Research-report No. 202779

Laboratory for I.C. Engines and Furnaces
May 2003

Comparison Study of Particle Measurement Systems for Future Type Approval Application

Swiss contribution to GRPE Particle Measurement Programme
(GRPE-PMP CH5)

Authors:
Martin Mohr & Urs Lehmann

Contractors:

Swiss Federal Roads Authority, FEDRO, Berne
Bundesamt für Strassen, ASTRA, Bern
Contract-No: 259/6.2.208/02 806.3189.002

Federal Office of Environment, Forests and Landscape, FOEFL, Berne
Bundesamt für Umwelt, Wald und Landschaft, BUWAL, Bern
Contract-No: 2002.I.07a 810.3189.004

Executive Summary

This report describes the work of an experimental study on the comparison of particle measurement instruments. The work was performed as a Swiss contribution in the framework of the Particle Measurement Programme (PMP). The measurements were carried out by EMPA and representatives of instrument manufacturers at the EMPA laboratories during a three-week period in June 2002.
The investigation was aimed at the generation of a uniform data set of comparable characteristic values for a wide range of particle measurement systems that allows the assessment with regard to their suitability for future type approval testing.
A total of 21 particle measurement systems were investigated by simultaneous measurements on a heavy-duty engine test bench and tests with an aerosol generator. The group of instruments included the following metrics: number, length, surface area, volume and mass.

The individual instruments applied one or a combination of the following methods:

Detection

- electrical mobility
- filter weighting
- laser-induced incandescence
- oscillating inertial microbalance
- photoacoustic absorption
- impaction
- coulometry
- condensation optical counting
- diffusion battery
- light scattering
- light extinction
- diffusion charging
- photoelectrical charging
- gas analysis

Dilution

- full-flow constant volume sampling (CVS)
- secondary dilution tunnel
- mini-dilution tunnel (partial-flow CVS)
- ejector pump dilution system
- rotating disc dilution system
- several instrument-internal dilution systems

The measurements were focused on providing information on the repeatability, sensitivity, linearity, time response, limit of detection and robustness of the particle measurement systems.
The outcome of the study revealed that several measurement techniques are equal or better in performance with regard to repeatability, sensitivity and limit of detection than the regulated filter method, and further investigation of these techniques can be recommended for Phase III of GRPE-PMP.

CONTENT

1 Definitions, Acronyms, Abbreviations

ACEA	Association of European Automobile Manufacturers
ASTRA	Swiss Federal Roads Authority (Bundesamt für Strassen)
BG	Background measurement
BUWAL	Swiss Agency for the Environment, Forests and Landscape (SAEFL)
CO	Carbon monoxide, gaseous pollutant
COV	Coefficient of variation, COV = 1 standard deviation / mean
CPC	Condensation Particle Counter
CVS	Constant Volume Sampler
DF	Dilution factor
d_p	Particle diameter
EC	Elemental carbon
ECE	Economic Commission for Europe
EMPA	Swiss Federal Laboratories for Materials Testing and Research (Eidgenössische Materialprüfungs- und Forschungsanstalt)
ESC	European steady-state test cycle
ETC	European transient test cycle
GRPE	Working Party on Pollution and Energy
LOD	Limit of Detection
METAS	Federal Office for Metrology and Accreditation Switzerland (METAS)
MMD(p)	Mass Medium Diameter of primary particles
MSD	Mass Surface Diameter
nm	Nanometre = $1 \cdot 10^{-9}$ metre
NO_X	gaseous pollutant comprising NO and NO_2
NSD	Number size distribution
OC	Organic carbon
PM	Particulate matter
PM10	Particulate Matter of particles with an aerodynamic diameter less than 10 µm measured by mass
PM2.5	Particulate Matter of particles with an aerodynamic diameter less than 2.5 µm measured by mass
PMP	Particle Measurement Programme (under auspices of UNECE WP29/GRPE)
ppm	Parts per million
SCT	Step change test cycle (own definition)
SM	Single Mode Test

SOF	Soluble Organic Fraction
SUVA	Swiss Institution for aAcccident iInsurance (Schweizerische Unfallversicherungsanstalt)
T.HC	Total hydrocarbons as measured by FID according to regulations, group of gaseous pollutants
TD	Thermodesorber
UNECE	United Nations Economic Commission for Europe

2 List of Diagrams, Figures and Tables

List of Figures

List of Tables

3 Introduction

Emissions primarily produced by automotive road vehicles are an important source under investigation. Particles in the exhaust gas of diesel engines in particular, and to a lesser extent particles from gasoline engines equipped with direct injection technology, are of major concern.
Because of the adverse effect of particles from combustion on human health, particle emissions of road vehicles have been restricted in terms of mass for many years. The continuous improvement of engine technology and the development of after-treatment systems has resulted in a sharp reduction in the particle emissions of present-day vehicles. The effective limits of measurement in the current legislative method are consequently being approached.
A more sensitive method would make it possible to continue the present progress in lowering limit values. Representatives from the United Kingdom, Germany, France, Sweden, the Netherlands and Switzerland have therefore initiated a programme for the development of a new particle measurement system. This Particle Measurement Programme (PMP) is a collaborative programme operating under the auspices of the UNECE WP29/GRPE Group. It is focused on a new approach to the measurement of particles in vehicle exhaust emissions, which may be used to complement or to replace the existing regulated mass-based measuring system. The output will be a draft text with a proposal for a new measurement system.
The PMP is divided in three phases. The first two phases are based on several isolated national sub-programmes with the focus on developing and validating new particle measurement systems. It is planned that the third part will deal with testing of the preferred systems on different advanced vehicle technologies at different laboratories in a round robin test.
Several national programmes covering the task of phase 1 of the programme were run. In Switzerland, two studies were carried out looking at the performance of the NanoMet system[1] in comparison with the scanning mobility particle sizer (SMPS 3934, TSI) ([HTL Biel (1), 2001], [HTL Biel (2), 2001]). The United Kingdom presented two reports of studies comparing different electrical mobility methods (SMPS, DMS), CPC, Oscillating Microbalance (QCM, TEOM) ([Ricardo, 2002], [AEAT, 2002]). The performance of a thermodesorber was investigated in Sweden ([MTC, 2003]).
All these studies significantly added to knowledge on recent particle measuring systems. However, as always a limited number of instruments were investigated in each study under different testing procedures, and the meaningfulness of an overall comparison is very limited.
The Swiss authorities therefore initiated an investigation to obtain a *uniform* overview of the performance and quality of the particle measurement system within the PMP. The intention was to compare all available measurement systems in the same test procedure at the *same* test facility and at the *same* time. The tests were carried out in the laboratories of EMPA in Duebendorf in June 2002.
This report presents the main results of this investigation. It is obvious that the study cannot deliver exact specifications for all the individual instruments. However, the study will provide comparable information about the performance of 21 particle measurement instruments and, it is hoped, will in this way contribute to the development of a future particle measurement system for certification purposes.

[1] The NanoMet system consists of a diffusion charger, a photoelectric charge, a diffusion battery and a rotating disk dilution system.

3.1 Financing

This study was financed by ASTRA, EMPA and BUWAL with contributions from Volvo, METAS, SUVA and R&P. The particle instrument manufacturers participated at their own expense.

4 Objectives of the Programme

The objective of this study was to obtain a *uniform* overview of a wide range of state-of-the-art particle measurement systems. The capability and quality of the systems was to be investigated with regard to application for future legislative purposes. Comparable information about **robustness**, **repeatability**, **linearity, sensitivity, limit of detection** and **response time** of the single instruments was to be obtained. Characterisation of the instruments and correlation between the instruments was also an important item in consideration of the selection of core candidate instruments for PMP phase 3.

5 Methodology and approach

The measurement programme was undertaken in co-operation with the participating instrument manufacturers. All interested manufacturers of particle measurement instruments and laboratories were invited to participate with their own system or systems. The maintenance and operation of the systems during the test programme were in the responsibility of the manufacturers' representatives. EMPA assisted with the installation and provided advice on the individual set-up. Representatives of the instrument manufacturers could decide to take the sample from the raw gas line or from the full-flow CVS tunnel and were free in the conditioning of the sample flow for their instrument.
The measurements were carried out *simultaneously* with all systems according to a well-defined standard test protocol.
The experimental phase of the programme was divided into two phases. In the main phase, the instruments were compared using a real diesel exhaust of a modern heavy-duty engine. These tests comprised transient and steady-state tests cycles. The tests were performed at two different emission levels: post-particle-trap level and about 60% of the Euro 4 limit value for particulate matter for the ETC cycle. This phase was aimed at evaluating the candidate systems under practical conditions. In a second phase, an aerosol generator was used as an emission source to obtain information about the performance of the instruments independently of the engine.
The instrument manufacturers were also involved in the data evaluation. Using detailed guidelines and specified data sheets, the representatives of the systems synchronised their individual raw data sets to the engine data and converted them to particle concentration (whatever metric). All further data evaluation (e.g. averaging, exclusion of outliers, system comparisons) and the compilation of this report were dealt with by EMPA.

6 Experimental

6.1 Particle Measurement systems

There was no pre-selection of any system for participation in this comparison study, and all manufacturers or institutes developing particle measurement systems were invited to participate. The candidate systems had to consist of a

- Sampling line
- Sample treatment unit (e.g. sample heater, dilution unit(s), thermodesorber) [optional]
- Size classification unit [optional]
- Detection unit
- On-line data recording [optional]
- Concept for calibration check

It was open to the manufacturer to decide where to take their sample, either from the full-flow CVS tunnel or directly from the raw exhaust line.
A total of 21 particle measurement systems were involved in the three-week measurement programme. This group comprises state-of-the-art and prototypes technologies. The AVL opacimeter (R24) is not considered as a PMP candidate system but was included by EMPA for its own interest, as it is part of the standard test bench facilities.

The instruments (detection units) and their measurement metrics are listed in Table 1.
A more detailed description of the instruments can be found in the appendix.

Code		Manufacturer	Principle	Metrics	Time resolved measurements	Particle size information	State
C03	DMS 500	Cambustion	electrical mobility electrical detection	number	Y	NSD	prototype
C04	Gravimetric filter methods	Operated by EMPA	weighing of filters before and after filter loading	mass	N	-	standard modified
C05	LI2SA	ESYTEC	laser-induced incandescence	mass	Y	Av. size of prim. part.	prototype
C06	MEXA 1370PM	Horiba	filter evaporation method gas analysis	mass	N	-	standard
C07	TEOM 1105	Rupprecht & Patashnick	osc. inertial microbalance	mass	Y	-	standard
C08	PASS	TU Munich	photoacoustic absorption	mass	Y	-	prototype
R10	Mass Monitor DMM (MasMo)	Dekati	el. mob., impaction electrical detection	mass	Y	Av. active surface area	prototype
R11	Coulometry	Operated by SUVA/EMPA	filter method elect.-chem. titration	mass	N	-	standard
R12	DustMonitor	Grimm	laser scattering	number	Y	NSD	standard
R13	Seq. SMPS^{+}C / /UPC 5400	Grimm	electrical mobility cond. optical counter	number	N	NSD	standard
R14	DPSO-1	Hartridge	light extinction opacimeter	k-value	Y	Av. size of prim. part.	prototype
R15	LQ1-DC	Matter Eng.	diffusion charging electrical detection	Active surface	Y	-	standard
R16	EDB 200	Matter Eng.	el. diffusion battery electrical detection	number	Y	calc. NSD	prototype
R17	PAS	Matter Eng.	photoelectrical charging electrical detection	mass	Y	-	standard
R18	PM-300	Sensors	laser light scattering	number	Y	NSD	standard
R19	CPC 3022A	TSI	cond. particle counter, laser scattering	number	Y	-	standard
R20	EAD 3070A	TSI	turbulent diff. charging electrical detection	length	Y	-	standard
R21	Scan. SMPS 3936-L10 / /CPC3010A	TSI	electrical mobility cond. optical counter	number	N	NSD	standard
R22	ELPI	Dekati	impactor principle electrical detection	number	Y	NSD	standard
R23	DQL	WIZARD	laser light extinction opacimeter	volume	Y	Av. size of prim. part.	prototype
R24	AVL 439	operated by EMPA	light extinction opacimeter	mass	Y	-	standard

Table 1: *Instruments and measurement metrics*

6.1.1 Particulate mass measurement by gravimetric filter method

The conventional mass measurement by filter loading (C04) was based on the European regulations. In order to evaluate the potential of an improved gravimetric filter method as much as possible, some specifications of the US EPA2007 regulations were adopted. Due to the short preparation period for this study, the complete US EPA2007 regulations could not be applied. In the following respects, the gravimetric filter measurement was modified to be in line with the US EPA2007 regulations:

- filter quality and dimensions (Pallflex TX40HI20WW)
- filter holder and pre-classifier assembly (supplied by Rupprecht&Patashnick)
- face velocity
- filtering of primary and secondary dilution air
- conditioning in temperature and humidity of microbalance workstation and filter stabilisation environment
- thermal isolation of transfer lines and pre-classifier (lower temperature limit of 315 K was not met in all cases.)

Parallel to the filter loading system, an identical assembly (incl. pre-classifier) was installed downstream of the secondary dilution tunnel for the particle measurement system of the manufacturer Horiba (C06). Downstream of the pre-classifier for the C06 branch, the flow was split once more to feed the TEOM (C07). To clarify, it should be mentioned that all three instruments use the same sampling line as far as downstream of the secondary dilution tunnel. All transfer tubes, both pre-classifiers and both filter holders were thermally isolated to keep the sample at a higher temperature, but always below the upper limit temperature of 325 K.
Using a mini-tunnel (AVL Smart Sampler SPC 472), additional filter sampling was carried out from the raw exhaust gas for the coulometric analysis (R11). The partial flow dilution system was operated in CVS mode with the same dilution ratio as the full flow system.
The filters were weighed on a microbalance (Mettler MT5) with a readability of 1 µg and a measurement uncertainty of 2.6 µg for the applied mass range.
Pure quartz-fibre filters of the same quality were used for MEXA (C06) and the coulometric analysis (R11).

6.2 Engine test facilities

6.2.1 Engine

The engine tests were carried out with a heavy-duty diesel engine manufactured by Volvo. This type of engine is typically installed in buses and was certified in combination with a particle filter system CRT™ according to the Euro 3 regulations. More technical information on the engine is provided in Table 2.

		Volvo HD engine
Certification level	[-]	Euro 3
Displacement	[litres]	7
No of cylinders	[-]	in-line, 6
Rated power	[kW]	190
Rated speed	[1/min]	2200
Max torque	[Nm]	1030
Engine technique	[-]	turbocharger (waste gate), intercooler
After-treatment system		CRT system (oxi-cat and particle filter)

Table 2: *Engine parameters*

To allow measurements to be performed at two different emission levels, a bypass was installed parallel to the CRT system to increase the particle concentration in the exhaust line. By having two gates, one in the bypass and the other upstream of the division, it was possible to adjust the particle emission level without changing the back-pressure settings of the engine. For measurements at a higher emission level, the gate of the bypass was adjusted to a level corresponding to about 60% of the future emission standard Euro 4 regarding the PM emissions in the ETC cycle. The specific emission (g/kWh) was therefore 40% lower than the corresponding limit value for the ETC. For the subsequent measurements at the low-emission level, the bypass was removed.

6.2.2 Engine Fuel and Lubricant

All engine tests were undertaken with diesel fuel, CEC-RF-06-99, with less than 10 ppm sulphur. The engine was run with high-quality lubricant oil, with the SAE classification 10 W-40 and about 3900 ppm sulphur. The specifications are given in the appendix.

6.2.3 HD test bench

The heavy-duty test bench at EMPA consists of an asynchronous motor, state-of-the-art emission measurement equipment and a full-flow dilution system for the regulated measurement of particulate matter and gaseous components. The dynamic test bed is suitable for transient test cycles. In order to exclude any contamination and interference, a separate full-flow dilution tunnel is used for engines powered by compressed natural gas (CNG) or liquefied petroleum gas (LPG). The air for primary and secondary dilution is temperature-controlled and filtered by coarse filters, activated carbon filters and fine filters. The filters fulfil the requirements of the US EPA 2007 regulations. The combustion air is filtered and temperature and humidity-controlled.
Further information on the HD test bench at EMPA can be found in the appendix.

