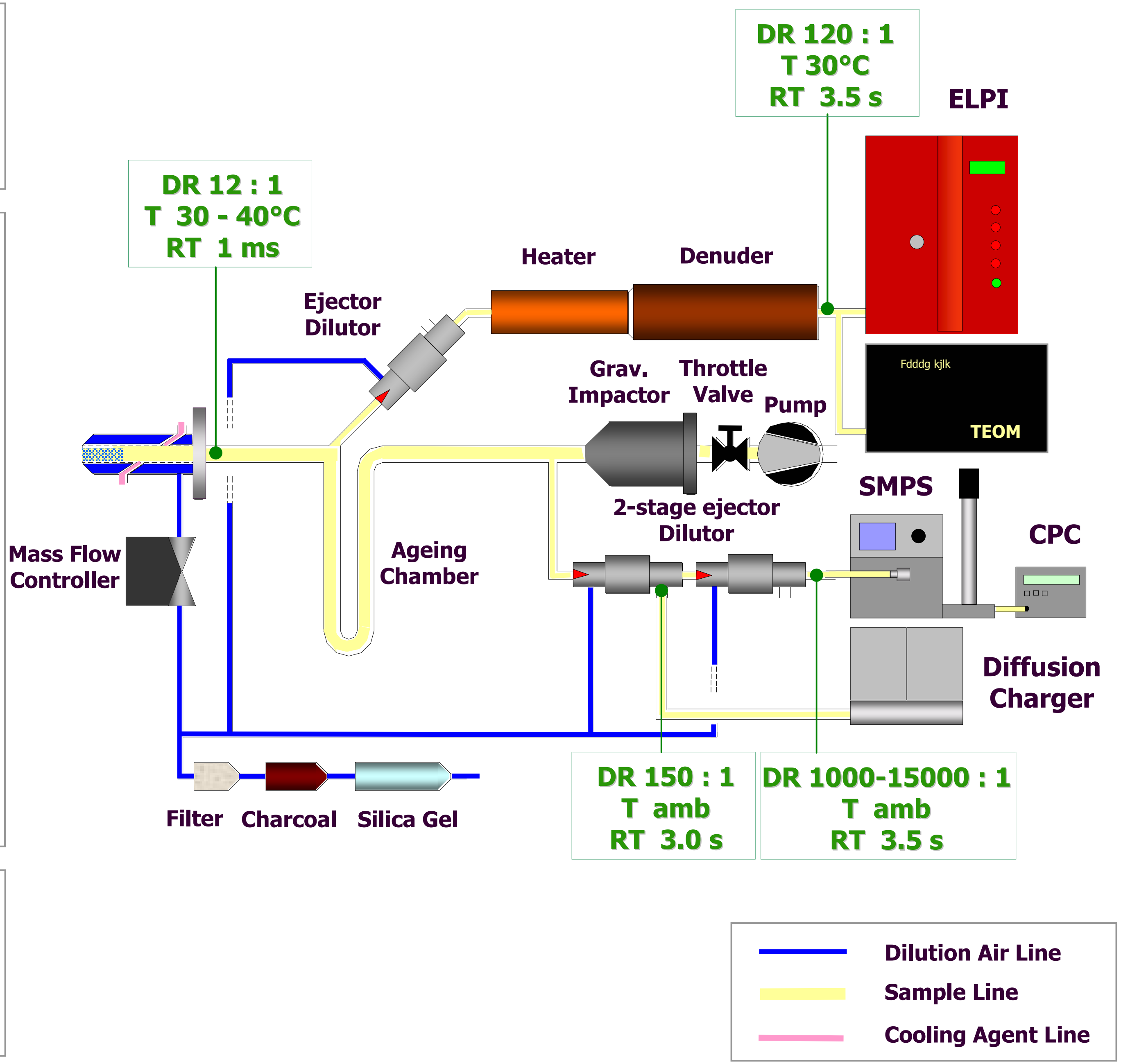
Dilution Parameter: Residence Time



Selection of sampling parameters

Conditions at different instruments

Example: Diesel engine emissions



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Validation of the Particulates Dilution Protocol

On-road chasing of exhaust plume

Conducted by Ford

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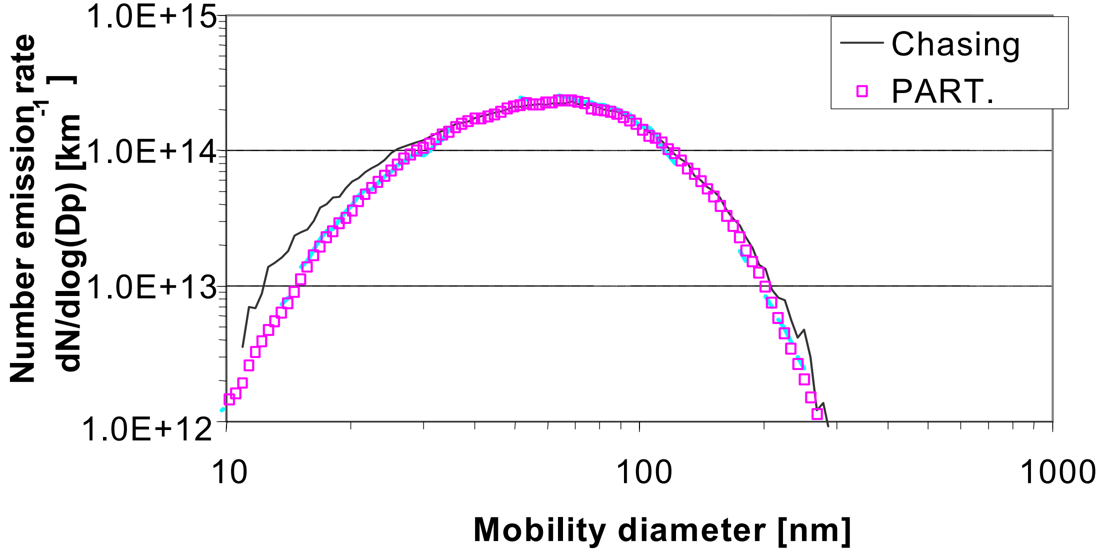
Test vehicle:
1.8 l Diesel
speed, fuel consumption
exhaust temperatures

Ford Mobile Lab:
SMPS, CPC, NOx,
CO, T and RH

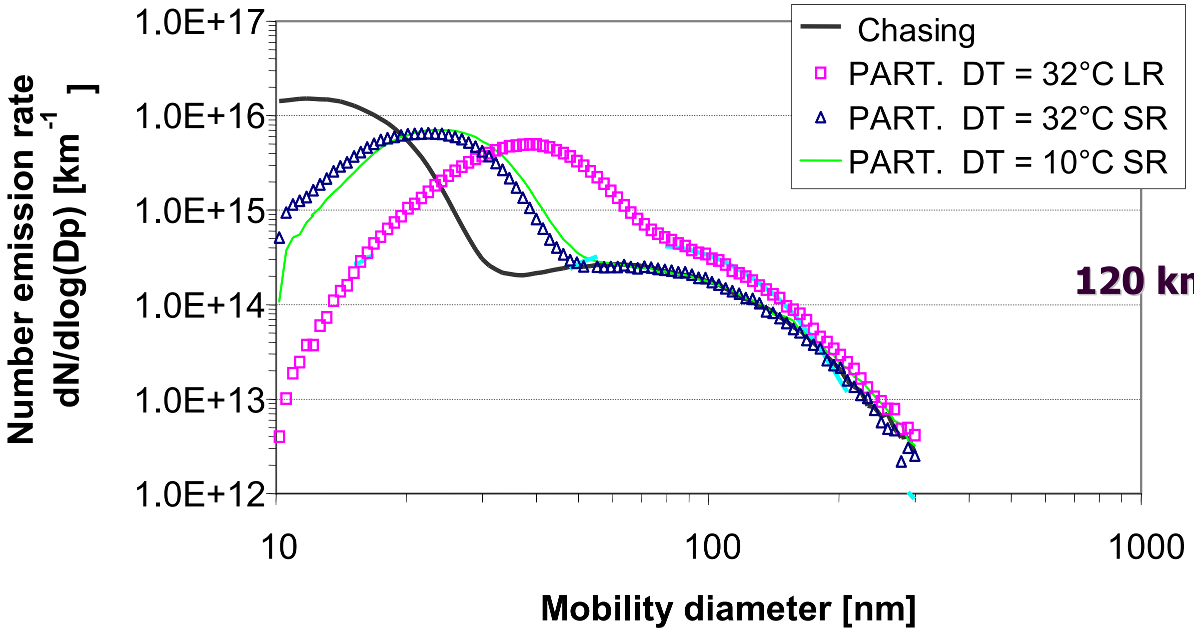
Test track:

high speed oval,
4 km/lap

Particle size distributions during chasing and with PARTICULATES system



50 km/h



120 km/h

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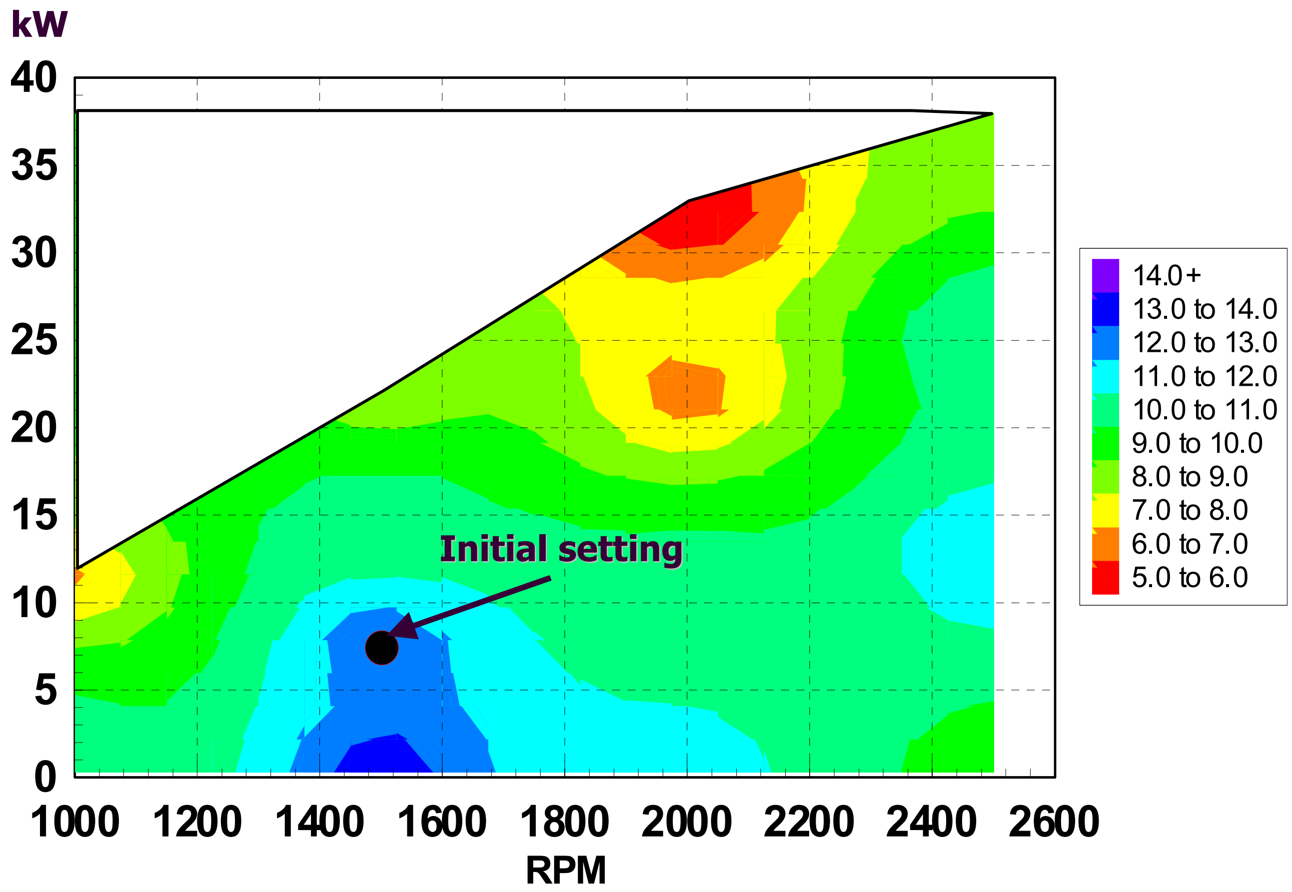
DR fluctuation when sampling close to engine outlet (1.5 m from exhaust manifold)



VW 1.9 TDI engine

DR fluctuation when sampling at the end of a 5 m tailpipe with a ceramic DPF installed instead of the muffler

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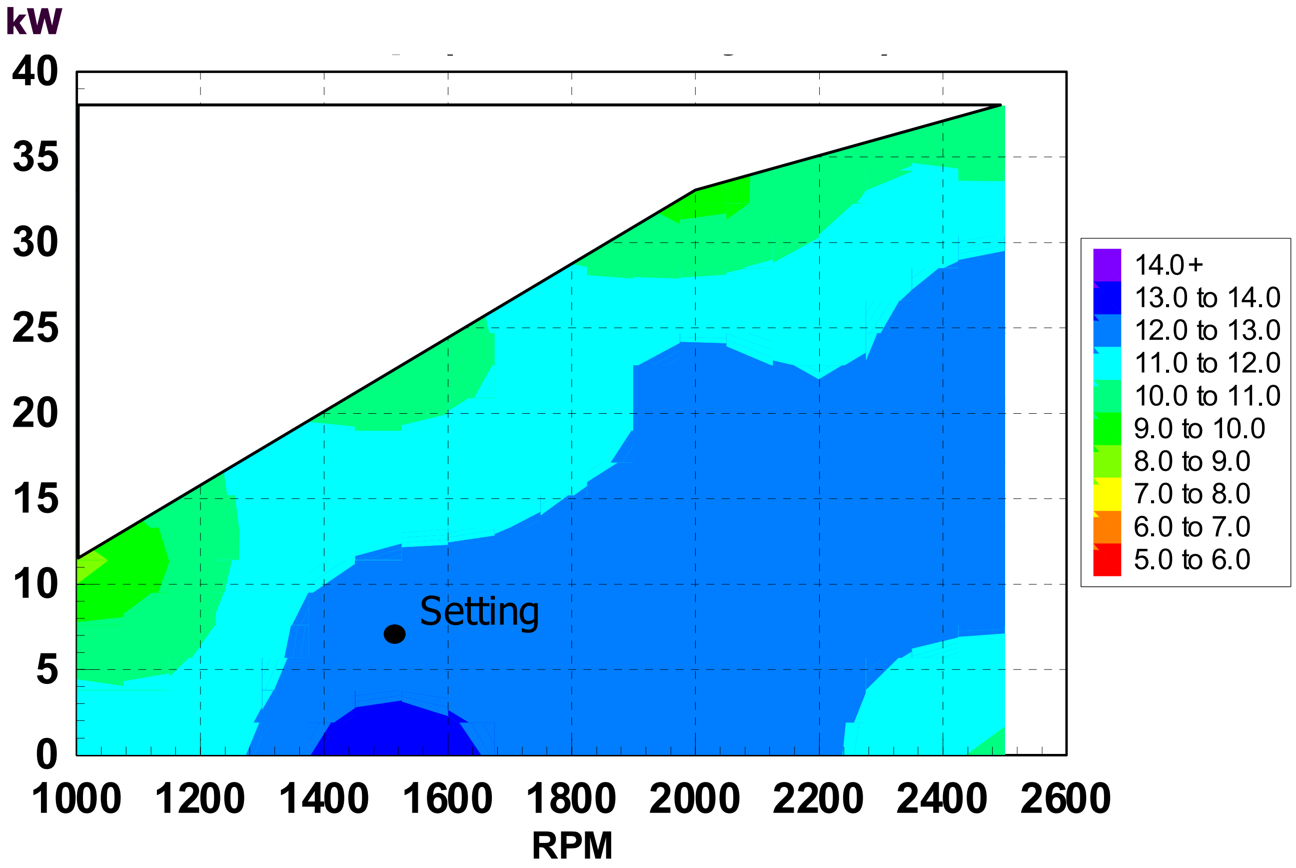
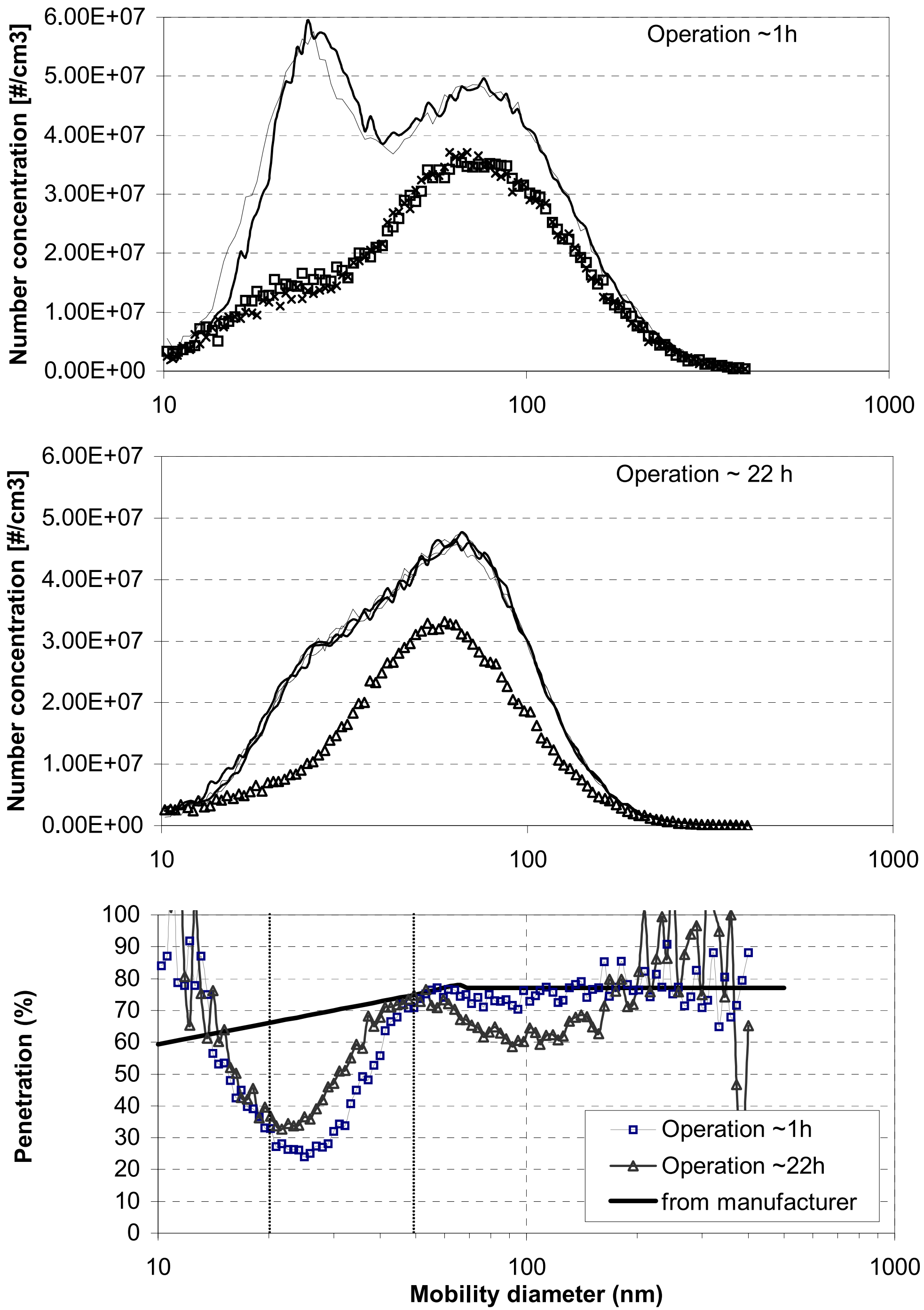