6.2.4 Experimental set-up

A schematic of the set-up is shown in Figure 1. The samples for the instruments were taken either from the primary full-flow CVS tunnel, from the secondary tunnel of the CVS system or from the raw exhaust gas line according to the preference of the manufacturers. The probes were placed at disposal and installed by EMPA. For the sampling from the CVS tunnel, all probe openings were in approximately the same plane at the end of the 4.5 m long tunnel. Due to the larger number of sampling points and the smaller diameter of the exhaust pipe, two locations - each for three probes - had to be defined for the raw gas sampling. In order to prevent any interference, the planes were about 0.5 m apart and at least 6 times the diameter of the exhaust pipe downstream of the last bend.

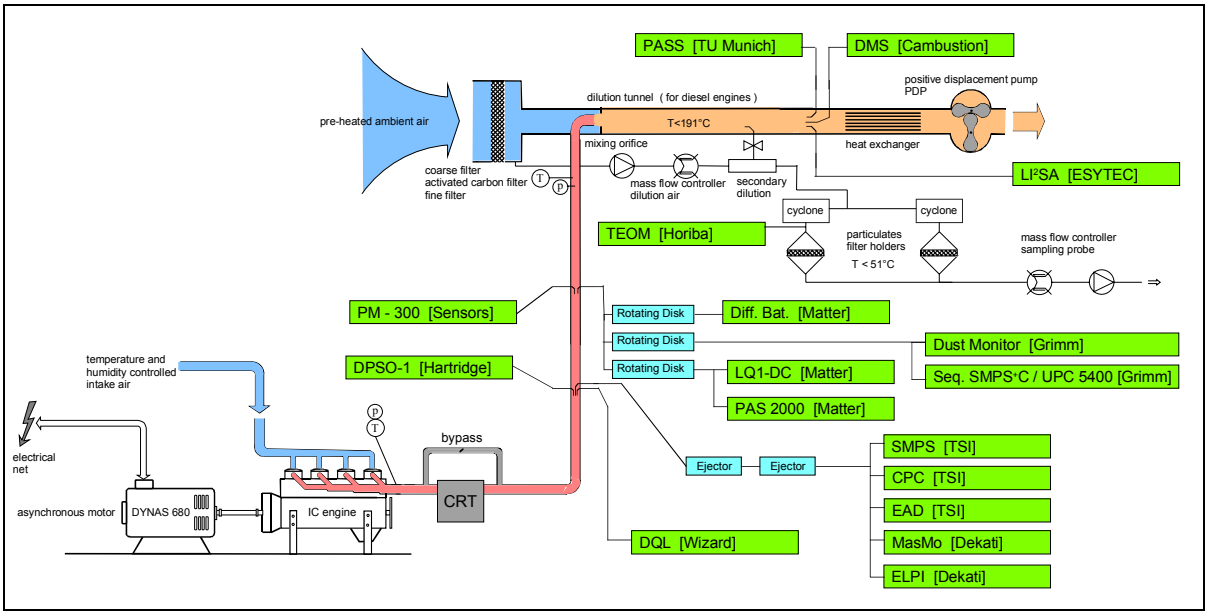


Figure 1: *Schematic of the experimental set-up*

The probes for the filter sampling for coulometric analysis (R11) and the standard opacity measurement (R24) were located in the raw gas line about 1 m and 2 m downstream of the other probes respectively.

The individual set-ups of the measurement systems, i.e. the transfer lines and the additional dilution units, were the responsibility of the representative; EMPA provided assistance and gave advice. For the raw gas sampling, the transfer lines to the first dilution unit or detection unit were heated for all instruments.

Table 3 presents an overview of the sampling location and dilution for the individual instruments. The dilution factors as stated in the table were used for high-emission measurements. For the low-emission measurements, the dilution factor was lower for some instruments (R10, R15, R16, R17; R19, R20, R21, R22).

Because of the application of different sampling and dilution systems, it cannot be assumed that the instruments will necessarily measure the same aerosol. In particular, the detection of nuclei particles/condensed material depends greatly on the sampling conditions.

Code	System	Location of sampling probe	Dilution	Dilution factor high/low emission	Max. temperature in sampling line
C03	DMS	CVS tunnel	-	>4	-
C04	Gravimetry	CVS tunnel	sec. dilution tunnel	>6	-
C05	LI2SA	CVS tunnel	-	>4	-
C06	MEXA 1370PM	CVS tunnel	sec. dilution tunnel	>6	-
C07	TEOM	CVS tunnel	sec. dilution tunnel	>6	-
C08	PASS	CVS tunnel	-	>4	-
R10	MasMo	raw gas line	double stage ejector, heated	95/10	473 K
R11	Coulometry	raw gas line	part. flow dilution tunnel	>6	-
R12	DustMonitor	raw gas line	rotating disc, heated	164	393 K
R13	SMPS^{+}C/UPC 5400	raw gas line	rotating disc, heated	164	393 K
R14	DPSO-1	raw gas line	internal	?	373 K
R15	LQ1-DC	raw gas line	rotating disc, heated	123/21	393 K
R16	EDB 200	raw gas line	rotating disc, heated	148/15	393 K
R17	PAS 2000	raw gas line	rotating disc, heated	123/21	393 K
R18	PM-300	raw gas line	internal	10	463 K
R19	CPC 3022A	raw gas line	double stage ejector, heated	95/10	473 K
R20	EAD 3070A	raw gas line	double stage ejector, heated	95/10	473 K
R21	SMPS 3936-L10	raw gas line	double stage ejector, heated	95/10	473 K
R22	ELPI	raw gas line	double stage ejector, heated	95/10	473 K
R23	DQL	raw gas line	internal	< 2	383 K
R24	AVL 439	raw gas line	-	1	373 K

Table 3: *Instruments and their sampling location/dilution during the measurements with the engine*

The regulated gaseous components were continuously measured in the raw and diluted exhaust gas during the tests. In addition, a NO_X analyser was installed upstream of the particle trap to measure the NO and NO_2 concentration emitted by the engine in order to determine the NO conversion rate of the CRT/bypass system. In this way, the stability of the flow split at the bypass could be checked for the different test cycles.

6.3 CAST test facilities

Besides the engine tests, additional measurements were carried out with a combustion aerosol generator. The purpose of these measurements was to obtain data independent of the more complex engine exhaust.

6.3.1 CAST

The CAST (Combustion Aerosol STandard) is a stand-alone soot generating burner based on a co-flow diffusion flame which generates air suspended sub-micron combustion soot particles. These particles correspond to the particles emitted by diesel engines in the most important characteristics. The concentration and size distribution of the particles are reproducible and are calibrated by the Swiss Federal Office of Metrology and Accreditation (METAS). Further details are presented at (http://www.sootgenerator.com/). During the measurement programme, the CAST was operated by a representative of METAS.

6.3.2 Experimental set-up

Downstream of the burner, the aerosol was diluted by two consecutive dilution units, first by a rotating disc dilution unit (MD19) and then by an ejector-based dilution unit (VKL100, Palas). After dilution, the aerosol flow of about 30 l/min was split by an 8-fold flow-splitter (T-connector) for simultaneous measurement by the instruments. The transfer tubes between the flow-splitter (8) and the instruments had an identical length of 2 m for all instruments. Figure 2 shows the set-up that allowed measurements with the CAST for up to 8 instruments at the same time. As a consequence of the limited aerosol flow rate, comparison of the candidate instruments had to be performed in two groups.

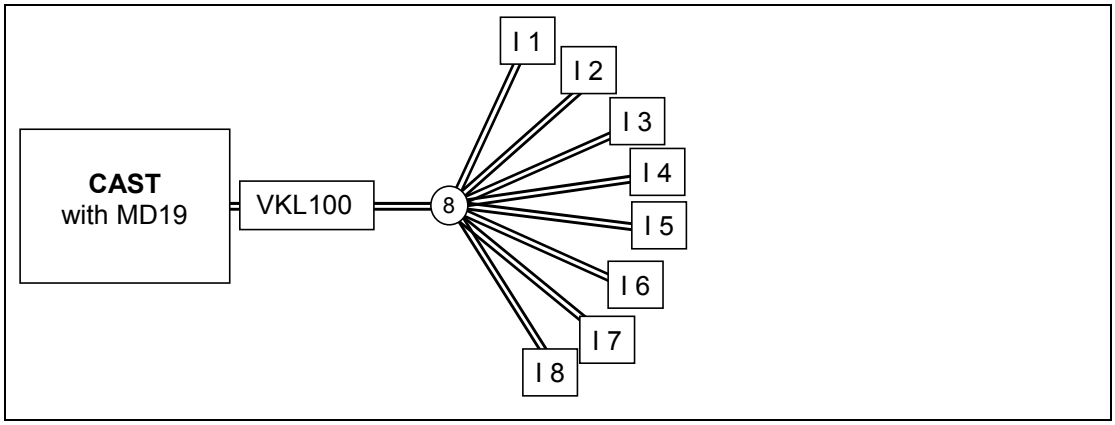


Figure 2: *Set-up of instruments for simultaneous particle measurements.*

7 Description of the test programme

The measurement programme started with a two-day test phase with the particle generator CAST (see section 7.1), followed by an eight-day test phase on the HD engine (see section 7.2) and ended with a repetition of the CAST measurements.

The candidate systems were operated and maintained by the representatives of the manufactures. They ran their systems at their own responsibility throughout the measurement programme.

7.1 CAST measurements

The purpose of these tests was to obtain information about the calibration, detection limit and linearity of the instruments.

7.1.1 Size settings / Emission levels

The CAST was set to two well-defined lognormal size distributions, each at four different concentrations (90%, 60%, 30%, 10%). Before and after the measurement programme, these settings were calibrated by METAS in Wabern (Switzerland) using a scanning SMPS (3934-C,TSI). The following mean values were determined:

			Setting A	Setting B
Mode	NSD	[nm]	35	140
Concentration	10%	[cm^{-3}]	13700	5300
	30%	[cm^{-3}]	50900	15600
	60%	[cm^{-3}]	110150	29700
	90%	[cm^{-3}]	155450	39700

Table 4: *CAST settings as determined by a SMPS 3934 (TSI)*

The four different concentration settings were made by changing the speed of the rotating disc dilution unit, while neither the combustion nor any detail of the set-up was changed.
Background measurements (concentration 0%) were also performed, by stopping the rotating disc dilution system.

7.1.2 Measurement programme

Because of the restricted aerosol flow of the CAST set-up, the measurements had to be carried out in two series. An additional CPC (TSI, 3022A) was operated during all tests as a monitoring instrument. Unfortunately, the instrument malfunctioned and the results could not be used for reference purposes. The settings of the CAST for each group were identical same and the measurements were performed according to a well-defined protocol.

before engine tests		after engine tests	
Group 1	**Group 2**	**Group 1**	**Group 2**
LI2SA	DMS	LI2SA	DMS
TEOM	MasMo	PASS	MasMo
PASS	CPC (R19)	PM-300	LQ1-DC
LQ1-DC	EAD	CPC (R19)	EDB
EDB	SMPS (R21)	EAD	PAS
PAS	ELPI	SMPS (R21)	ELPI
PM-300	DQL		
CPC EMPA	CPC EMPA	CPC EMPA	CPC EMPA

Table 5: *Groups for the CAST measurements*

The test procedure of the two series followed the same schedule:
- warm-up CAST: 45 min
- concentration setting
- stabilisation phase: 5 min
- measurement period: 10 min
- next concentration setting
- stabilisation phase after size change: 20 min

The detailed sequence of the tests can be found in the appendix.

7.2 Engine measurements

7.2.1 Test cycles

The test programme comprised two steady-state and two transient test cycles. The main focus was on the European transient cycle (ETC), which is the official transient certification test cycle in Europe. For the steady-state test, five operation modes were selected from the European steady-state cycle (ESC) for a so-called single mode test cycle (SM). The modes were run for 15 minutes one after the other without interruption.
To obtain information about the time response of the particle systems, a so-called step change test (SCT) was defined, consisting of a repeated switch between two loads, with a three-minute stabilisation phase between two switches. Finally some runs of the complete European steady-state certification test cycle (ESC) were carried out. Details of the test cycles are presented below (Table 6) and in the appendix.
At the beginning of each day of measurement, background measurements (BG) were carried out by running the complete CVS dilution system and all measurement instruments, but the engine was switched off. The tests were run for 30 minutes, which is the same duration as for the ETC test cycle.

Test	Name		Phases	Duration [min]
ETC	European transient cycle	transient	urban, rural, highway	30
SM	Single mode test cycle	steady-state	B100, C75, A50, B25, idle	75
SCT	Step change test	transient	12 steps; repeated switch between 90% and 10% load at engine speed of 1630 rpm	34
ESC	European steady-state cycle	steady-state	13 steps	28
BG	Background measurement	-	-	30

Table 6: *Test cycles for the measurements using the engine*

7.2.2 Conditioning of the engine

The conditioning of the engine and the engine exhaust system was carried according to the EPEFE protocols (European Programme on Engines, Fuels and Emissions, ACEA, Brussels).

1. Standard warm-up of the engine (until the oil temp was 80°C)
2. Running the engine at rated power for one minute
3. Running the engine at idle for about one minute
4. Running the engine at B100 for two minutes

In the case of the SCT test, the engine was run at 90% load for 4 minutes in addition to the described conditioning procedure before starting the test.

7.2.3 Measurement programme

The engine tests started with the bypass set-up (high-emission), followed by the tests with the full trap set-up. Preconditioning of the engine, trap, exhaust lines and CVS tunnel were carried for several hours between the two series. Table 7 shows the test sequence for the engine test programme.

High-emission (bypass set-up)			
Day 1	Day 2	Day 3	Day 4
BG	BG	BG	BG
ETC	ETC	ETC	ESC
ETC	ETC	SM	ESC
ETC	ETC	ESC	
SM	SM	SCT	
SCT	SCT		

Low-emission (full trap set-up)		
Day 1	Day 2	Day 3
BG	BG	BG
ETC	ETC	ETC
ETC	ETC	SM
ETC	ETC	SCT
SM	SM	ESC
SCT	SCT	ESC

Table 7: *Engine test programme*

8 Measured parameters and calculations

8.1 Data evaluation methodology

Measurements and data recording for the particle measurement systems were carried out by the individual representatives. During the tests EMPA supplied each participant with a starting trigger signal to synchronise the data sampling from the test bench and the particle systems. A back-up of the raw data from each system was collected at the end of each measurement day by EMPA for quality control purposes. For the data evaluation, the participants had to fill in their time-resolved raw data for each test on a separate specified spreadsheet and had to transfer them to emission values as guided by a detailed formula provided by EMPA.
After receiving the filled-in tables of each participating instrument, EMPA carried out a careful check of the data and performed the subsequent data evaluation.
The data evaluation followed the standard ISO/FDIS 16183 for conversion of the values to emission values.
All engine tests were carried out at least three times, with the exception of the ESC cycle for low-emission (twice). Special attention was paid to the ETC and the background measurements that were performed seven times for each configuration. For this reason, all emission values shown in this report are mean values of the measured tests unless otherwise stated. The variation of the single measurements is given by the standard deviation (stdv).

$$s = \sqrt{\frac{1}{n-1} \cdot \left(\sum_{i}^{n} (\bar{x} - x_i)^2 \right)}$$

n: number of test runs

In the bar charts (diagrams), the **range bars** indicate +/- one standard deviation.

For the steady-state tests the variation of the second-by-second values x_k (k: consecutive numbers) over the tests were calculated according to

$$stdv\ x_i = \sqrt{\frac{1}{m} \cdot \left(\sum_{k=1}^{m} (x_{i,k} - x_i)^2 \right)}$$

m: number of the one-second intervals of the whole test

The coefficient of variation (**COV**) is a measure of relative dispersion and is given by

$$COV = \frac{standard\ deviation}{mean} = \frac{s}{\bar{x}}$$

For the time-resolving systems, the uncertainty of the single measurements **(noise)** was determined, defined as three times the standard deviation of the single measurements:

$$noise / mean := \frac{1}{n} \sum_{i=1}^{n} \frac{3 * stdv\ x_i}{x_i}$$

Noise-to-mean ratios were determined for the background measurements with the engine (the engine was shut off) (see section 7.2.1) and for the CAST measurements for the 10% and 90% concentration settings (see section 7.1).

8.2 Limit of detection

The limit of detection (LOD) of the particle measurement systems was calculated by taking three times the standard deviation of the mean value of a set of measurements at very low concentrations.
We decided to calculate the LOD from the ETC low-emission tests and not from the engine background tests, as the repeatability was better for the ETC tests than for the background measurements at the same low concentration level. In addition, for the background measurements temperatures and flow rates are significantly different than real exhaust measurements. The LOD as defined and determined provides a comparison of the instruments within this programme and cannot be used generally.

$$LOD = 3 \cdot s(ETC\ low)$$

8.3 Sensitivity

The sensitivity of the systems is deduced from the ratio of the concentrations measured for the measurements at high and low-emission level of the individual test cycles (see section 8.6). This characterisation is influenced by the limit of detection of the instruments, by the measured particle composition and naturally also by the sampling conditions. The quantification by the sensitivity therefore provides a comparison of the instruments within this programme; it cannot be used generally.

8.4 Response time

The response time is the time a system or functional unit takes to react to a given input. A special test cycle was defined to determine the response time of each instrument. This so-called step-change-test (SCT) consists of one repeated change of engine power every 3 min by switching between 90% and 10% load at a constant engine speed of 1630 rpm (see Figure 3). The duration of the whole test cycle consisting of 11 steps was 34 minutes. The test cycle (as shown in Figure 3) started after a well-defined conditioning phase (see section 7.2.2).

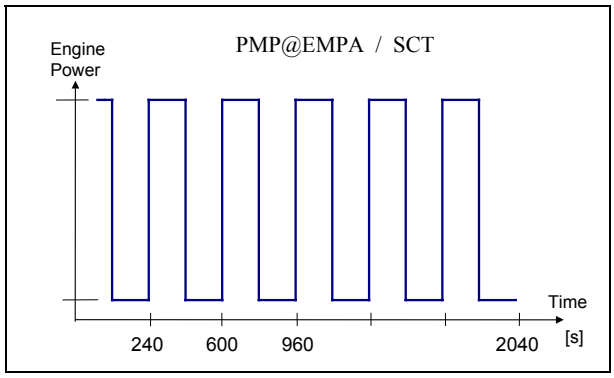


Figure 3: *Pattern of the SCT cycle*

Each cycle consisted of 5 up-steps and 6 down-steps. For the data evaluation and the calculation, the individual cycle sequences were divided into two groups: the up-step and the down-step. For the purposes of the calculations, the first down-step was not taken into account for further calculations.

The definition of the characteristic times is shown schematically in Figure 4 for an up-step as well as for the down-step sequence.

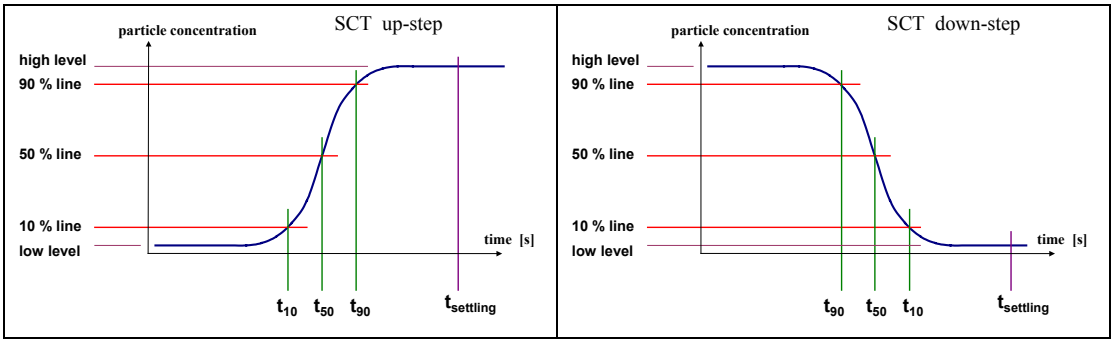


Figure 4: *Definition of characteristic times in the SCT cycle*

According to these definitions, the following two characteristic times were calculated for each step and for each instrument.

up-step		down-step
$t_{50} - t_{10}$	corresponds to	$t_{50} - t_{90}$
$t_{90} - t_{10}$	corresponds to	$t_{10} - t_{90}$

In addition $t_{settling}$ was defined. This characteristic time was defined as the time when the concentration started to be stable within +/- 10% of the final value. However, the exhaust of the engine became not adequately stable within the 3 minutes to determine characteristic times of the instruments. For the three SCT runs, the mean value and the standard deviation of all 15 up-steps as well as of the 15 down-steps were calculated for the instruments. The characteristic times for the individual instruments are given in section 9.1.5.1.

8.5 Linearity

Linearity is the relationship that exists between two quantities when a change in one of them produces a directly proportional change in the other. The instruments were checked for linearity by means of four different concentration settings with the CAST.

8.6 Repeatability

Repeatability is defined as the closeness of agreement between independent test results obtained under repeatability conditions, i.e. the independent test results are obtained using the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time. Repeatability depends only on the distribution of random errors and does not relate to the true value (ISO 5725).
The degree of repeatability is usually expressed in terms of the standard deviation of the test results. In this report, the "coefficient of variation" (**COV**) is defined as one standard deviation.

Precision
The closeness of agreement between independent test results obtained under stipulated conditions. Repeatability conditions are a particular set of extreme conditions. As precision demands weaker conditions, this report is focused on repeatability.

Accuracy
The closeness of agreement between the result of the measurement and the accepted reference value of the quantity. As no reference values of the particle emissions for the individual metrics were available, the accuracy of the individual instruments could not be determined.

Reproducibility
The closeness of agreement between independent test results obtained under repeatability conditions, i.e. the test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment. By definition, it was not possible to determine reproducibility within the EMPA measurement programme.

8.7 Outliers

Inconsistent values in a set of measurement values were identified by a simple test according to Dixon [Dixon, 1953]. In addition, the outlier had to deviate by at least 40% from the mean of the other measurements in the same set. A maximum of one value per set was defined as an outlier.

8.8 Robustness

No analysis of the robustness of the particle measurement systems was carried due to the short duration of the programme. Only a personal impression is reported, based on availability during the tests in consideration of the schedule of test series and the ambient conditions.

9 Results and Discussion

Table 8 presents an overview of the available data, which were available to EMPA for data evaluation.

		ETC		SM		SCT		ESC		CAST		BG
	Code	High emission	Low-emission	High-emission	Low-emission	High emission	Low-emission	High-emission	Low-emission	Before engine tests	After engine tests	Engine background tests
DMS	C03	✓	✓	✓	✓	✓	✓	✓	✓	n.m.	✓	✓
Gravimetry	C04	✓	✓	✓	✓	✓	✓	✓	✓	n.m.	n.m.	✓
LI2SA	C05	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
MEXA 1370PM	C06	✓	✓	✓	✓	✓	✓	✓	✓	n.m.	n.m.	✓
TEOM	C07	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
PASS	C08	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
MasMo	R10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Coulometry	R11	✓	✓	✓	✓	✓	✓	✓	✓	n.m.	✓	✓
DustMonitor	R12	✓[1]	n.m.	✓[1]	n.m.	✓[1]	n.m.	✓	n.m.	n.m.	n.m.	✓[2]
SMPS$^+$C/UPC	R13	✓[1]	n.m.	✓[1]	n.m.	✓[1]	n.m.	✓	n.m.	n.m.	n.m.	✓[2]
DPSO-1	R14	✓	n.d.	✓	n.m.	✓	n.m.	✓	n.m.	n.m.	n.m.	n.d.
LQ1-DC	R15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EDB	R16	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
PAS	R17	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
PM-300	R18	✓	✓	✓	✓	✓	✓	✓	✓	✓	n.m.	✓
CPC 3022 A	R19	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EAD 3070A	R20	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SMPS 3936-L10	R21	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ELPI	R22	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
DQL	R23	✓	✓	✓	✓	✓	✓	✓	n.m.	n.m.	n.m.	n.d.
Opacimeter	R24	✓	✓	✓	✓	✓	✓	✓	✓	n.m.	n.m.	✓
Exhaust Gas An.		✓	✓	✓	✓	✓	✓	✓	✓	n.m.	n.m.	✓

Table 8: *Available Data*

✓[1]	number of measurements was significantly lower than scheduled
✓[2]	Less than three background measurements
n.m.	not measured
n.d.	no data were delivered to EMPA

9.1 Engine measurements

9.1.1 Robustness

None of the participating instruments had serious problems in running the tight and 2.5 week long test programme. This cannot be regarded as a matter of course because the instruments were exposed to ambient temperature up to 30° C for more than a week. Some losses of data occasionally occur, mainly due to incorrect operation, missing of the start signal or failure in communication. The prototype DMS was still being optimised during the measurement programme, skipping some measurements at the beginning.

9.1.2 Repeatability

The results for the determination of the repeatability of the instruments are based on the particle concentration per exhaust gas volume, i.e. [x/Ncm^3]. The repeatability of the instruments is characterised by what is known as the coefficient of variation (COV), defined as one relative standard deviation of the test (see section 8.2)

9.1.2.1 European Transient Test (ETC) / ETC high-emission

Seven ETC cycles were carried out at a high-emission level, i.e. by using the bypass (see section 6.2). These cycles were measured on three successive days.

The stability and repeatability of the engine is shown in Figure 5, looking at some important engine-related data and the regulated gaseous components. The engine was very stable during the seven tests on three different days, which is an important condition to be met for the investigation of the performance of the particle instruments.

Although the variations in the engine exhaust emissions are very small, their contribution to the variation of the particle measurement results cannot be determined. Within a group of instruments with the same metrics, the instrument with the lowest variation provides the upper limit of the engine's contribution.

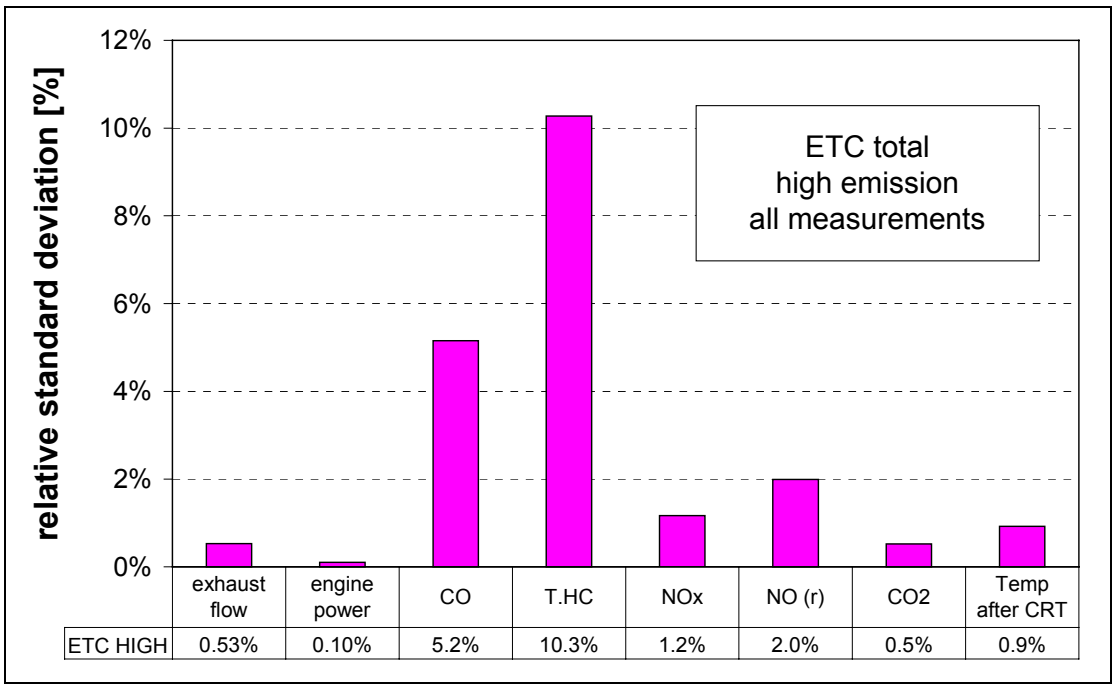


Figure 5: *Variation of engine parameters/gaseous emissionsETC high-emission*

The absolute concentrations of CO and T.HC are very low, causing a higher variation. The NO concentration was measured in the raw gas downstream of the trap. Because the CRT system affects the NO/NO_2 ratio, the good repeatability of the NO concentration is an indication of the stable flow-splitting during test series. In Figure 6, the integrated NO conversion rate of the CRT system is plotted against time for all ETC cycles. The conversion rates for bypass and full-trap configuration are different, as expected, but show roughly the same variation. This is another indication of stable flow-splitting during the test series.

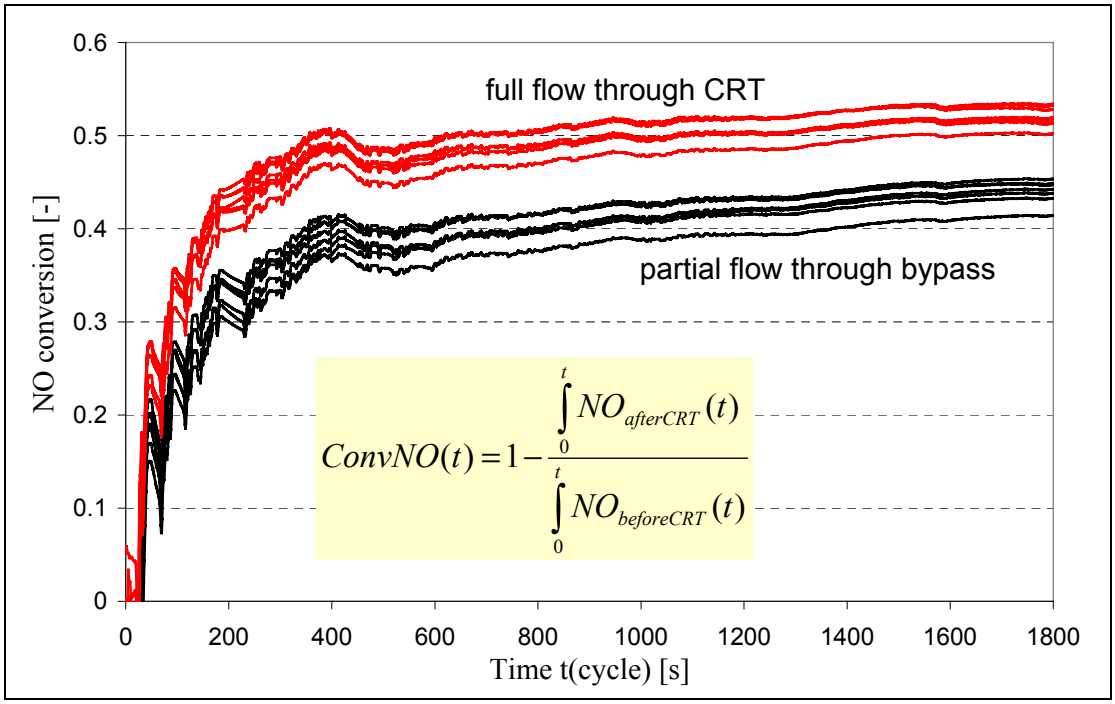


Figure 6: *NO conversion rate as a function of time for all ETC cycles.*

Figure 7 shows the coefficient of variation (COV) defined as one relative standard deviation for the ETC high-emission tests. The four graphs represent the COV of the three repetitions within the first and second day, of the first per day measurement on three days and for all seven tests. Looking at the repeatability for all measurements, the COV for most of the instruments is within the range of about 10% or better. Exceptions are coulometry (R11) and DSPO (R14). Coulometry showed fairly poor repeatability throughout the test programme, which is surprising and could not be explained. The huge variation in the DPSO is caused by insufficient sensitivity and a cross-sensitivity to NO_2.