VW 1.9 TDI engine

LAT

Thermodenuder losses



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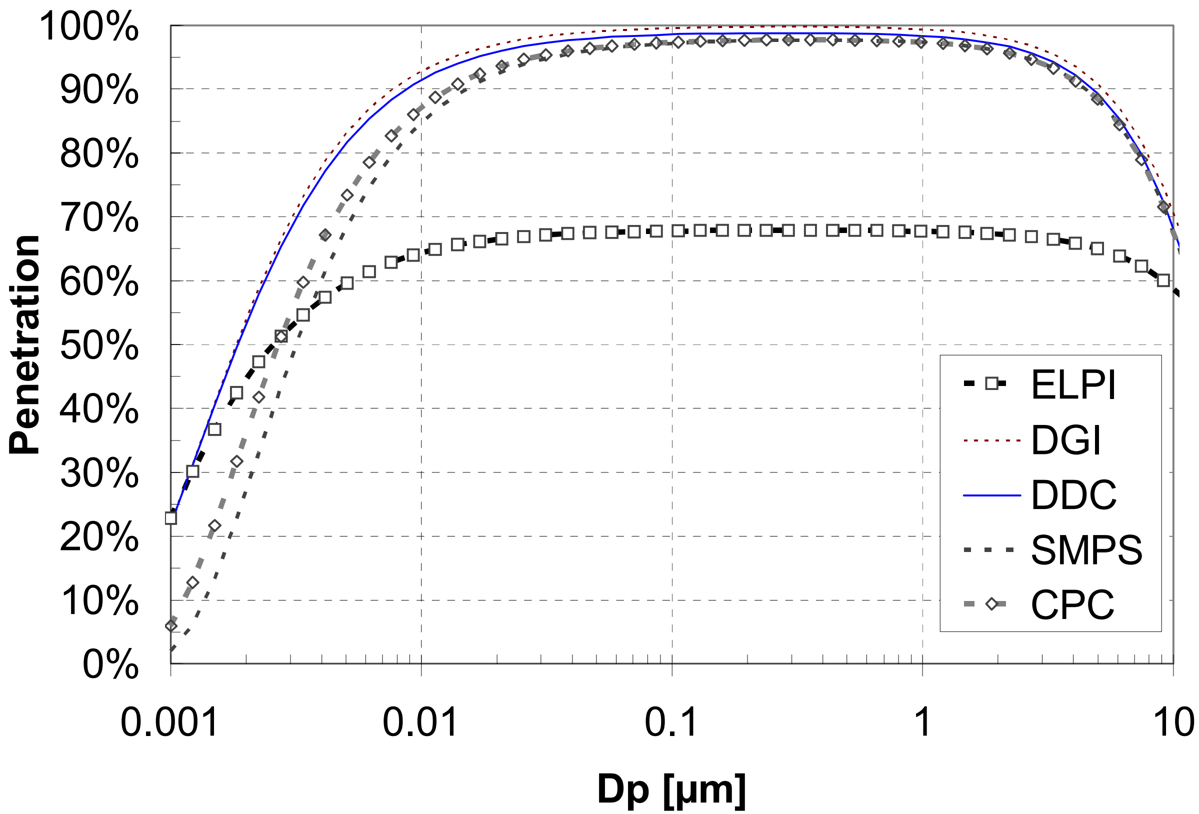
Calculated penetration as a function of particle size for transfer lines to different instruments

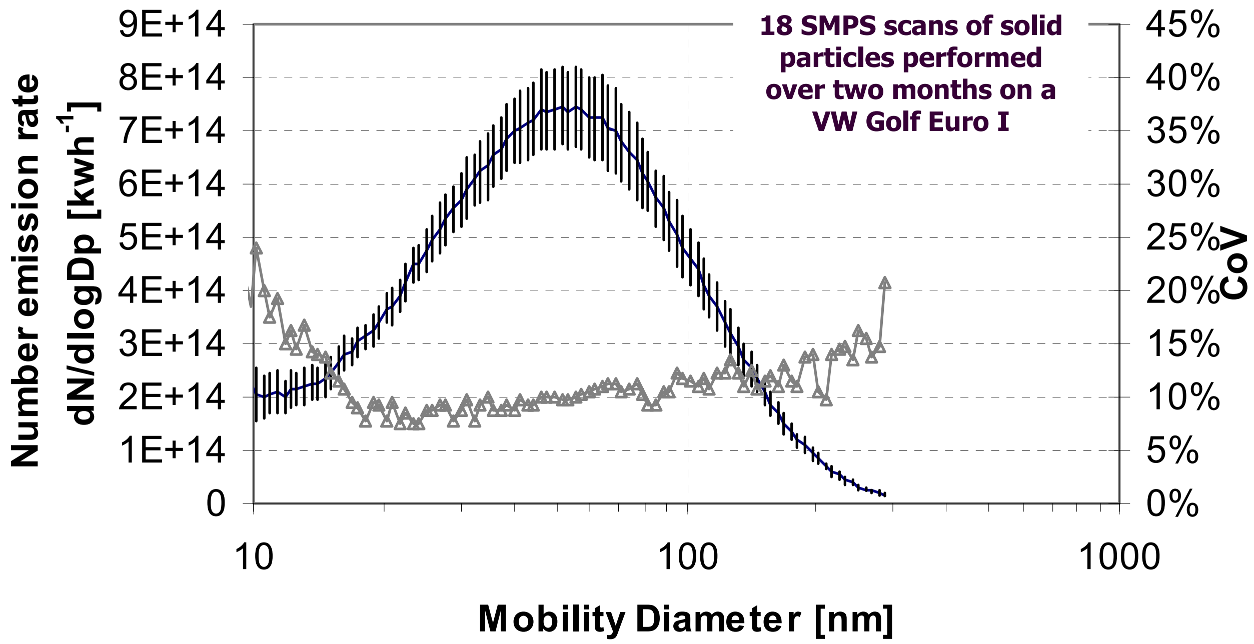


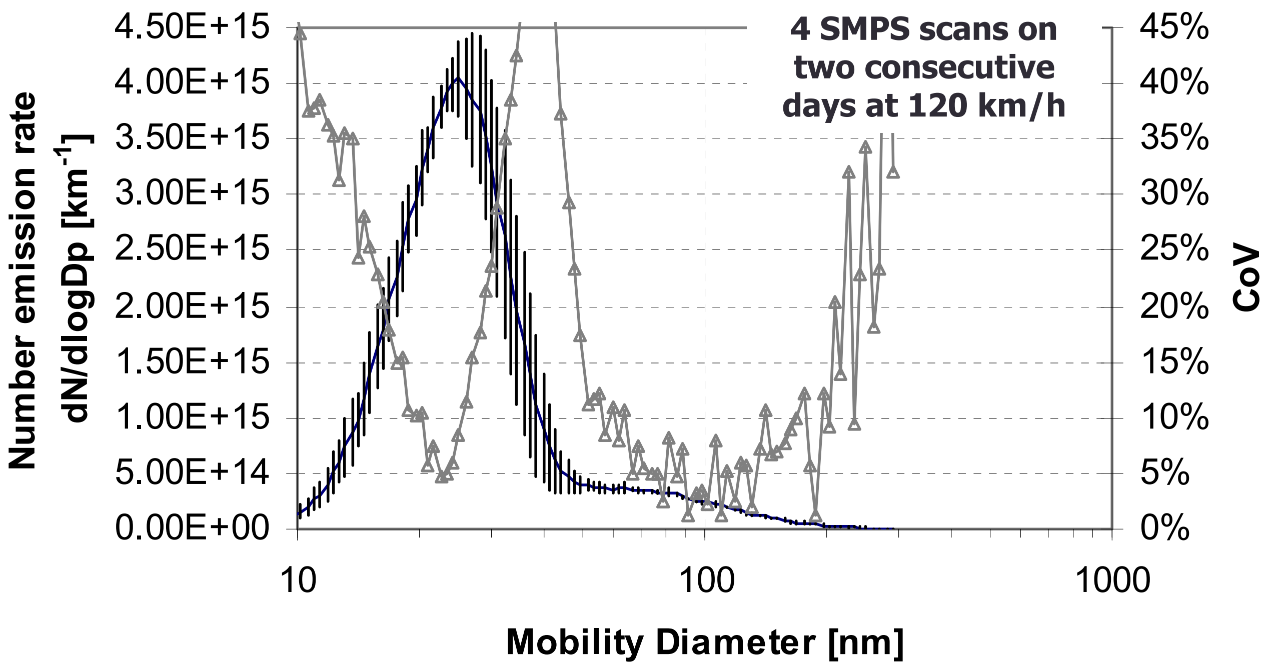
The low penetration for the ELPI is due to TD losses