Notes to the following figures:

One outlier was not taken into account for calculation

Less then 6 measurements were available for calculation

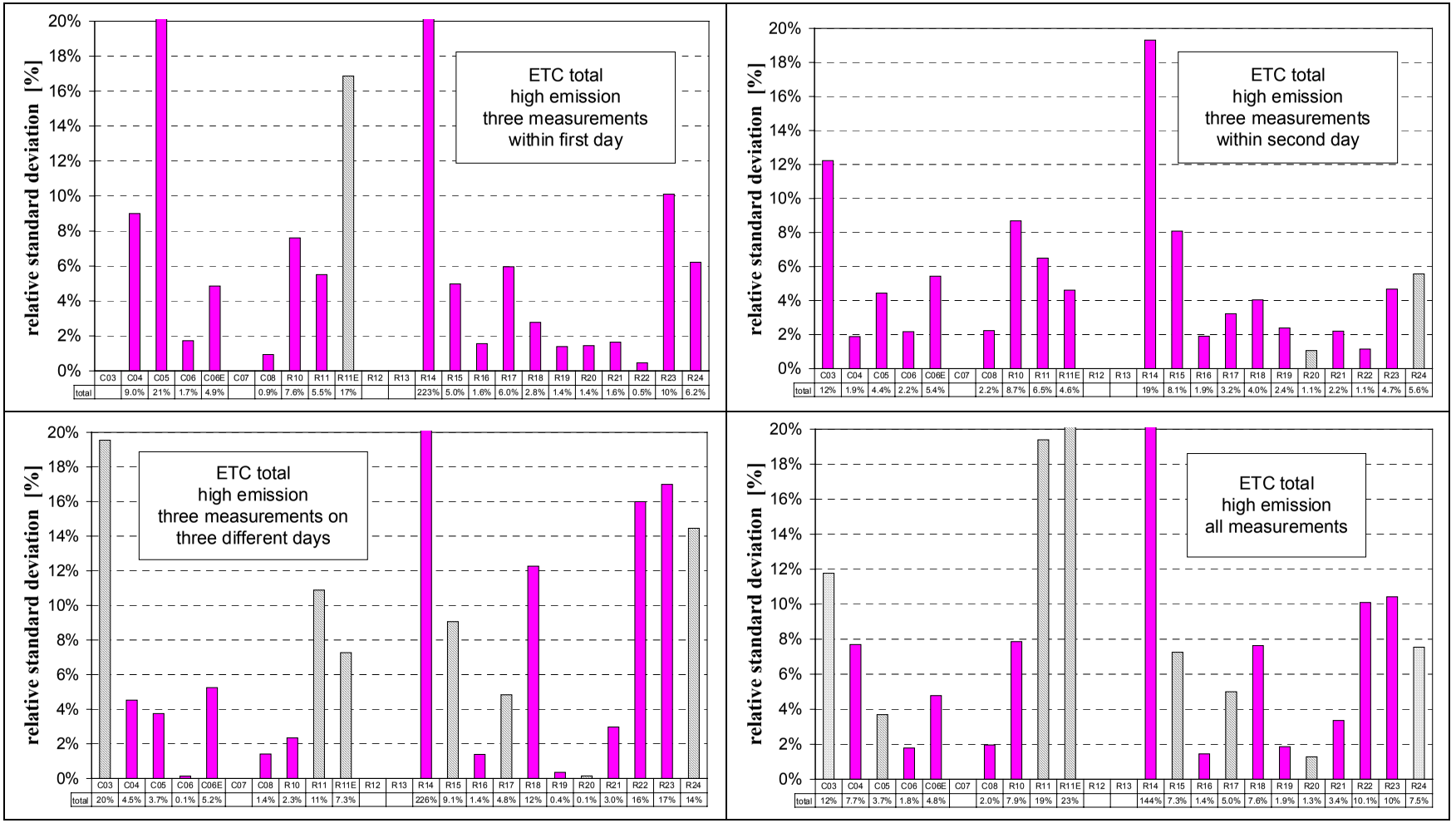
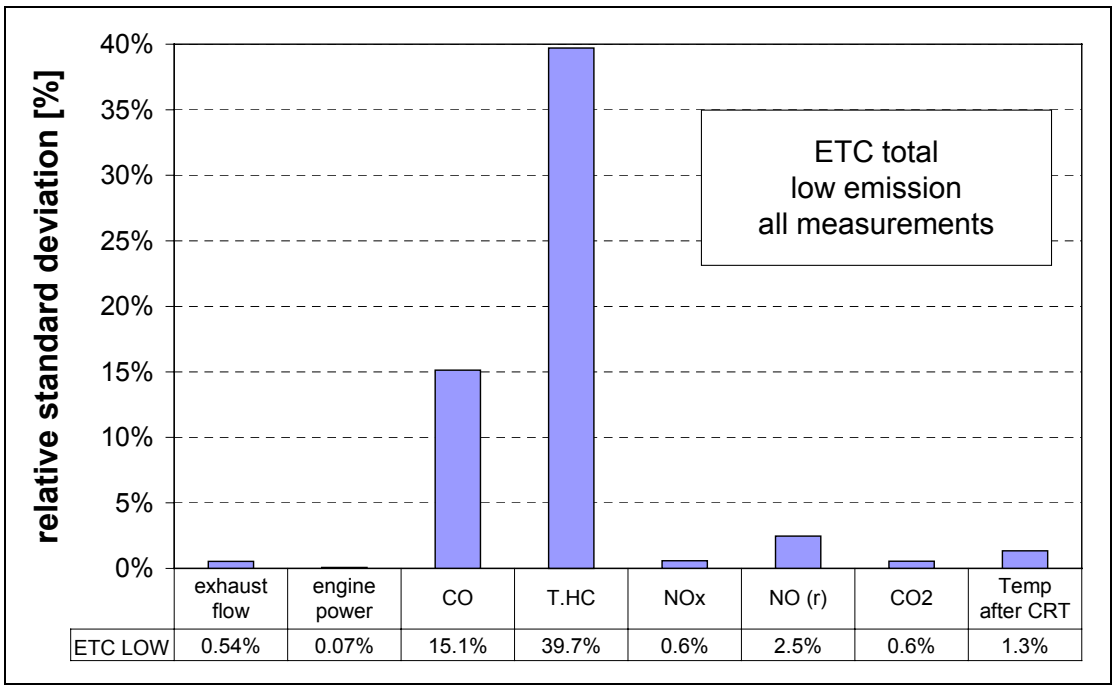


Figure 7: *Relative standard deviation of each instrument (R21 here total number) /ETC high-emission*

9.1.2.2 European Transient Test (ETC) / ETC low-emission

The low-emission measurements refer to the set-up without filter bypass installed, i.e. the full exhaust passed the CRT system. In line with the high-emission tests, seven measurements were conducted, spread over three successive days. Figure 8 shows the repeatability for the low-emission tests. The variations of CO and T.HC are higher than for the high-emission measurements as the absolute values are close to the detection limit for both components.



	exhaust flow	engine power	CO	T.HC	NOx	NO (r)	CO2	Temp after CRT
ETC LOW	0.54%	0.07%	15.1%	39.7%	0.6%	2.5%	0.6%	1.3%

Figure 8: *Variation of engine parameters/gaseous emissions/ETC low-emission*

The low-emissions of CO and T.HC are achieved by the oxidation catalytic converter of the CRT system. No significant change is observed for the other parameters and components.

Notes:

One outlier was not taken into account for calculation

Less then 6 measurements were available for calculation

R21 The DMA of R21 was set to select 80 nm particles on the first day
→ there are no ETC data of R21 on the first day

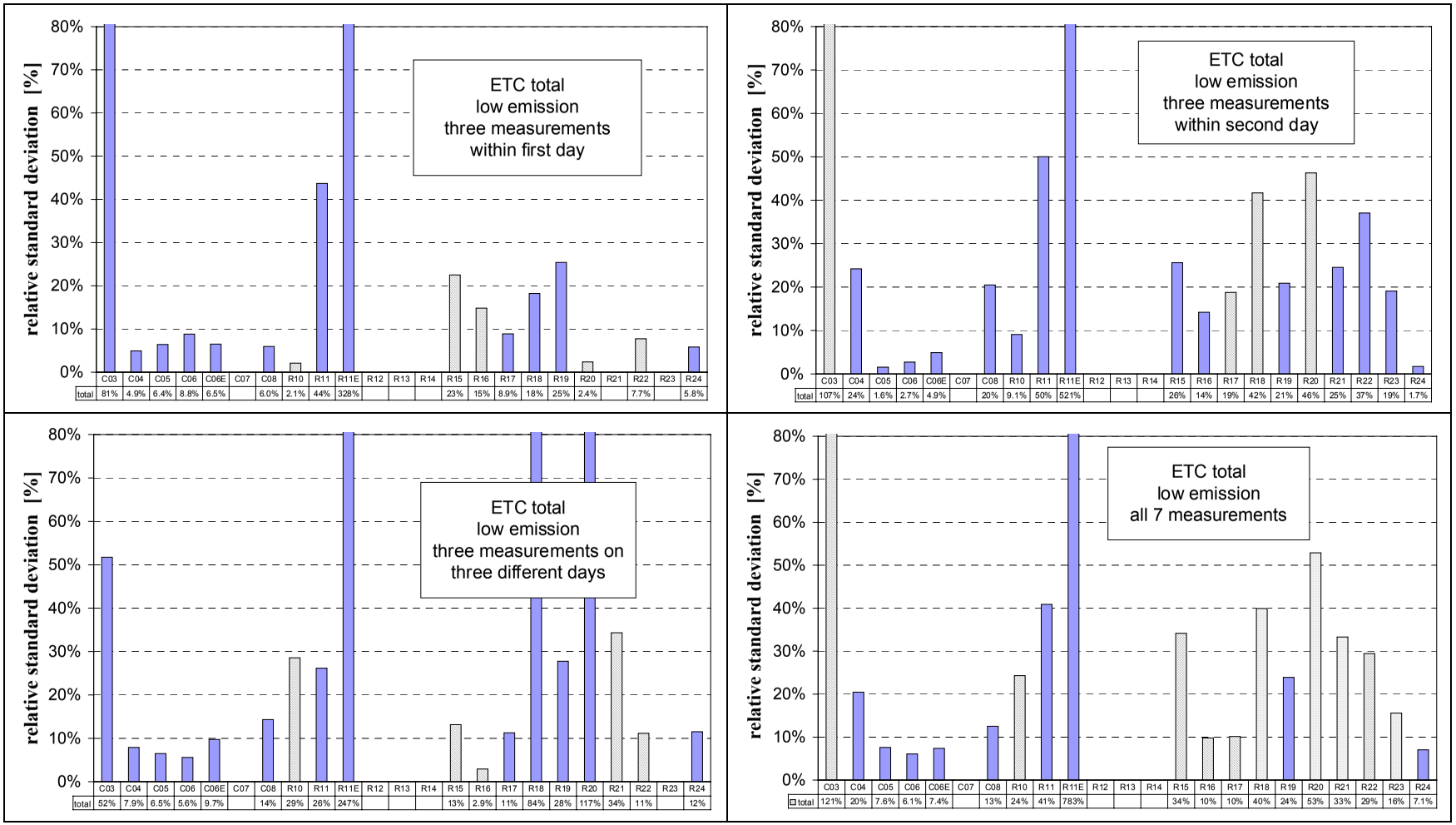
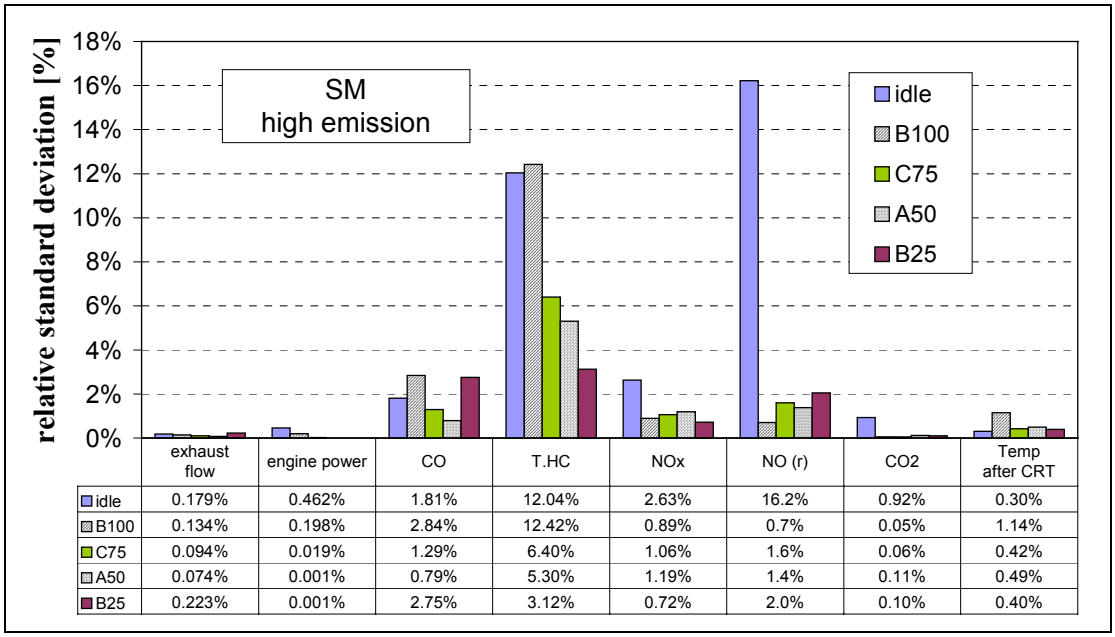


Figure 9: *Relative standard deviation of each instrument (R21 here total number)/ETC low-emission*

Figure 9 shows the COV for the low-emission tests. The variation is higher than for the high-emission tests for all instruments. An exception is the opacimeter AVL439 (R24), although the absolute value is similar to the value for the high-emission configuration. This implies that the signal at both configurations is caused by NO_2 rather than by the particulate matter. Most of the instruments still show acceptable repeatability for the low post-trap concentration. The COV of the soot-sensitive instruments (C05, C06E, C08, R17) is in the range of 10%, although the soot fraction is very low downstream of the trap. An exception is the repeatability of the EC value measured by coulometry (R11E), which shows very poor repeatability for this very low concentration close to zero. The high variation of the DMS (C03) can be explained as being mainly due to nucleation effects measured with this instrumental set-up.

9.1.2.3 Steady-State Tests (SM) / SM high-emission

The same analysis of the repeatability was carried out for the single mode tests. Here each data set comprises three measurements for each of the five modes. Figure 10 shows the COV of some engine parameters and gaseous components. With the exception of the idle mode, the variation is similarly low as in the case of the ETC. The good repeatability of the NO concentration indicates stable operation of the flow-splitting and after-treatment system.



	exhaust flow	engine power	CO	T.HC	NOx	NO (r)	CO2	Temp after CRT
idle	0.179%	0.462%	1.81%	12.04%	2.63%	16.2%	0.92%	0.30%
B100	0.134%	0.198%	2.84%	12.42%	0.89%	0.7%	0.05%	1.14%
C75	0.094%	0.019%	1.29%	6.40%	1.06%	1.6%	0.06%	0.42%
A50	0.074%	0.001%	0.79%	5.30%	1.19%	1.4%	0.11%	0.49%
B25	0.223%	0.001%	2.75%	3.12%	0.72%	2.0%	0.10%	0.40%

Figure 10: *Relative standard deviation of the engine parameters / gaseous emissions for each step in the SM test / SM high-emission*

Figure 11 and Figure 12 show the variation for the idle and for the four load modes respectively. No significant change in repeatability is observed for the steady-state conditions compared to the transient conditions. Similarly to the ETC tests, the COV of several instruments is within the range of 10% or better. The DMS (C03) measured a very high absolute concentration for B100, which is most probably caused by nucleation effects. An unstable nuclei mode could be the reason for the wide variation.

At idle, the COV for LI2SA (C05) is rather high compared to the other modes, which might be explained by the low EC concentration. Owing to problems during the measurements, no results are available for the PM-300 (R18).