Repeatability

Upper figure: solid (accumulation mode) particles

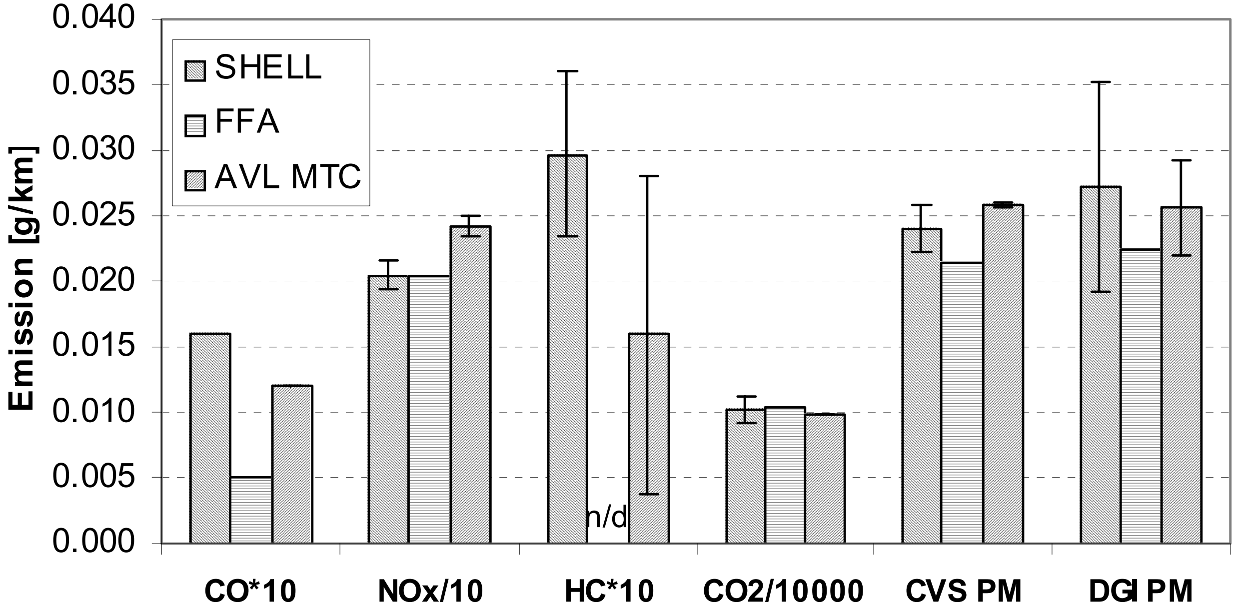
Lower figure: nucleation and accumulation mode

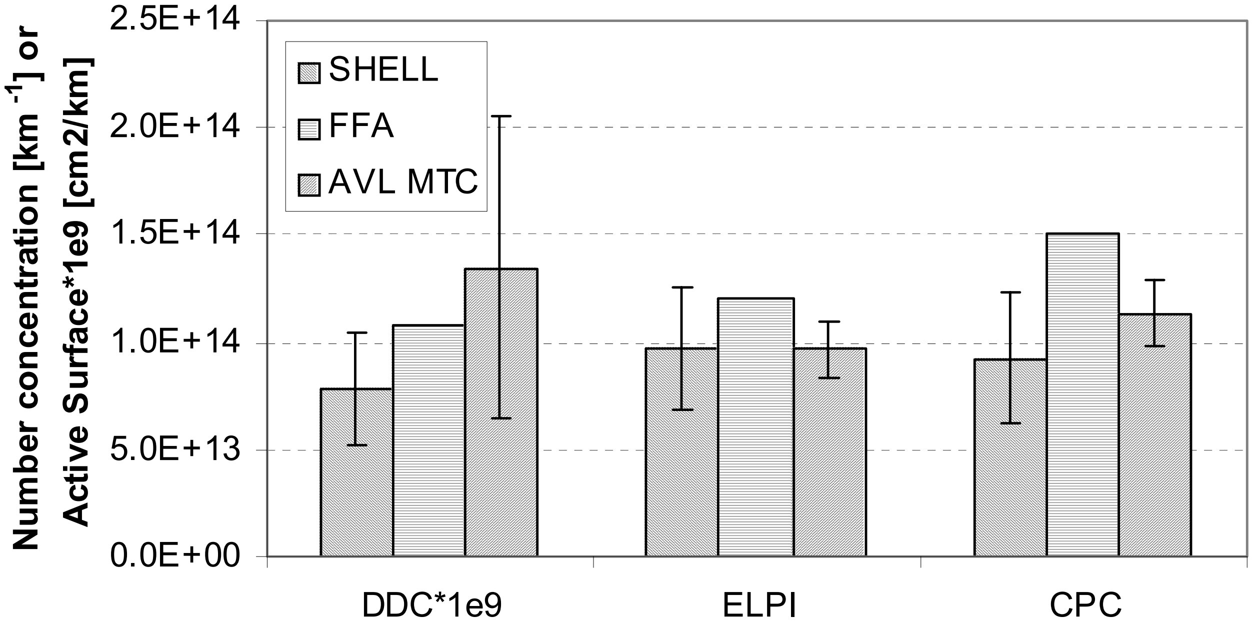




Reproducibility: same or similar vehicle (VW Golf Euro III) at 3 labs

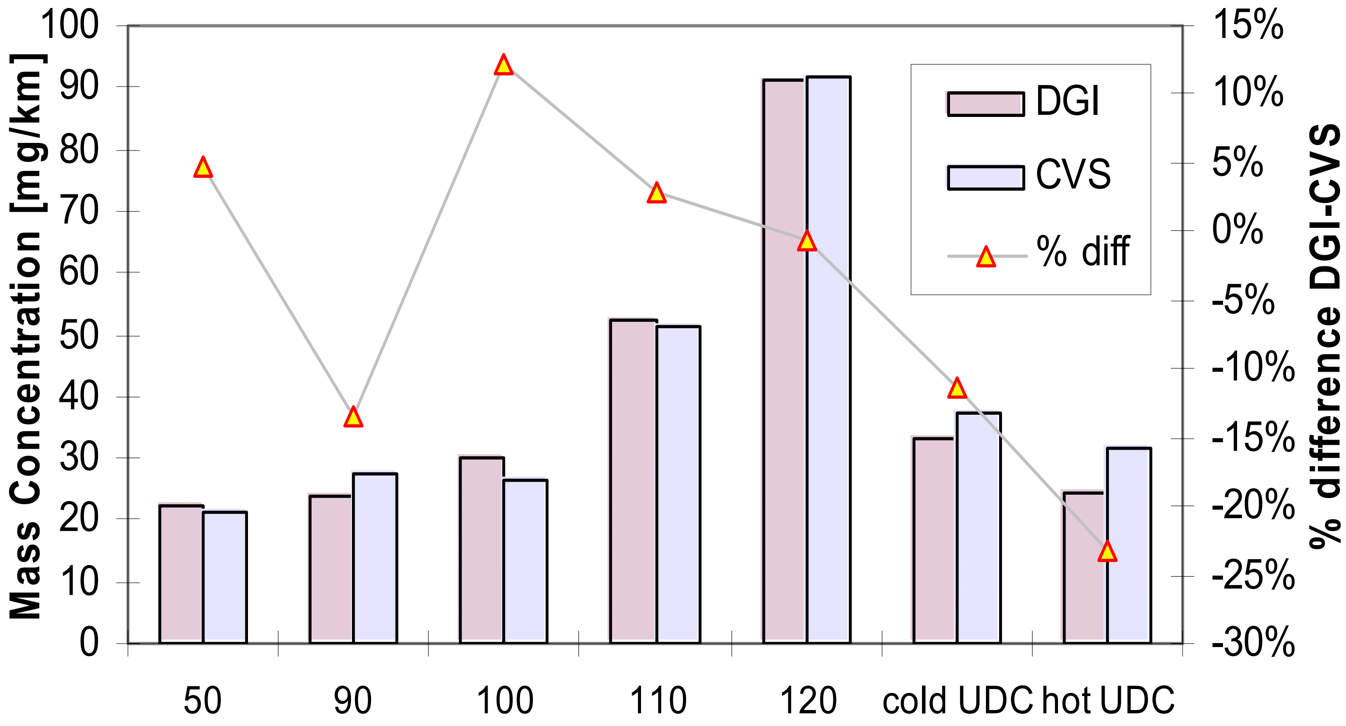
50 km/h steady state





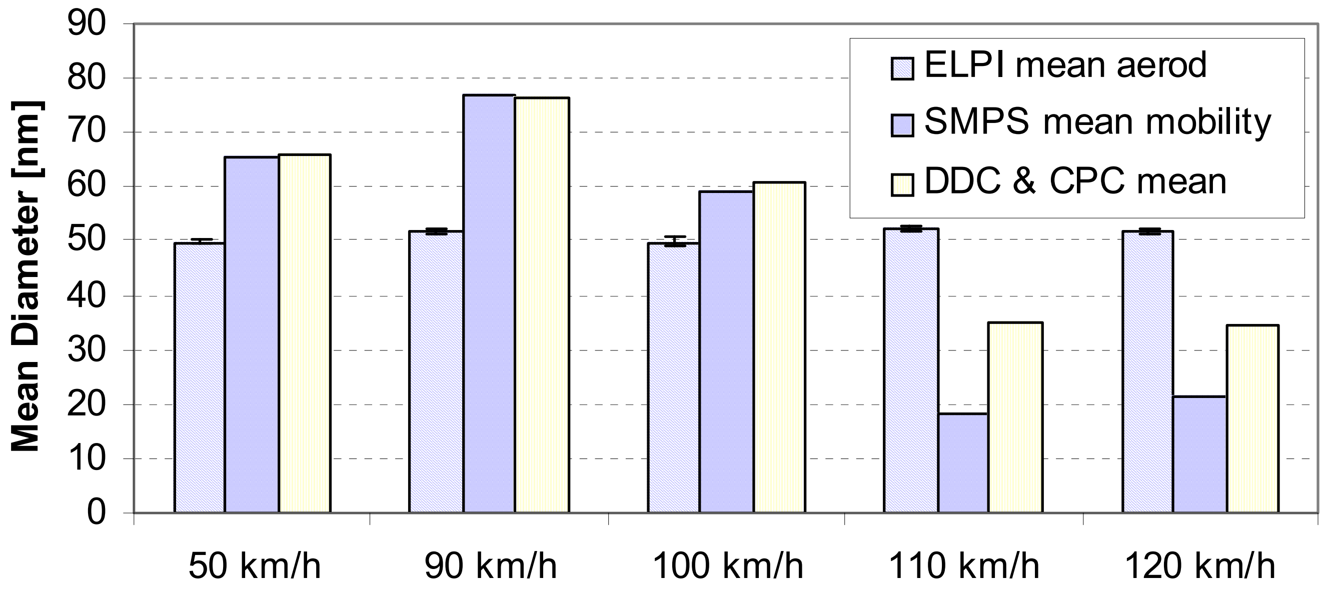
Comparison between CVS and gravimetric impactor

VW Golf TDI Euro III



Comparability between wet and dry branch

VW Golf TDI Euro III



Sampling: Cycles

LDV

- NEDC
- CADC
- Steady Speeds
  (50, 90, 120 km/h)

HDV

- ECE R49
- ESC
- ETC

Some also conduct:

- Aftertreatment tests
- More transient cycles
- More steady state tests

CONCAWE LD Programme

- Daily Test Schedule
  - Cold NEDC (1180 s)
  - Hot NEDC (1180 s)
  - Artemis Urban (993 s)
  - Artemis Road (1082 s)
  - Artemis Motorway 130 km/h (1068 s)
  - 120 km/h Road-Load (600 s)
  - 50 km/h High-Load (600 s)
  - 50 km/h Road-Load (600 s)
  - 50 km/h Road-Load with High Dilution [W1] (600 s)

  - Fuel Change
  - Pre-condition

Monday – Data processing and Pre-condition
Tuesday to Friday – Full Test Days

Diesel Fuel Analyses

Fuel Code		D-1 to D-4	D-5	D6	D7
Fuel Description	Units	**Sulphur Matrix**	**Swedish Class 1**	**EN590: pre-2000**	**5% RME Blend**
Cetane Number		**54.0**	**55.1**		**54.5**
Density	kg/m^3	**845**	**810**	**856**	**846**
T50	°C	**282**	**226**	**279**	**284**
T95	°C	**358**	**282**	**366**	**358**
FBP	°C	**368**	**294**	**373**	**367**
Flash point	°C	**68**	**66**	**71**	
CFPP	°C	**-33**	**-39**	**- 14**	**- 33**
KV @ 40 C	mm^2/s	**3.04**	**1.79**	**3.15**	**3.08**
Poly-aromatics	% m/m	**4.3**	**<0.1**	**7.3**	**5.0**
Mono-aromatics	% m/m	**14.1**	**1.7**	**31.0**	**12.9**
Carbon	% m/m	**86.8**	**85.9**	**87.1**	**86.3**
Hydrogen	% m/m	**13.2**	**14.4**	**12.9**	**13.1**
LHV	MJ/kg	**42.8**	**43.9**	**42.4**	**42.5**
Ash	% m/m	**0**	**<0.01**	**<0.01**	**<0.01**
Water	mg/kg	**36**	**35**	**50**	**40**
Oxidation Stability	g/m^3	**<1**	**10**	**0.2**	**0.3**
HFRR	µm	**375**	**386**	**389**	**237**
FAME		**Nil**	**Nil**	**Nil**	**5% v/v**
Sulphur	**mg/kg**		**3**	**307**	**7**
D-1	**pre-1996**	**1550**			
D-2	**2000**	**280**			
D-3	**50 ppm S**	**38**			
D-4	**10 ppm S**	**8**			

Gasoline Analyses

Fuel Code		G-1	G-2	G-3
Fuel Description	**Units**	**EN 228: Year 2000**	**EN 228: 50 ppm S**	**EN 228: 10 ppm S**
RON		**96.4**	**96.8**	**96.8**
MON		**85.3**	**86.0**	**86.0**
Density	kg/m^3	**753**	**749**	**748**
RVP	kPa	**58.7**	**57.7**	**57.7**
E70	% v/v	**29.4**	**32.5**	**32.5**
E100	% v/v	**50**	**51.2**	**51.2**
E150	% v/v	**85.5**	**86.1**	**86.1**
FBP	°C	**195**	**193**	**193**
Residue	% v/v	**1.0**	**1.1**	**1.1**
Olefins	% v/v	**8.8**	**9.9**	**9.9**
Aromatics	% v/v	**35.4**	**33.4**	**33.4**
Benzene	% v/v	**0.8**	**0.6**	**0.6**
Sulphur	mg/kg	**143**	**45**	**6**
Induction time	minutes		**693**	**>480**
Existent gum	mg/100ml		**<1**	**<1**
Cu Corrosion			**OK**	**OK**
Lead	mg/l	**<1**	**<1**	**<1**
Phosphorus	mg/l	**<1**	**<1**	**<1**
Carbon	% m/m	**86.3**	**86.0**	**86.0**
Hydrogen	% m/m	**13.0**	**13.2**	**13.2**
Oxygen	% m/m	**0.7**	**0.8**	**0.8**

Properties determination in a single run

- Total “active” surface [RT]
- Total particle number [RT]
  - Surface and number give mean size [RT]
- Size segregated solid particle number [RT]
- Solids particle mass [RT]
- Gaseous pollutants [RT]
- Particle mass (VF/nVF) - CVS [CYCLE]
- Mass weighted size distribution [CYCLE]
- Number weighted size distribution[SS]

- RT: Real Time
- CYCLE: Mean value over cycle
- SS: Steady State

Laboratory

- AV
- LA
- MT
- SH
- TU
- VO
- VT
- EM

Vehicle

- AVL SCANIA
- AVL PROTOTYPE + CRT
- AVL PROTOTYPE + SCR
- LAT RENAULT LAGUNA
- LAT TOYOTA COROLLA
- LAT BMW 318
- LAT VW GOLF
- MTC PEUGEOT 607
- MTC HONDA ACCORD
- MTC MITSUBISHI CHARISMA
- MTC PEUGEOT 406
- MTC VW GOLF TDI

Engine Principle

- DIESEL
- GASOLINE

AfterTreatment

- NO
- CRT
- SCR
- TWC
- OXICAT
- CAT DPF
- DPF
- NOX STORAGE
- OXICAT + DPF

Fuel

- D6 (300 PPM S)
- G3
- G1
- ETD5
- OILD5
- D6
- D7
- G2
- BIODIESEL
- D1
- RME30
- UG (33 PPM S)

Test Temperature

- AMBIENT
- -7 C
- -15 C
- -20 C

Vehicle Type

- HDE
- LDV
- HDV

Cycle

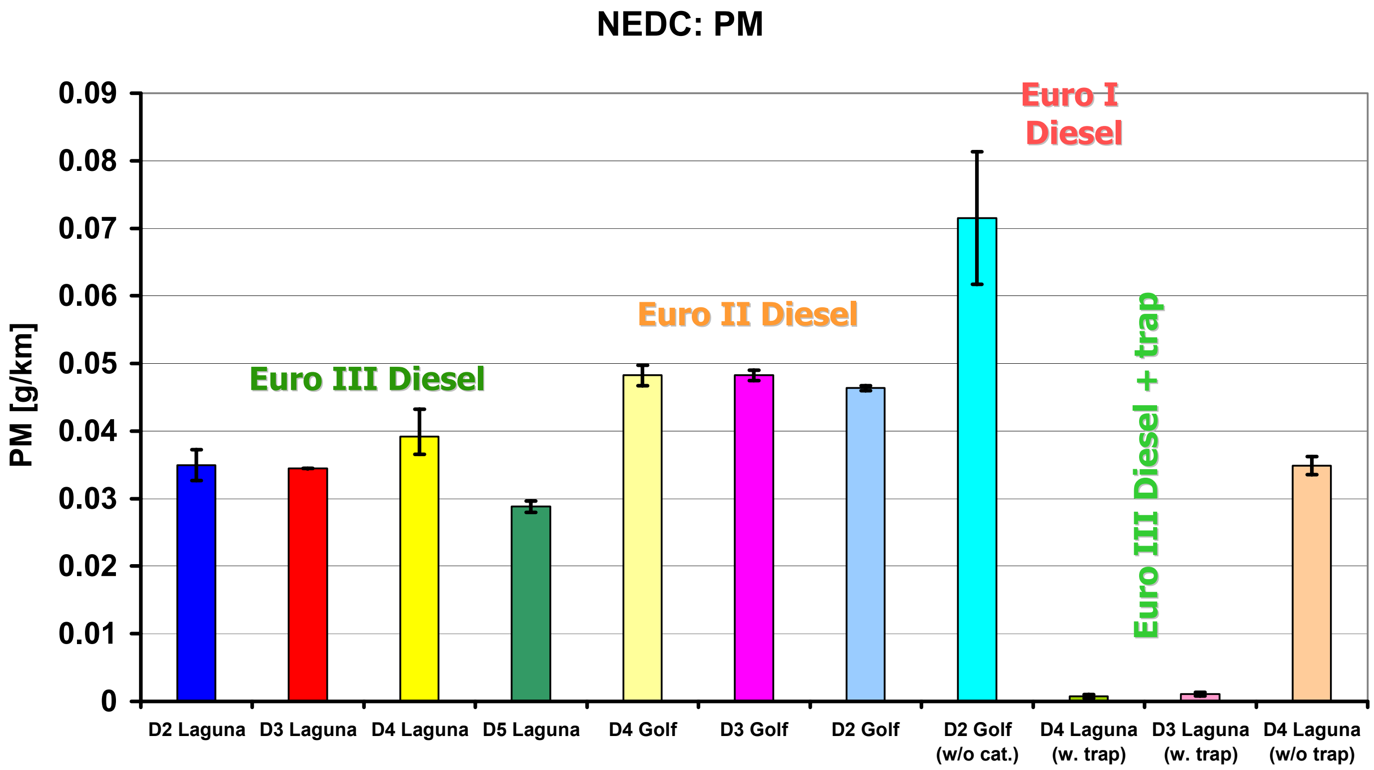
- ESC MODE 1
- ESC MODE 2
- ESC MODE 3
- ESC MODE 4
- ESC MODE 5
- ESC MODE 6
- ESC MODE 7
- ESC MODE 8
- ESC MODE 9
- ESC MODE 10
- ESC MODE 11
- ESC MODE 12
- ESC MODE 13
- OVERALL ESC
- ETC URBAN STREETS
- ETC RURAL ROADS
- ETC MOTORWAYS
- ETC OVERALL
- ST1 (R49-2)
- ST2 (ESC 5)