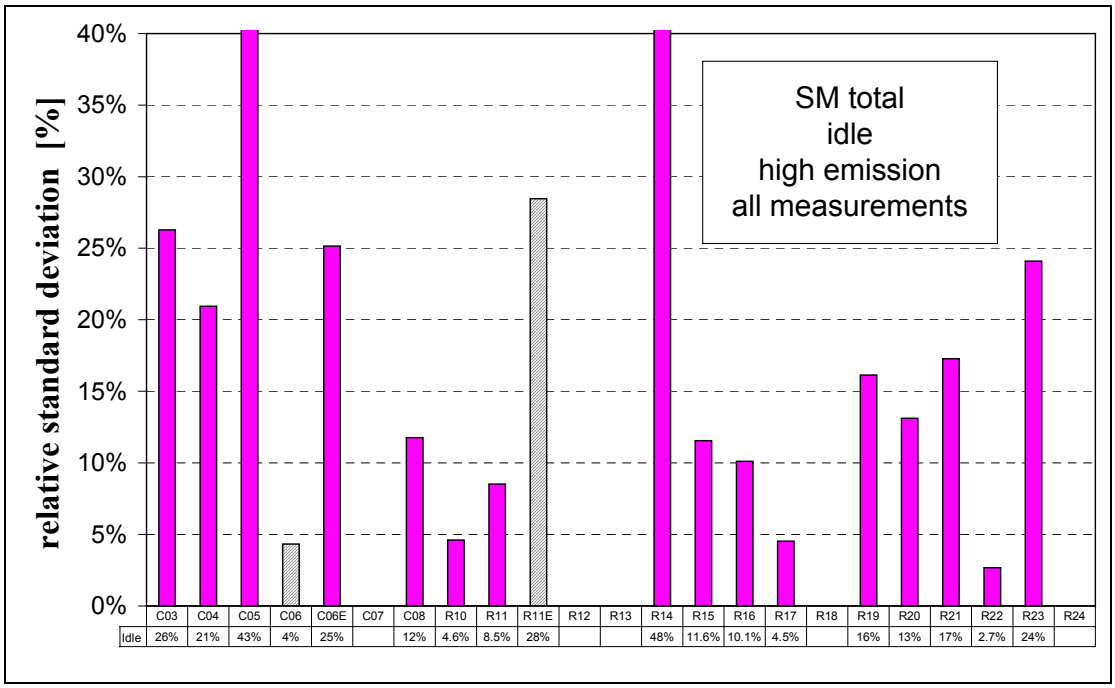


Figure 11: *Relative standard deviation of all SM measurements for each instrument / SM (total) high-emission*

Only two measurements included due to outlier or absent data

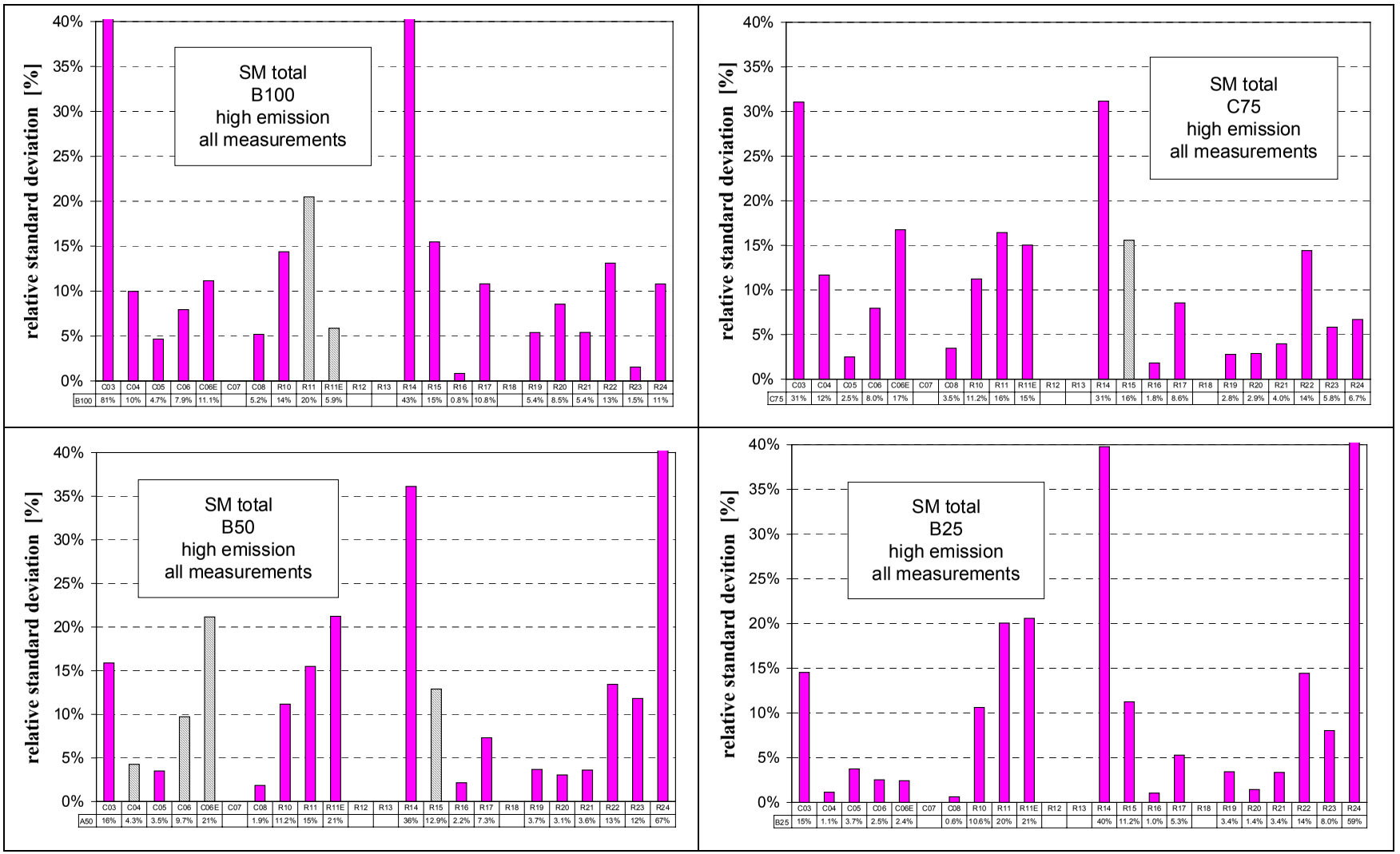
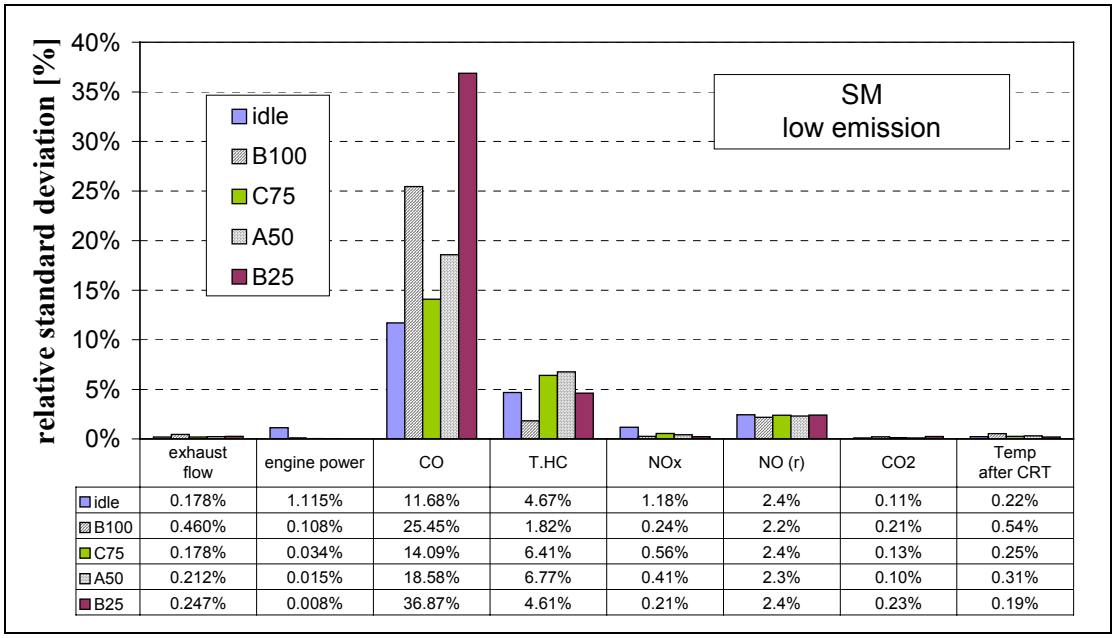


Figure 12: *Relative standard deviation of each instrument / SM high-emission*

9.1.2.4 Steady-State Tests (SM) / SM low-emission

In Figure 13 the repeatability of some engine parameters and gaseous components is shown for each single mode for the low-emission configuration.
In agreement with the ETC tests, CO and T.HC show increased relative standard deviations for the low-emission configuration, which is explained by the very low absolute values, as mentioned previously.



	exhaust flow	engine power	CO	T.HC	NOx	NO (r)	CO2	Temp after CRT
idle	0.178%	1.115%	11.68%	4.67%	1.18%	2.4%	0.11%	0.22%
B100	0.460%	0.108%	25.45%	1.82%	0.24%	2.2%	0.21%	0.54%
C75	0.178%	0.034%	14.09%	6.41%	0.56%	2.4%	0.13%	0.25%
A50	0.212%	0.015%	18.58%	6.77%	0.41%	2.3%	0.10%	0.31%
B25	0.247%	0.008%	36.87%	4.61%	0.21%	2.4%	0.23%	0.19%

Figure 13: *Relative standard deviation of the engine parameters / gaseous emissions for each step in the SM test / SM low-emission*

Figure 14 shows deviation of the three individual measurements from the mean value for the exhaust flow and by way of example for the PASS (C08). Although the variation in the exhaust flow is fairly small, a similar time course at a much higher variation level is also observed for the particle concentration even if expressed in [x/Ncm^3]. This clear correlation was observed for all instruments in the case of B100.

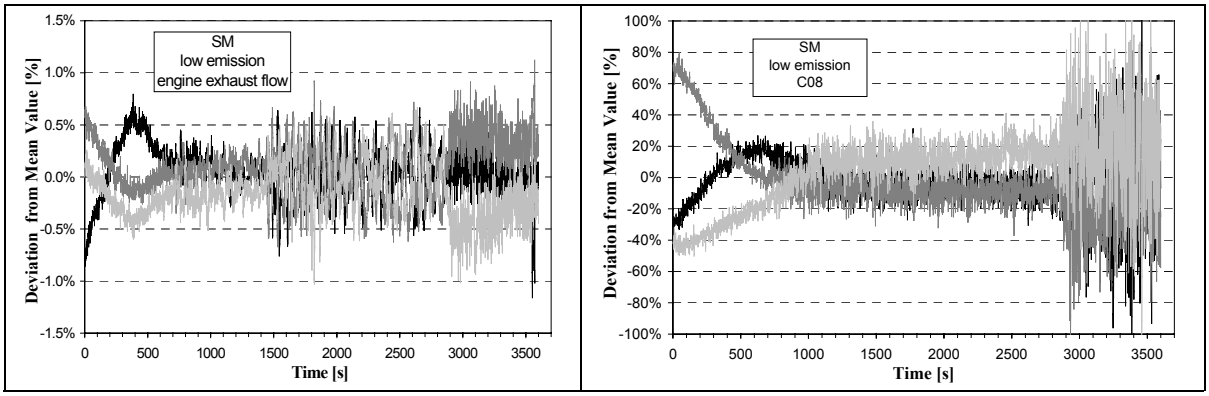


Figure 14: *Time-resolved deviation of the individual measurements from mean value during the SM low-emission. Comparison between exhaust flow and PASS (C08) as an example.*

Figure 15 shows the relative standard deviations of each instrument in the SM test with the low-emission configuration. Detailed analysis of the time-resolved result show that at least in the B100 mode the variation is significantly superimposed by the engine variation.

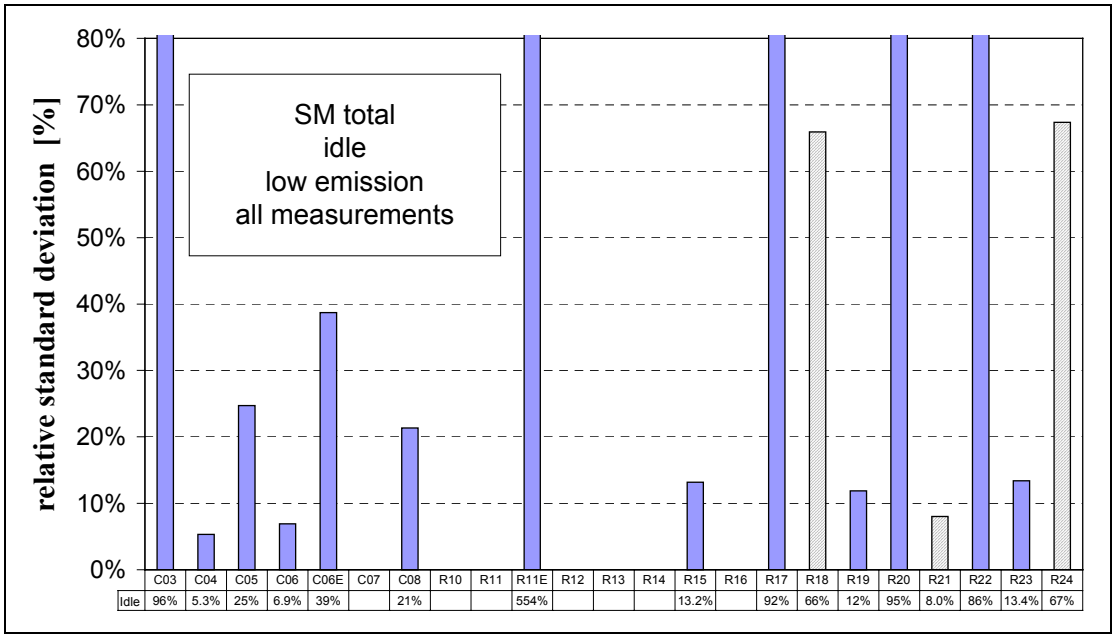


Figure 15: *Relative standard deviation of all SM measurements for each instrument / SM (total) low-emission*

Note:

At least one outlier - was not taken into account for calculation

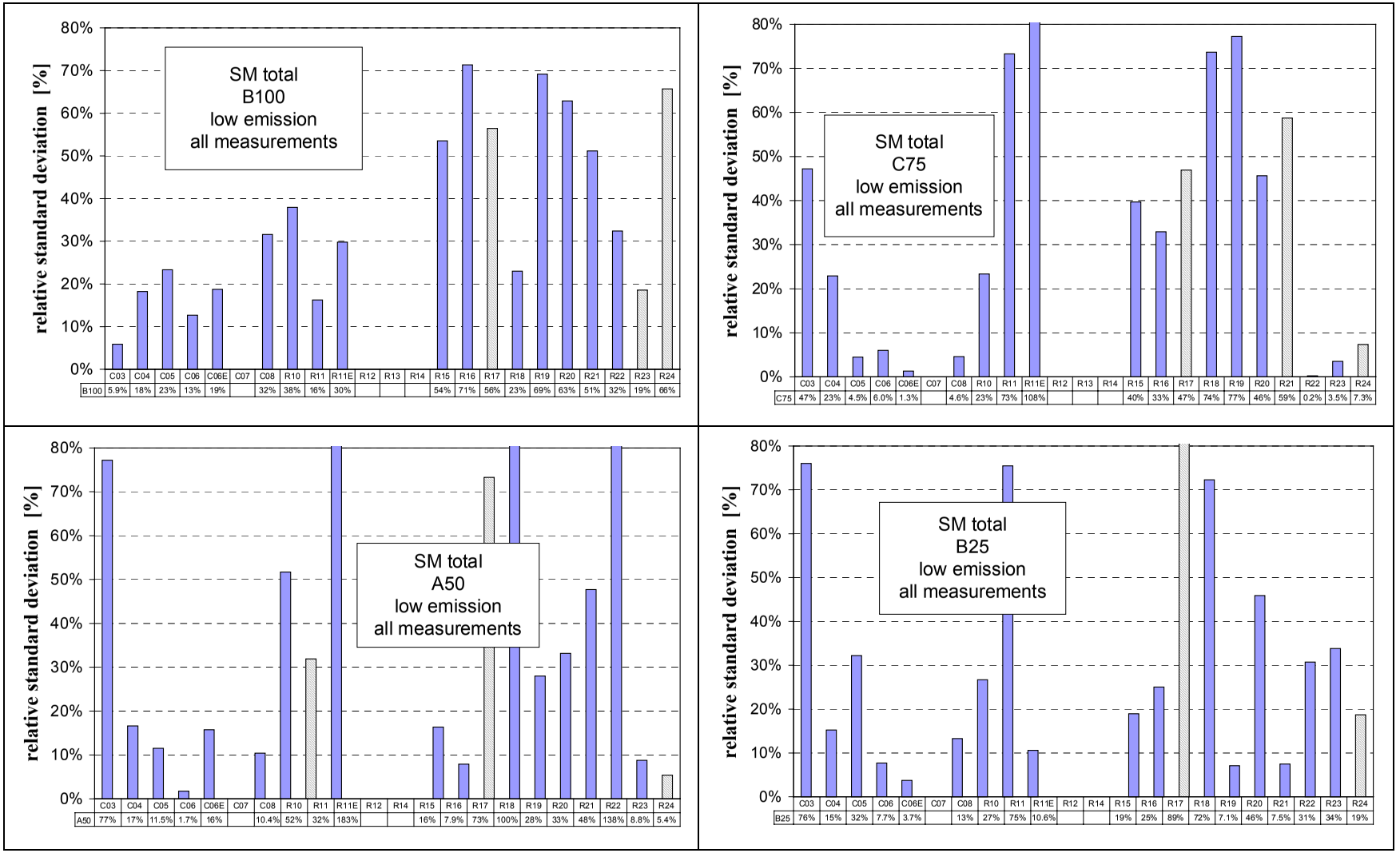


Figure 16: *Relative standard deviation of each instrument / SM low-emission*

9.1.3 Background measurements

9.1.3.1 Noise and repeatability

Background measurements in the exhaust line system were carried out at the beginning of each day with engine tests. The pump of the CVS system was running, but the engine was switched off. As it was the first measurement of the day, the complete exhaust and dilution system was at ambient temperature. The set-up for the instruments was exactly the same as for the engine tests. Note that the background concentrations were *not* subtracted from the test cycle results according to the PMP methodology protocol.