Emission Standard

- EURO III
- EURO III+CRT
- EURO III+SCR
- EURO I
- EURO III+DPF
- ULEV
- EURO II
- EURO II+CRT

Regulated PM emissions

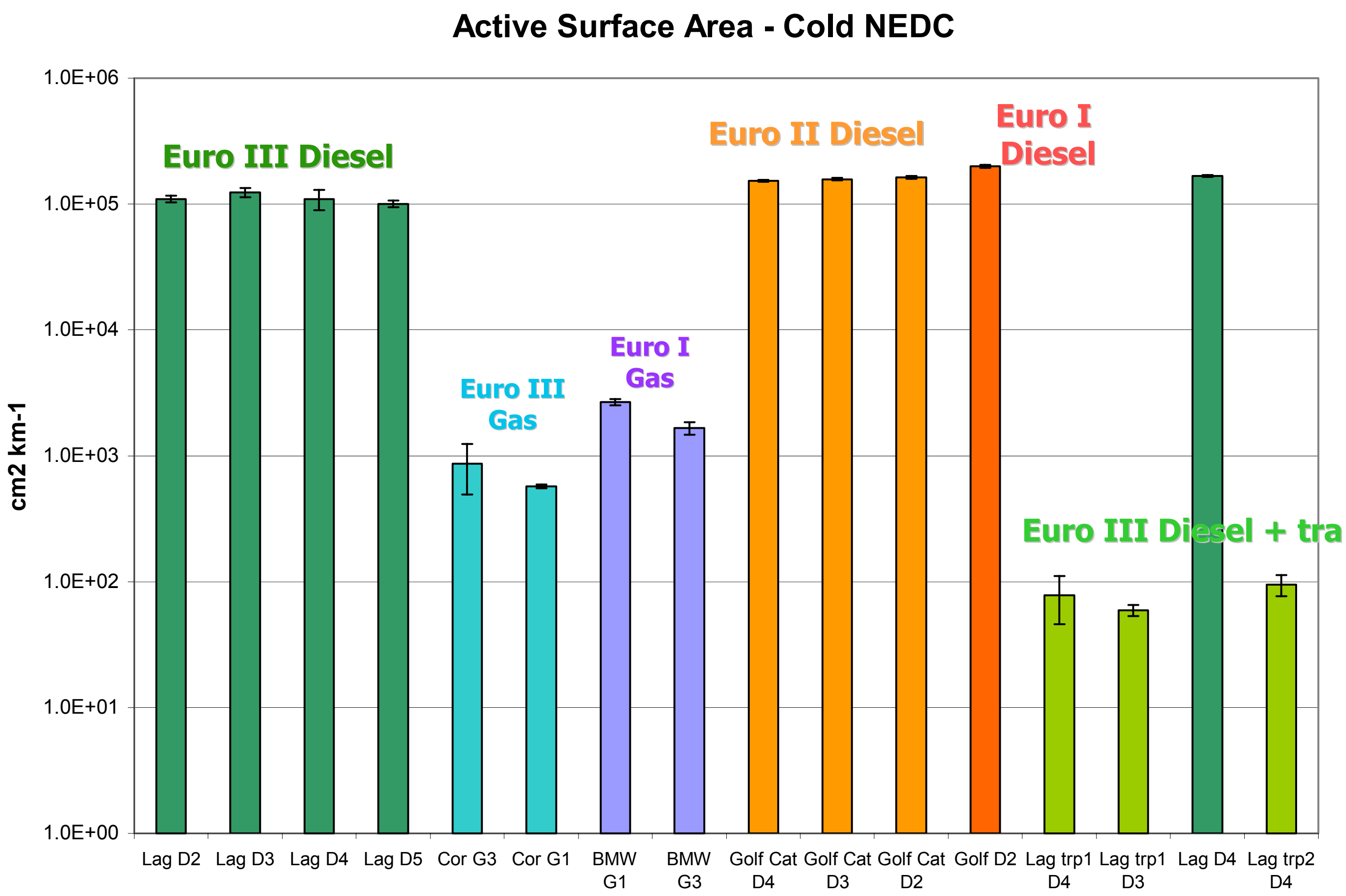
(LAT data)



Note: Confidence intervals correspont to max, min of all repetitions

Active surface area

(LAT data)



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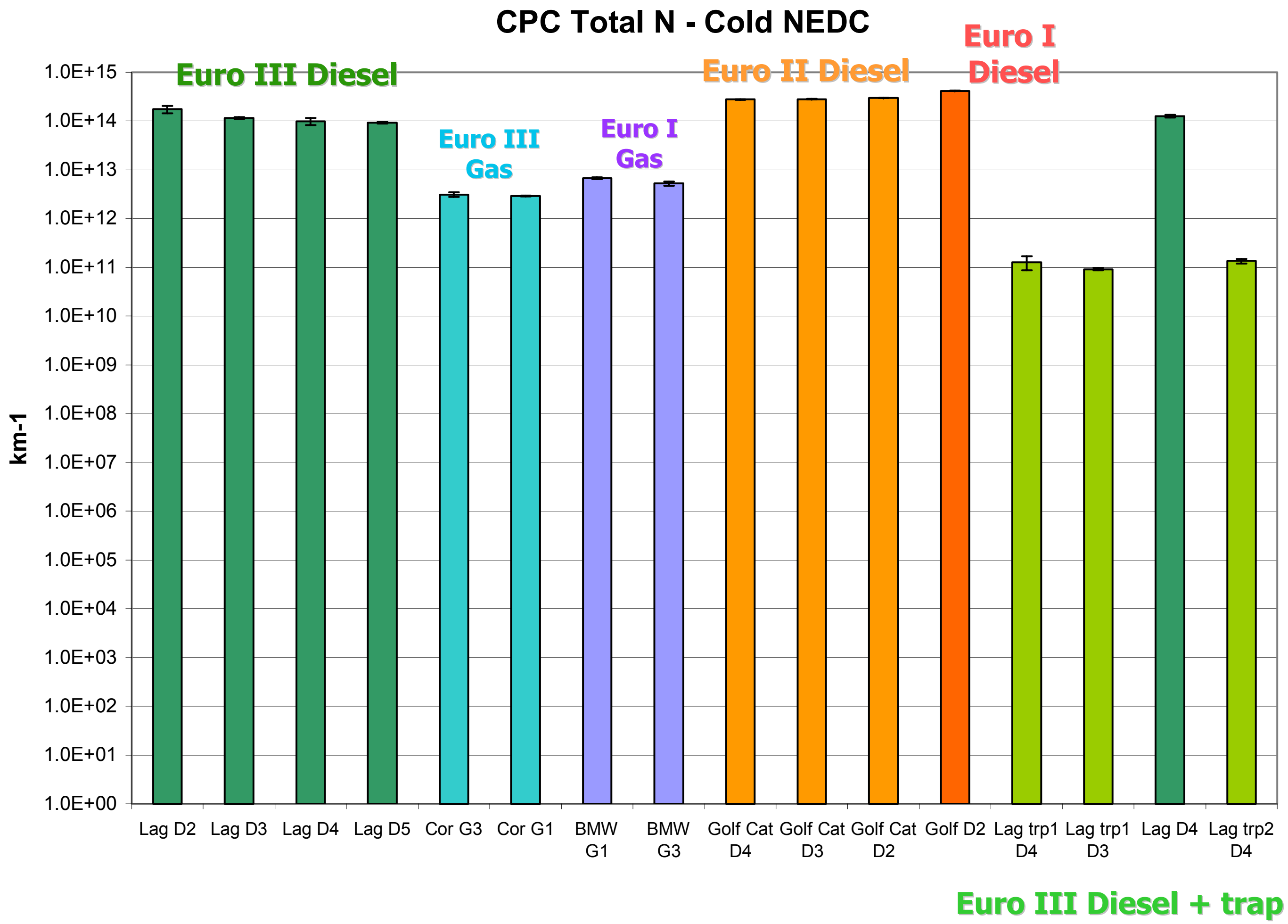
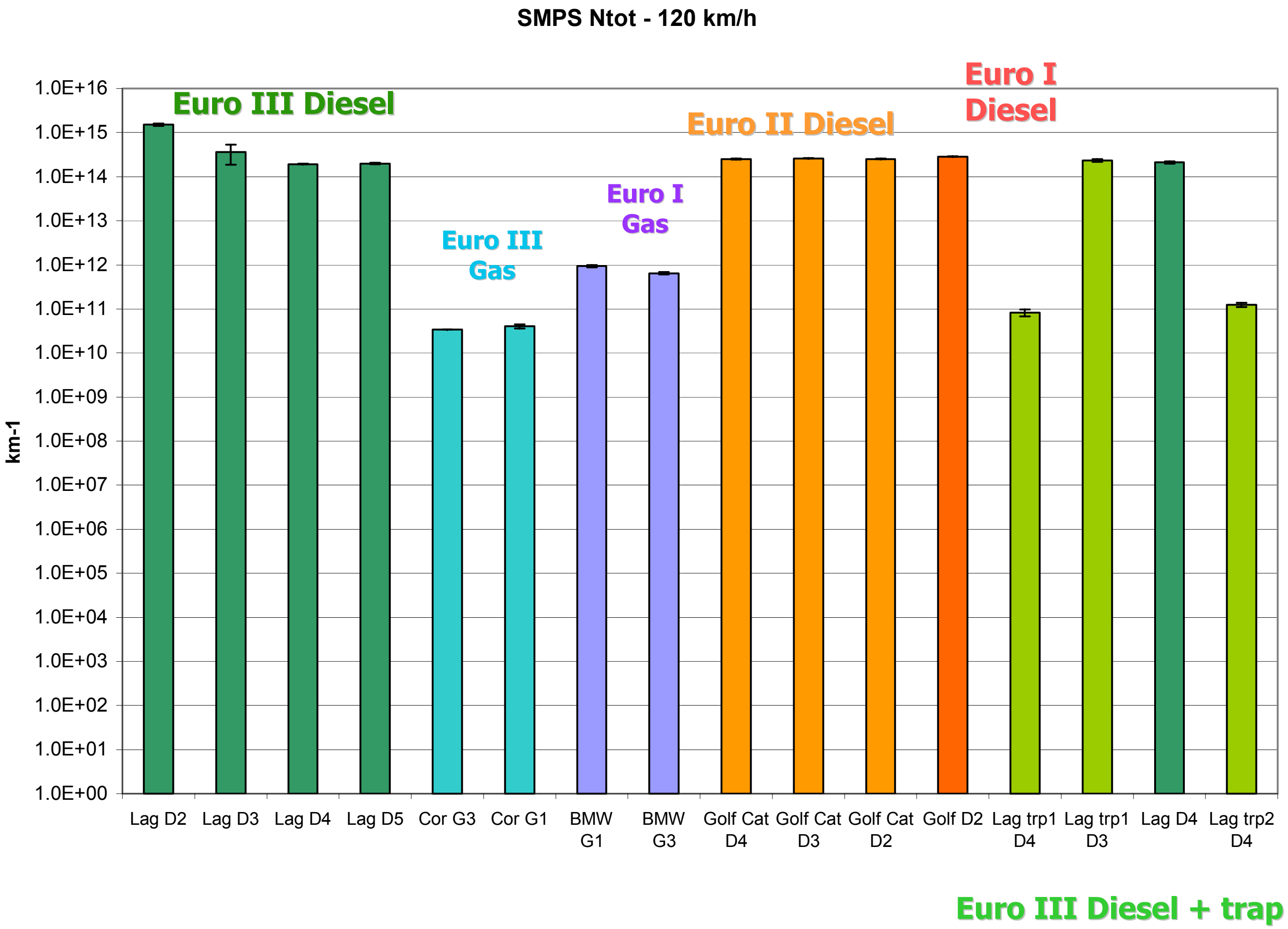
Total number of particles (wet branch)