Two different variations were considered for the analysis of the background tests: the *noise* describes the variation of the second-by-second values during a test run, whereas the COV describes the test-to-test variability. For the instruments that are able to provide time-resolved data, both characteristic values were determined from the background measurements.

Figure 17 shows the noise/mean ratio within the 30 min test run. The values were averaged from the eight engine background measurements. Obviously the ratio cannot be determined for the filter sampling methods (C04, C06, C06E, R11, R11E). For most of the instruments the noise is greater than the measured value. The exceptionally high ratio for EAD (R20) can be explained by a zero-point drift problem of the instrument. This problem was observed during the whole measurement programme. The low ratio of LI2SA might also be caused by the lack of sensitivity at this low concentration. In some cases lack of sensitivity was observed during the CAST measurements.

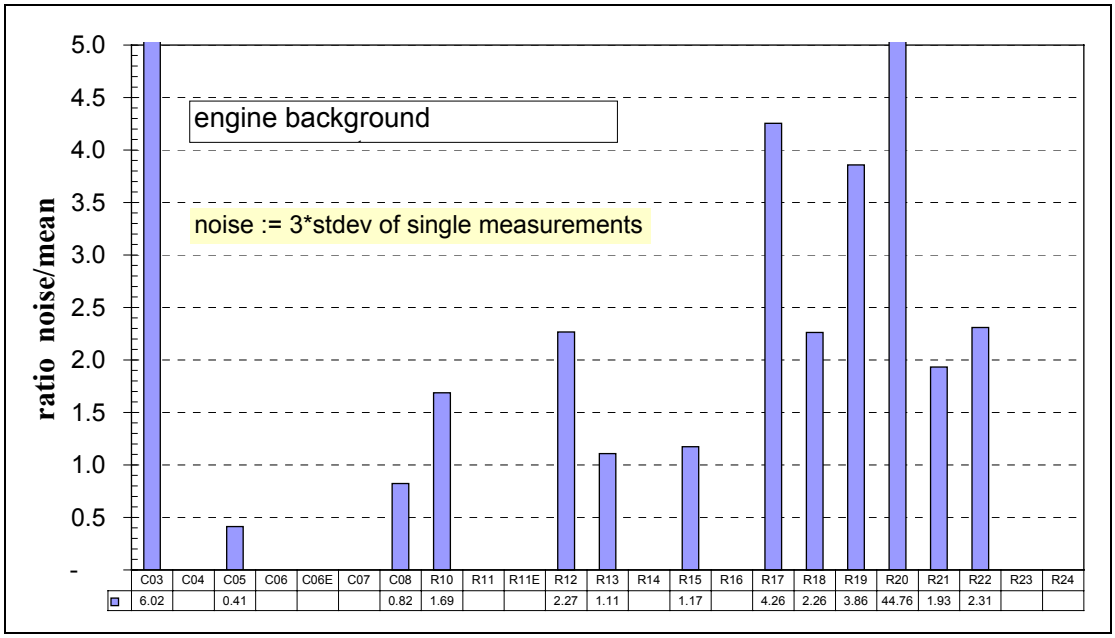


Figure 17: *Noise-to-mean ratio for the background measurements at the engine test bench*

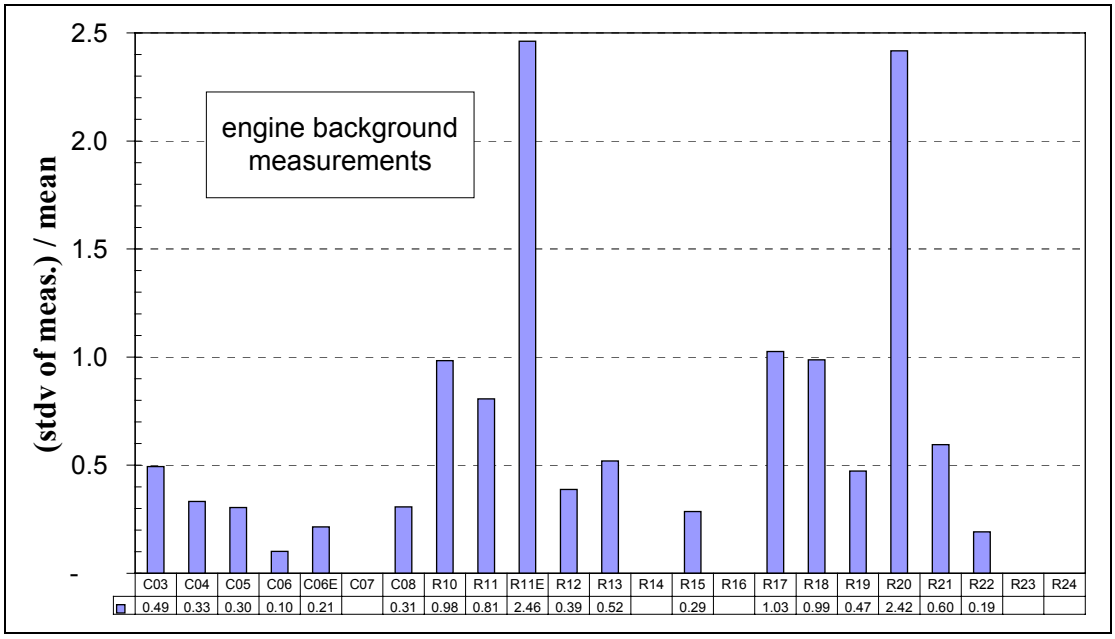


Figure 18: *Relative standard deviation of the background measurement.*
DMA of R21 was fixed to select 80 nm particles
R12, R13: only 2 measurements

Figure 18 shows the relative standard deviation of the background concentration as measured by the instruments during the seven background tests. Each test was carried out on a different day. For most instruments, the standard deviation for the background measurements were found to be higher than for the ETC low-emission measurements. For this reason we conclude that the variation is dominated by the aerosol and not by the measurement uncertainty of the measurement systems. The wide difference between the instruments may be related to the different properties of the particles that are measured. It cannot be taken for granted that all particle properties vary to the same extent for the different tests. Coulometry (R11) and EAD (R20) show exceptionally high uncertainties. For the EAD (R20), it is assumed that the zero drift causes the problem, whereas no explanation could be found for the wide scattering of coulometry (R11).

9.1.3.2 Ratio of ETC emission levels to background levels

The comparison between the concentrations measured during the ETC (high and low-emissions) and the background tests makes the emission levels of the different tests and configurations clearer. The data shown in the diagrams in this section are based on the *effective concentrations measured by the instruments* (Figure 19 to Figure 21).
Figure 19 and Figure 20 show the ratio of the concentration for ETC and background tests for the high and the low-emission levels respectively. The majority of the instruments measured approximately the same concentration for the background test and the ETC in the low-emission configuration (Figure 19). The high ratio for DMS (C03) is probably caused by nucleation during the ETC. The high ratio for PM-300 (R18) could not be fully explained, but indicate clearly different measurement performance depending on transient or steady-state cycle. This finding is supported by the steady-state test results. No explanation can be given for the low ratios determined for coulometry (R11) and MasMo (R10).

The situation is completely different for the high-emission configuration (partial flow through the bypass, Figure 20). A wide difference is observed between the instruments. Mass-based instruments show a significantly lower ratio than those that are based on number, length or surface area.

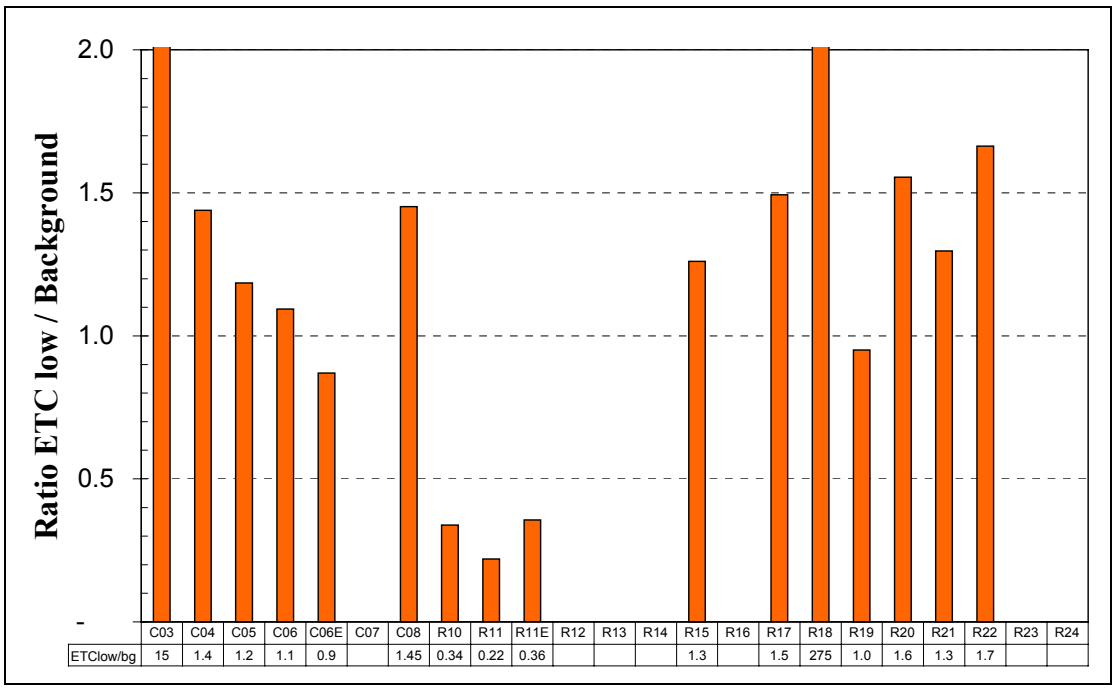


Figure 19: *Ratio of measured raw concentrations for ETC low-emission and engine background tests, R21 total size range*

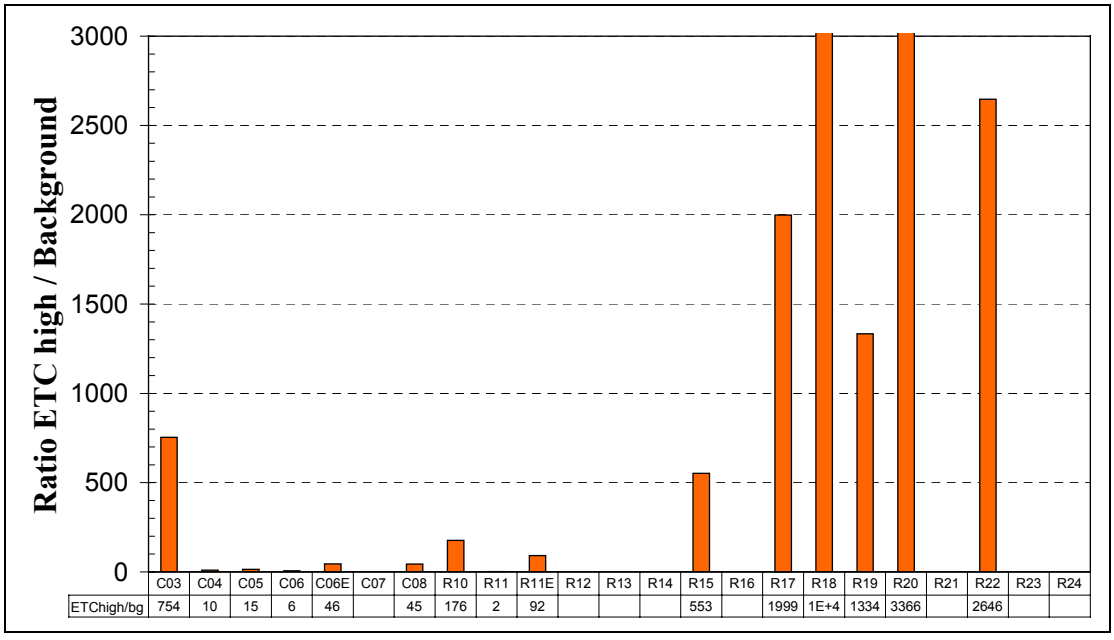


Figure 20: *Ratio of measured raw concentrations for ETC high-emission and engine background tests*

An exception is PAS (R17), which is calibrated for mass but applies the principle of particle charge measurement in a similar way to EAD (R20), ELPI (R22) and LQ1-DC (R15). However, the charging efficiency for PAS depends heavily on the surface composition. The high value of the ratio might therefore also be caused by different composition of the particles.
The exceptionally high ratio of PM-300 (R18) reveals the inconsistency in the results for the different test cycles.
The SMPS (R21) was operated using different settings for the ETC and background measurements. For the background measurements, the SMPS was in the scanning mode, while during the ETC cycles the counter of the SMPS measured only the 80 nm particles or the total number of particles depending on the concentration level. Therefore the ratio between ETC high and background cannot be compared with the other instruments and is not included in the Figure 20.

9.1.4 Limit of detection (LOD)

The results represent the situation for this specific set-up and configuration of the exhaust gas system and particle measurement instruments and not a general specification. In this study, the Limit of Detection (LOD) is determined by taking 3 times the standard deviation of the ETC low-emission measurements (Table 9). We decided to calculate the LOD from the ETC low-emission tests and not from the engine background tests, as the repeatability was better for the ETC tests. Moreover, the test conditions for the ETC were defined better and closer to the engine exhaust measurements than for the engine background tests. For the latter, temperature and flow rates are significantly different than the real engine measurements. This approach is in line with the regulations and the PMP methodology protocol that the background concentrations are *not* subtracted from the test cycle results.
For the comparison of the LOD of the systems, it has to be borne in mind that one group was connected to the raw exhaust line and the other to the CVS tunnel.

			3*stdv ETC low
DMS	C03	[1/Ncm3]	1.62E+06
Gravimetry	C04	[ng/Ncm3]	0.189
LI2SA	C05	[ng/Ncm3]	3.70E-02
MEXA 1370PM	C06	[ng/Ncm3]	6.05E-02
	C06E	[ng/Ncm3]	4.19E-03
TEOM	C07		-
PASS	C08	[ng/Ncm3]	2.94E-02
MasMo	R10	[ng/Ncm3]	3.59E-03
Coulometry	R11	[ng/Ncm3]	0.357
	R11E	[ng/Ncm3]	0.139
DustMonitor	R12	[1/Ncm3]	-
SMPS+C/UPC	R13	[1/Ncm3]	-
DPSO-1	R14	[ng/Ncm3]	-
LQ1-DC	R15	[µm2/Ncm3]	97.023
EDB	R16	[1/Ncm3]	1.67E+04
PAS	R17	[ngEC/Ncm3]	1.97E-03
PM-300	R18	[1/Ncm3]	8.96E+04
CPC 3022A	R19	[1/Ncm3]	4.04E+03
EAD 3070A	R20	[mm/Ncm3]	0.181
SMPS 3936-L10	R21	[1/Ncm3]	4.02E+03
ELPI	R22	[1/Ncm3]	5.34E+03
DQL	R23	[cm3/Ncm3]	9.51E-11
Opacitymeter	R24	[ng/Ncm3]	1.219

Table 9: *Absolute values of LOD*

The ratio between the concentration measured during the ETC test cycle for the high-emission level and the LOD also gives an indication of how closely the instruments measure at their LOD for this typical emission level (Figure 21).
For most of the instruments based on number, length and surface, the concentration is higher by more than a factor of 400 compared to the LOD (=3 x stdv ETC low). In contrast, most mass-based instruments show a significantly lower ratio. There are some instruments that do not fit into this picture. The very high LOD of the DMS (C03) is caused by strong nucleation effects during the ETC low-emission measurements. The MasMo measured a comparatively low absolute mass concentration for the ETC low-emission measurements, resulting in a low LOD. In the case of SMPS (R21) the relatively low ratio is explained by the different operating mode of the instrument (bandpass mode, DMA fixed to 80 nm), which results in lower concentration than the total number measurement.

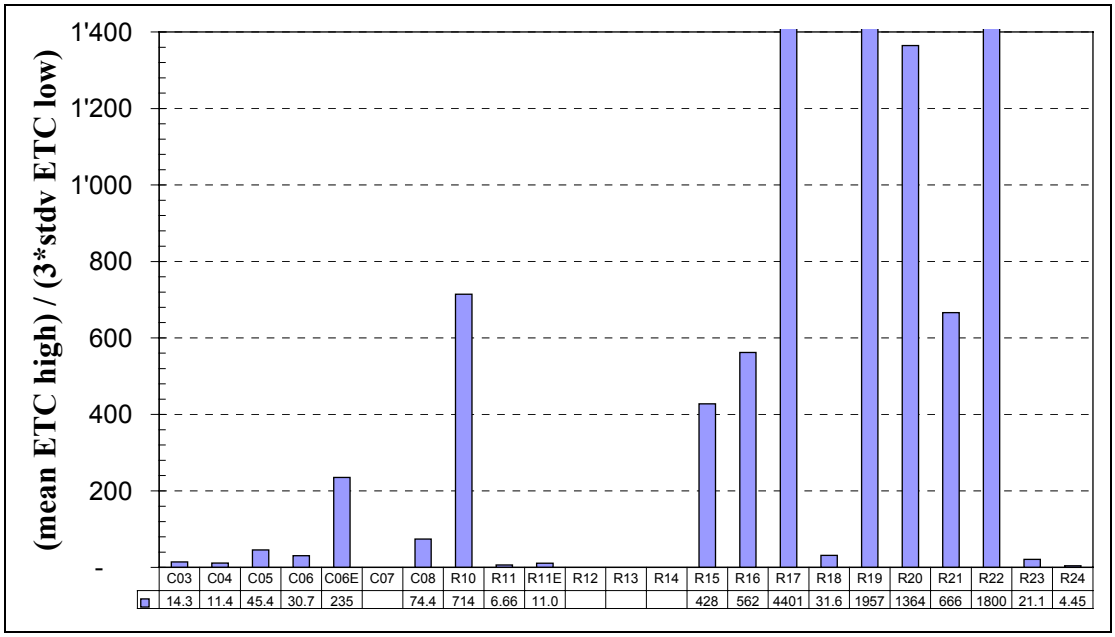


Figure 21: *Ratio of measured raw concentrations for ETC high-emission and the LOD. R21: DMA fixed to 80 nm for ETC high-emission*

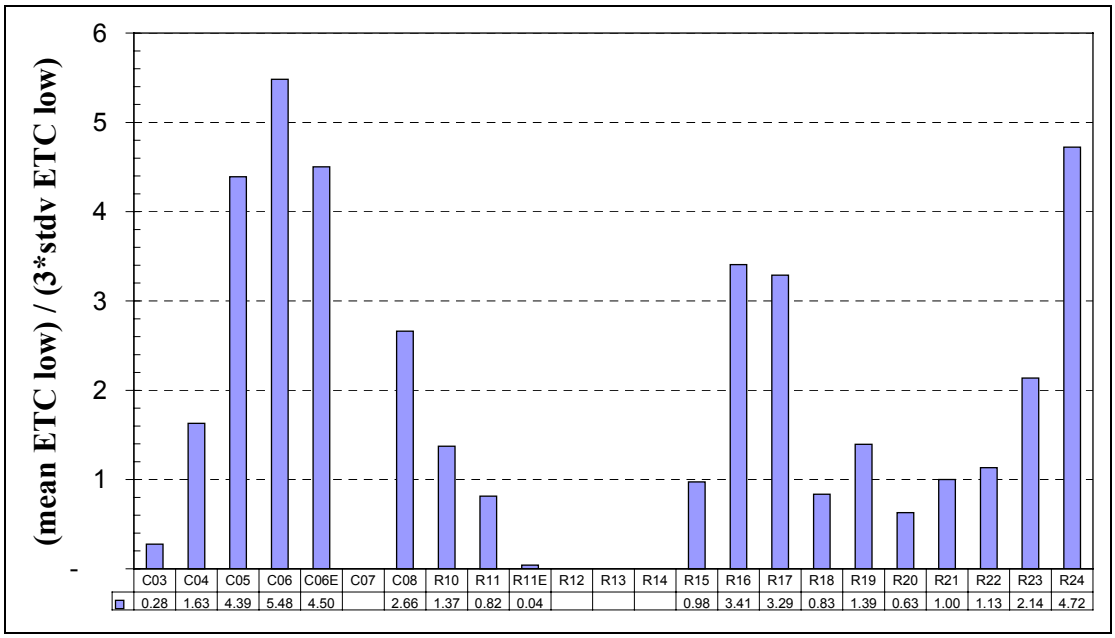
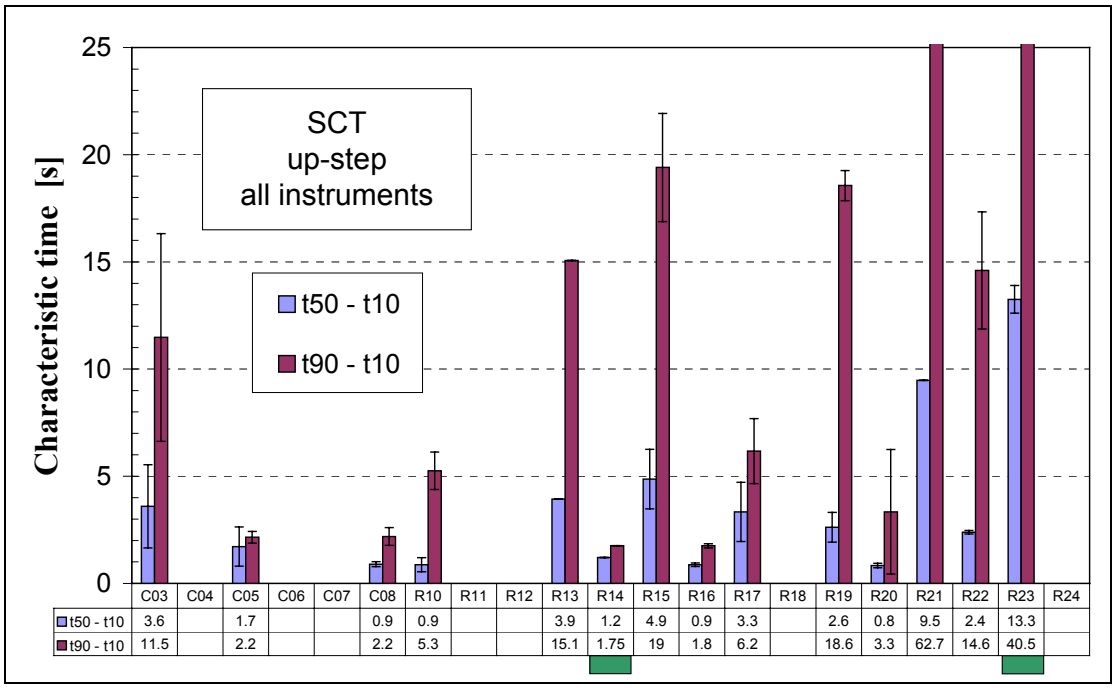


Figure 22: *Ratio of measured raw concentrations for ETC low-emission and the LOD.*

9.1.5 Response Time

9.1.5.1 Characteristic response times

A so-called «step change test (SCT)» was used to determine characteristic response times for the instruments on a typical test bench set-up as applied. The test consists of abrupt changes every three minutes between two loads at constant speed. Details are described in section 8.4. It is obvious that the response is affected not only by the instruments but also by the engine and the dimensions of exhaust and sampling lines. The data evaluation is merely based on one-second resolved data of the total emissions (i.e. expressed in [x/s]) in order to improve the comparability between the instruments connected to the CVS tunnel and raw exhaust line.
During the measurements it was observed that the particle emissions were not completely stable during the three-minute constant load steps. For this reason, the determination of a settling time as described in Figure 4 was omitted.
SCT runs were carried out for the high and low-emission configurations. However, at the low-emission level almost no instrument showed a response that could be clearly related to the particle emissions. The analysis was therefore limited to the high-emission configuration.
Figure 23 and Figure 24 show the characteristic response times for the increase and decrease in particle concentration respectively. The values represent the average of 15 step changes.

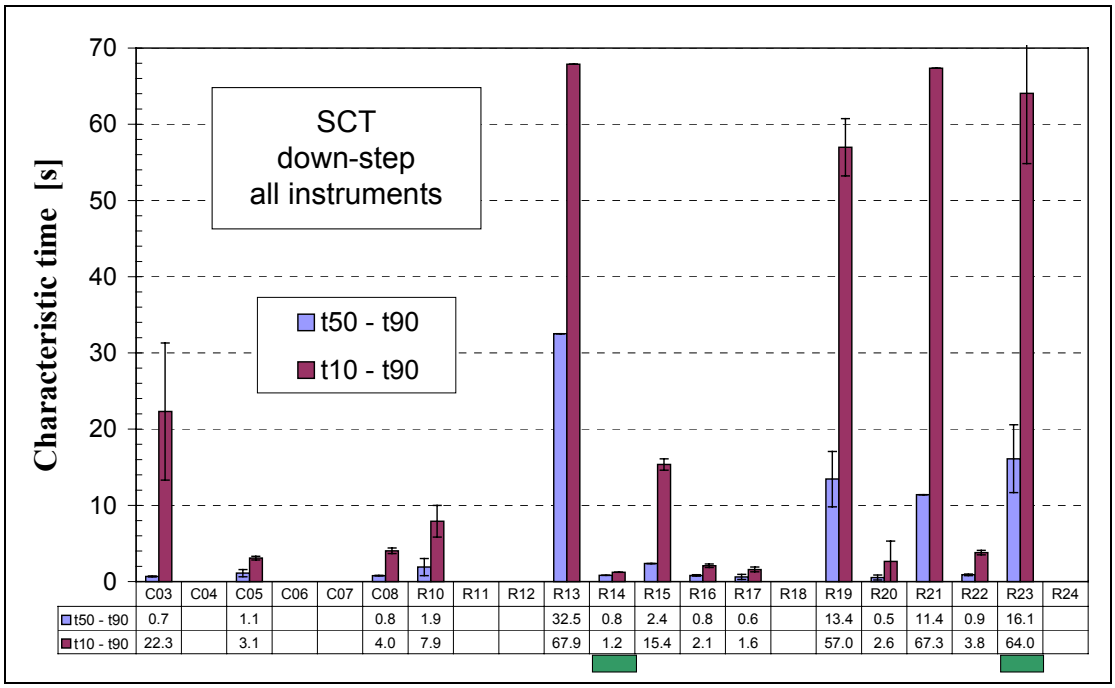


	C03	C04	C05	C06	C07	C08	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24
t50 - t10	3.6		1.7			0.9	0.9			3.9	1.2	4.9	0.9	3.3		2.6	0.8	9.5	2.4	13.3	
t90 - t10	11.5		2.2			2.2	5.3			15.1	1.75	19	1.8	6.2		18.6	3.3	62.7	14.6	40.5	

Figure 23: *Characteristic times in the SCT cycle regarding the up-step / average over all steps, R21 fixed to 80 nm, data for R14 and R23 are based on raw data (marked)*

The instruments DPSO-1 (R14) and DQL (R23) measured such a low response compared to the absolute concentration that this results in a phase-opposite response when the concentrations are converted to emissions expressed by [#/s]. For these two instruments, the characteristic times were calculated on the basis of the raw data (in units [#/Ncm3]).

The instruments DustMonitor (R12), PM-300 (R18) and the AVL opacimeter (R24) showed an opposite-phase response for the raw concentrations compared to the other instruments and the definition in Figure 4. These instruments were not considered in the data evaluation.
The instruments show wide differences regarding the characteristic times. For t50-t10, the response varies between about 1 s and 10 s and for t90 – t10 between about 2 s and 1 min. The wide differences could be caused by the different particle properties that are measured by the instruments. It is obvious that the emission of carbonaceous material becomes stable more quickly than volatile material, which is affected far more by the non-stable temperature profile in the exhaust line, for example.
The DMA upstream of the CPC3010 (R21) was set to select 80 nm particles. Taking this into account, the very long response time of scanning SMPS in the DMA-bandpass mode (R21) can be explained by the comparatively low flow rates and the additional transport volume through the long DMA and the interconnecting SMPS hardware.



	C03	C04	C05	C06	C07	C08	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24
t50 - t90	0.7		1.1			0.8	1.9			32.5	0.8	2.4	0.8	0.6		13.4	0.5	11.4	0.9	16.1	
t10 - t90	22.3		3.1			4.0	7.9			67.9	1.2	15.4	2.1	1.6		57.0	2.6	67.3	3.8	64.0	

Figure 24: *Characteristic times in the SCT cycle regarding the down-step /average over all steps, R21 fixed to 80 nm, data for R14 and R23 is based on raw data (marked)*

Time-resolved results are shown in the appendix.

9.1.6 Time-resolved results

Time-resolved particle concentrations (on a second-by-second basis) are presented for the investigated systems in this section.

9.1.6.1 Time-resolved data / SCT cycle

The time-resolved data of the SCT cycle are shown in the appendix.

9.1.6.2 Time-resolved data / ETC cycle

The time-resolved data of the ETC cycle are plotted for a selected sequence (three minutes) of one of the seven measurements at high-emission level.
Figure 25 to Figure 28 show the data for the number, mass, length/surface and opacity-related instruments. The purpose of the graphs is to give a qualitative impression of the time response of the individual instruments more than detailed analysis. With the exception of DPSO-1 (R14) and DQL (R23), all the instruments show a clear correlation to the engine power. However, it cannot be concluded that the correlation is always based on the particle emission, as it could also be related to the NO_X emission. It is notable that CPC3022A (R19) and scanning SMPS in the DMA-bandpass mode (R21) measured a relatively high concentration during the idle phase.