(LAT data)



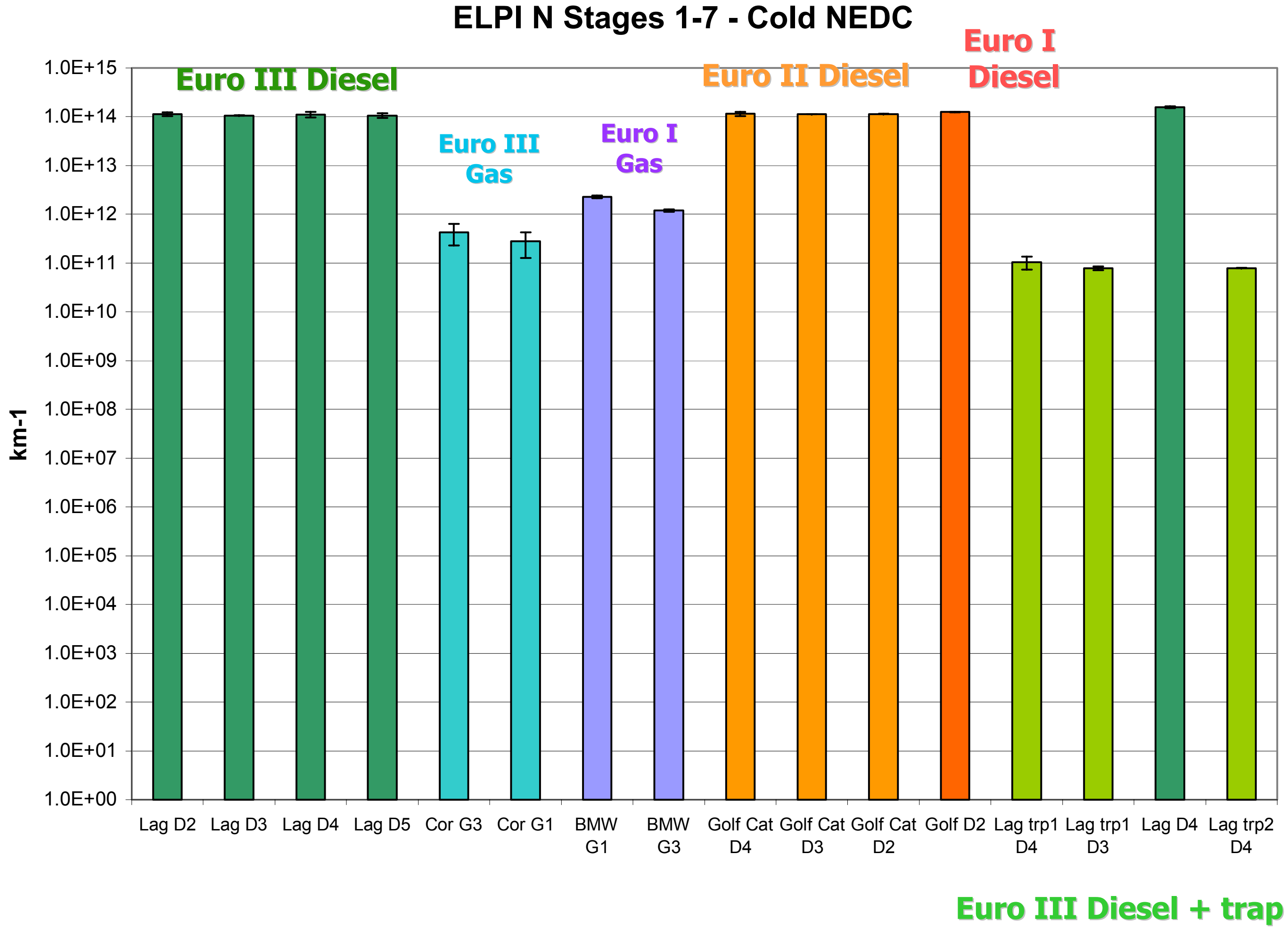
Total number of particles (wet branch)

(LAT data)



Number of solid particles (dry branch)

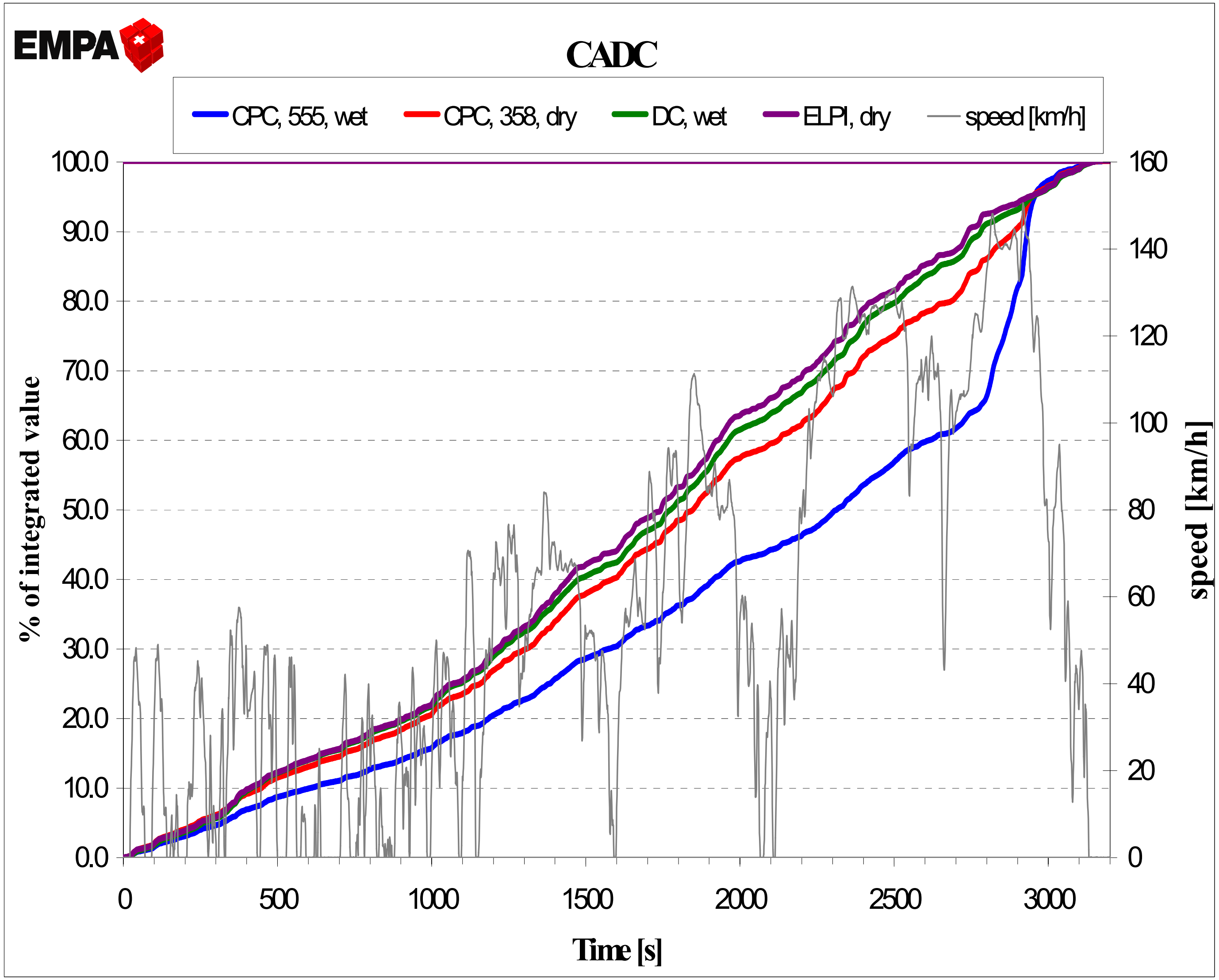
(LAT data)



Cumulative emissions

CADC
-20 ºC

(EMPA data)

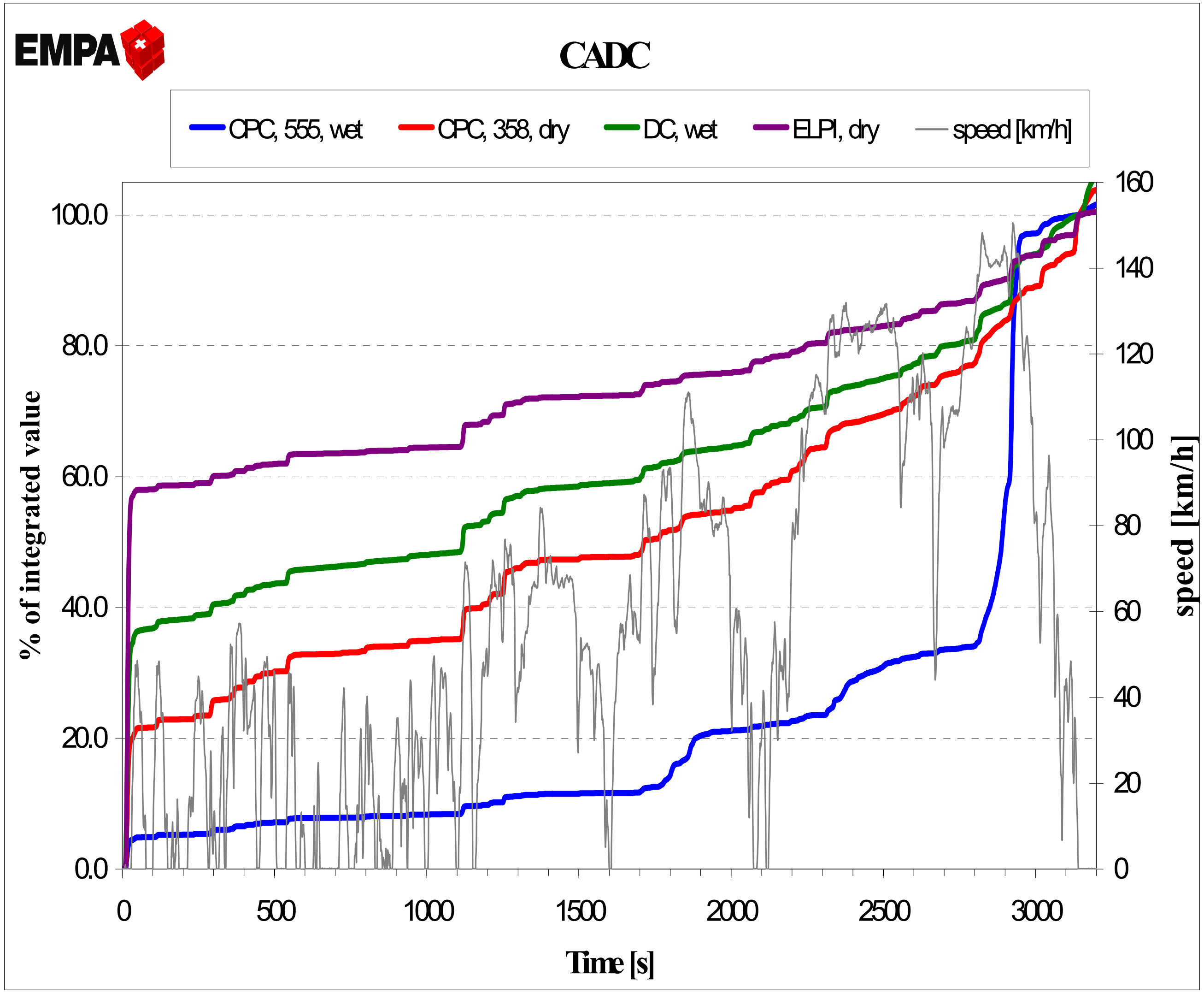


Ford Galaxy, 1.9 TD Diesel

Cumulative emissions

CADC
-20 ºC

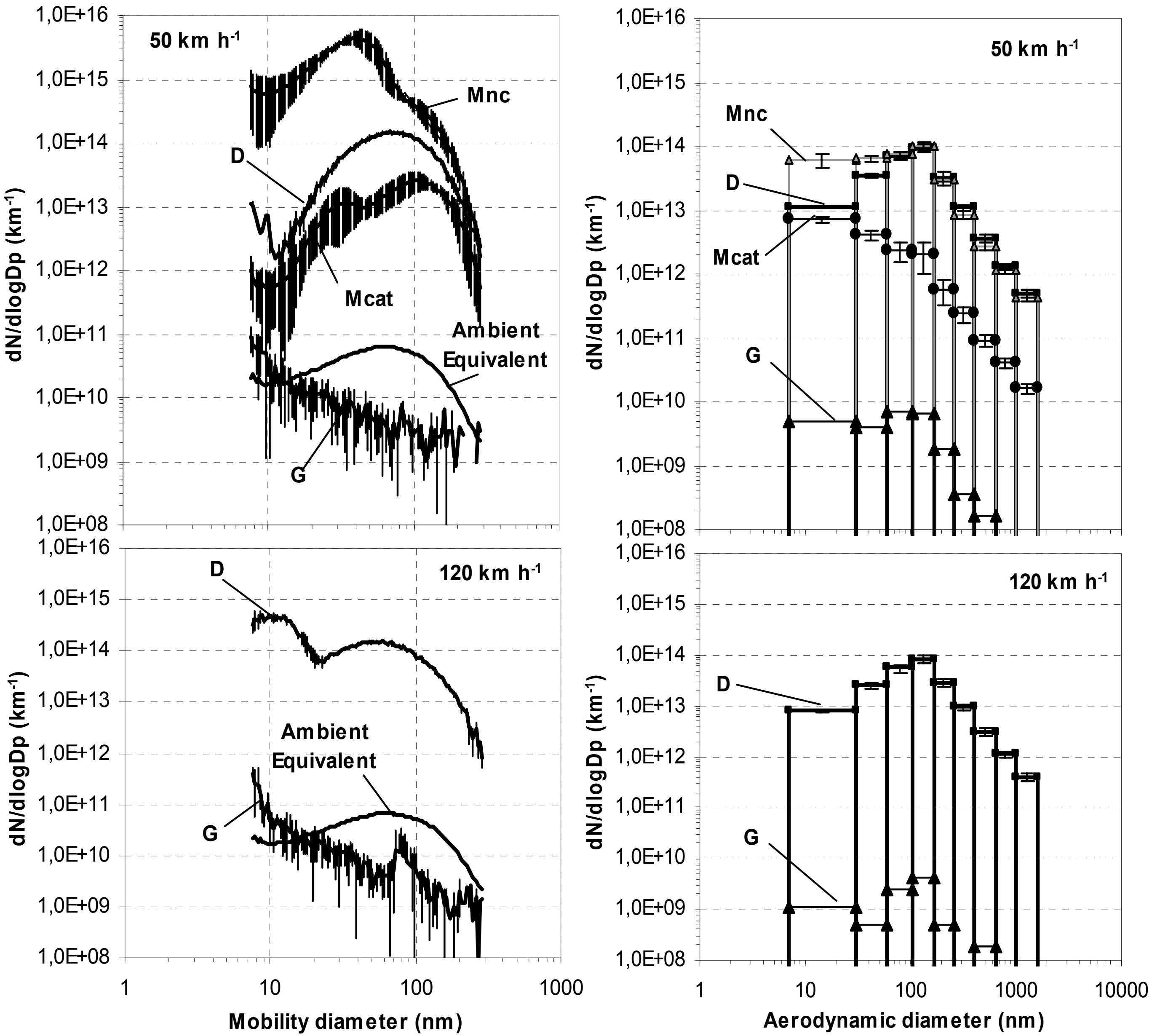
(EMPA data)



Renault Mégane, 1.6 16V Gasoline

Gasoline / Diesel vehicle emissions comparison

Mnc: Non-cat moped
Mcat: Cat Motorcycle
D: Diesel Euro III
G: Gasoline Euro III



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Summary & Conclusions

- Sampling parameters are critical if nucleation mode particles are to be taken into account
- Soot particles are easier to characterise
- Necessity to sample and analyze total aerosol but difficult to regulate in certification tests
- Candidate metrics:
  - mass: will remain legislation metric
  - "active" surface : more sensitive than mass, emphasis to small particles
  - total number concentration : nuclei particles are in general unstable

Summary & Conclusions

- Diesel engines and vehicles equipped with a particulate trap produced extremely low particulate mass, low numbers of carbonaceous particles and low total numbers of particles when operating on low sulphur fuels.
- The fuel sulphur effect was greatest under high speed/temperature operation. Under these conditions, higher sulphur fuels resulted in both higher particle mass and number emissions
- Direct injection gasoline vehicles produced measurable amounts of particulate mass emissions over the NEDC cycle, far below conventional diesel vehicles, but higher than trap-equipped diesels