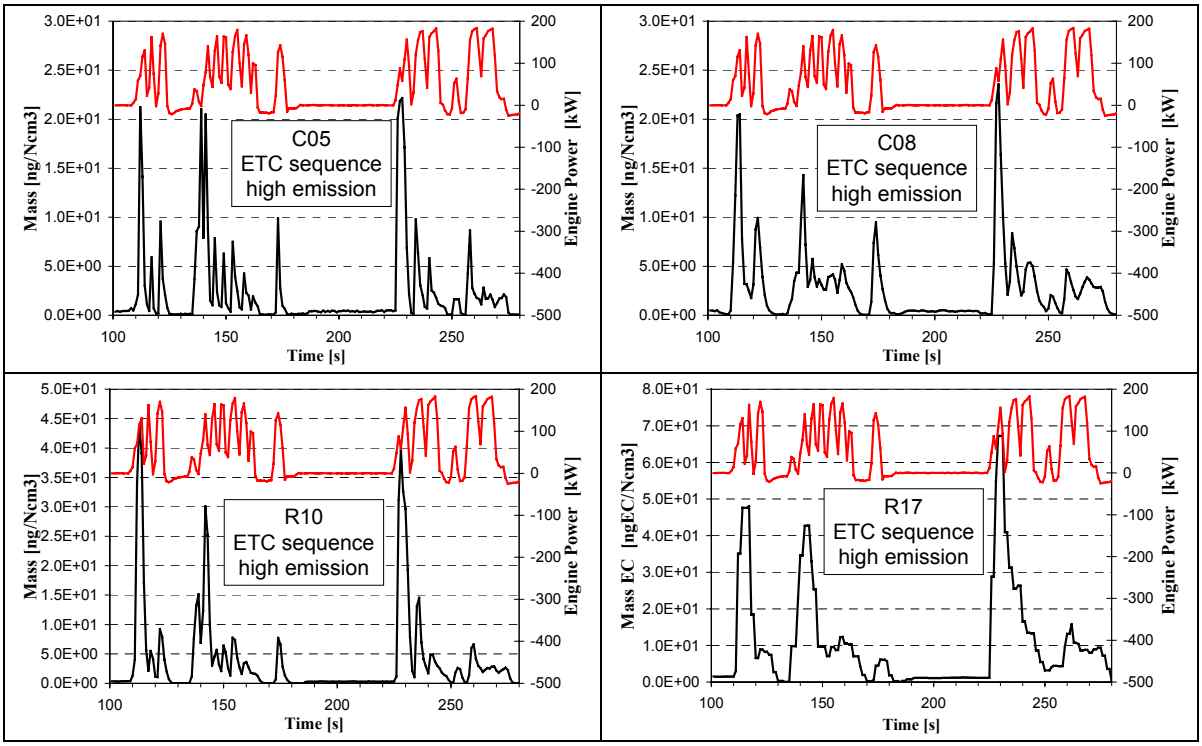


Figure 25: *Time-resolved sequence of the ETC cycle / ETC high-emission / Mass*

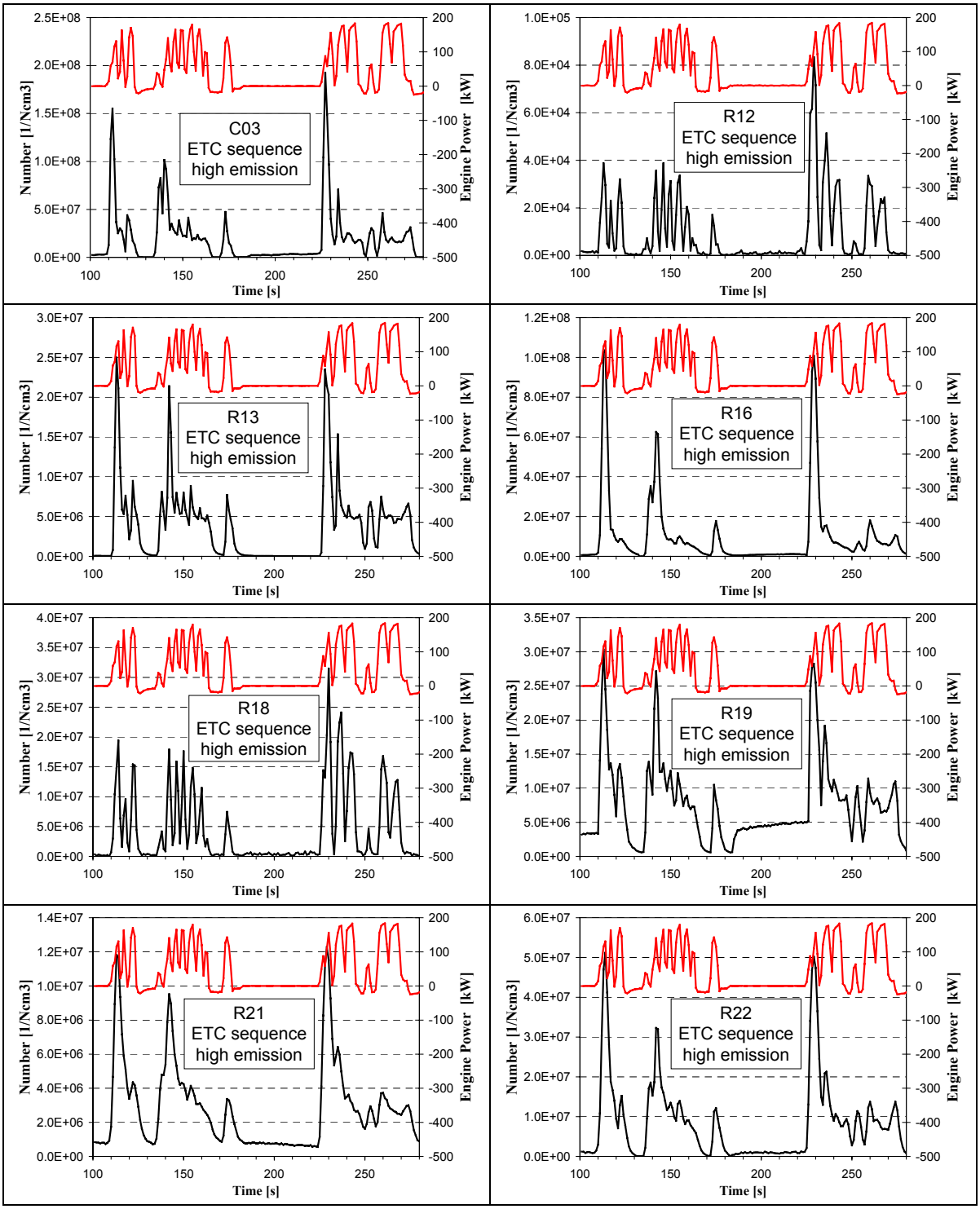


Figure 26: *Time-resolved sequence of the ETC cycle / ETC high-emission / Number*

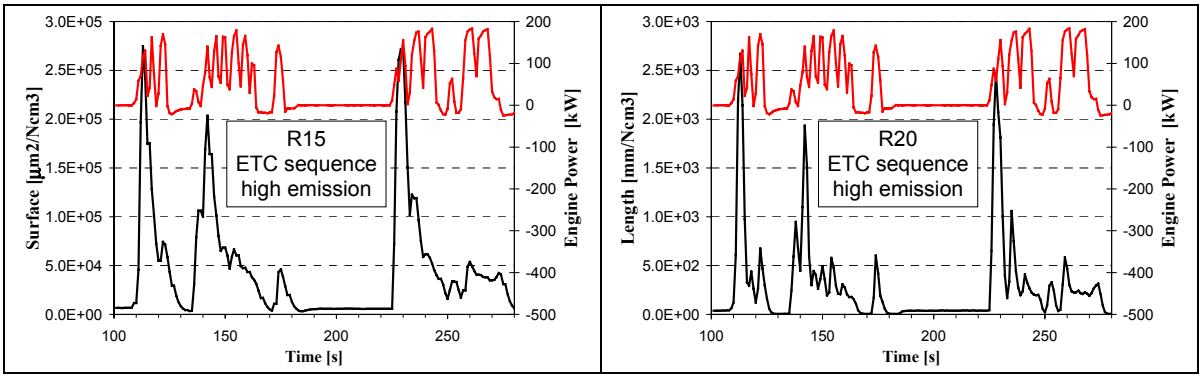


Figure 27: *Time-resolved sequence of the ETC cycle / ETC high-emission / Surface*

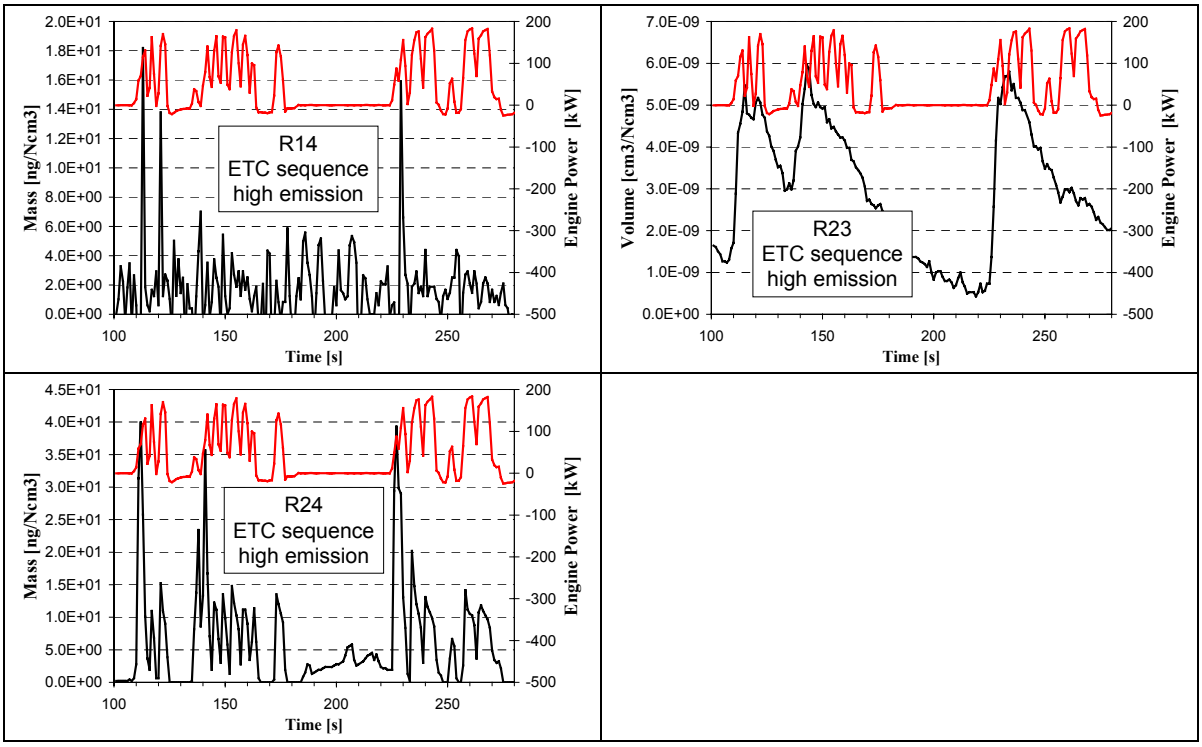


Figure 28: *Time-resolved sequence of the ETC cycle / ETC high-emission / Opacity*

9.1.7 Absolute values

In this section, the results of the absolute values are plotted for the different instruments. The purpose of the presented figures is *not* to assess the individual instruments by analysing the discrepancy between the absolute values. As the instruments for the most part are based on completely different measurement principles and measure different particle properties, the absolute values have to be different. The objective of the comparison is to analyse the plausibility of the results of an instrument in comparison with others. For example, an instrument that measures only elemental carbon should detect an equal or lower mass than an instrument that is calibrated for total mass.
For the figures, the measurement systems are divided into two groups according to the calibrated metrics: number and mass. The instruments LQ1-DC (R15), EAD 3070A (R20) and DQL (R23) are not calibrated for either of them but to length and active surface area respectively. In order to enable at least a rough comparison of these instruments to the others to be made, their results were converted to number values, using very simple assumptions for the particle properties. The conversion was calculated for spheres of a unified size of 60 nm in diameter. The results from ELPI are based on the aerodynamic diameter sizing and were not corrected for particle density. The total number were calculated without the filter stage fraction (d_{50} = 35 nm). It is evident that a quantitative analysis of the number results is *not* possible for these instruments.

9.1.7.1 European Transient Test (ETC)

9.1.7.1.1 High-emission

Figure 29 and Figure 30 show the absolute particle concentration for the ETC cycle in the high-emission configuration for the mass and number-based instruments respectively. For the number results, the values vary by about one order of magnitude. An exception is the DustMonitor (R12), which measures a three orders of magnitude lower concentration. This is probably explained by the insufficient sensitivity for small particles of this optical instrument. Looking only at the instruments measuring total particle number (C03, R13, R16, R19, R22) and excluding the DMS due to its completely different dilution concept, the difference between the instruments is reduced to less than a factor of two. The manufacturer of the PM-300 (R18) gives a lower size detection limit of 300 nm (see Appendix).
For the mass measurement instruments, the concentration varies by about a factor of five. By excluding the instruments PAS (R17) and the opacimeter (R24), the factor is reduced to 1.4 for the total mass instruments (C04, C06, R10, R11) and to 2.2 for the carbon-sensitive instruments (C05, C06E, C08, R11E).

Notes:

At least one outlier - was not taken into account for calculation

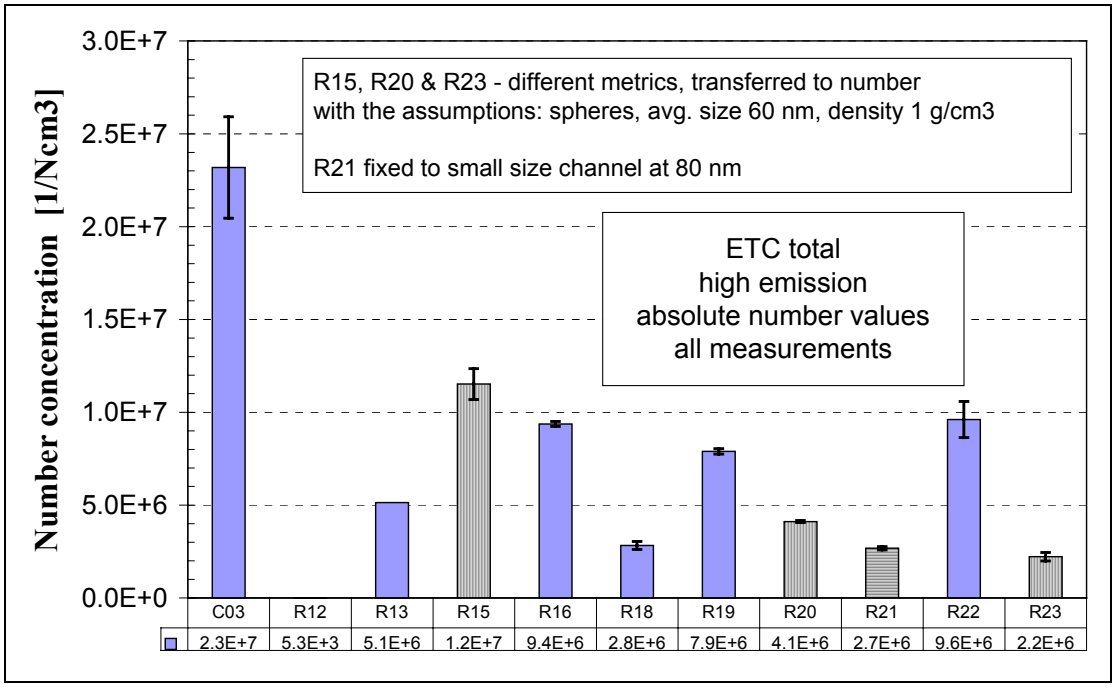


Figure 29: *Absolute value of total number concentration on ETC high-emission R21 fixed to 80 nm,R22 total number w/o filter stage*

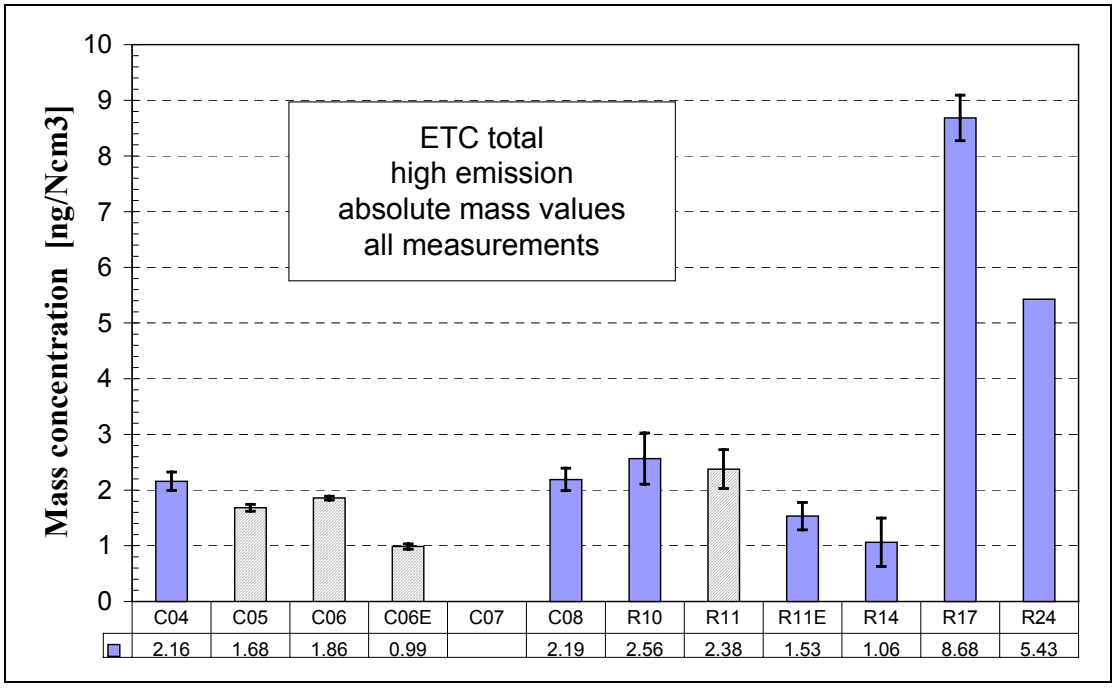


Figure 30: *Absolute value of total mass concentration on ETC high-emission*

9.1.7.1.2 Low-emission

In Figure 31 and Figure 32 the absolute values for number and mass are plotted for the low-emission configuration. The number concentrations vary by about two orders of magnitude. The large concentration measured by the DMS (C03) is probably caused by the large fraction of nucleates, as can be seen from the NSD shown in Figure 61. The sampling from the CVS tunnel without additional dilution as applied only to the DMS, raises the suspicion of stronger nucleation effects than for other measurement systems. The lowest concentrations are measured by the single counting measurement instruments, the CPC's (R19, R21). The mass detection instruments show a variation of more than one order of magnitude. The opacimeter (R24) is not taken into account for this comparison as the exceptional high concentration suggests strong NO_2 interference. The filter methods (C04, C06, C011) show good agreement within 10%. It is reasonable that the carbon sensitive methods (C05, C06E, C08, R11E) detect a lower concentration than the total mass instruments. This shows that the EC fraction is rather low downstream of the particle trap.
The low mass concentration measured by MasMo (R10) may be explained by the fact that the predominant volatile fraction is removed by the hot dilution procedure.

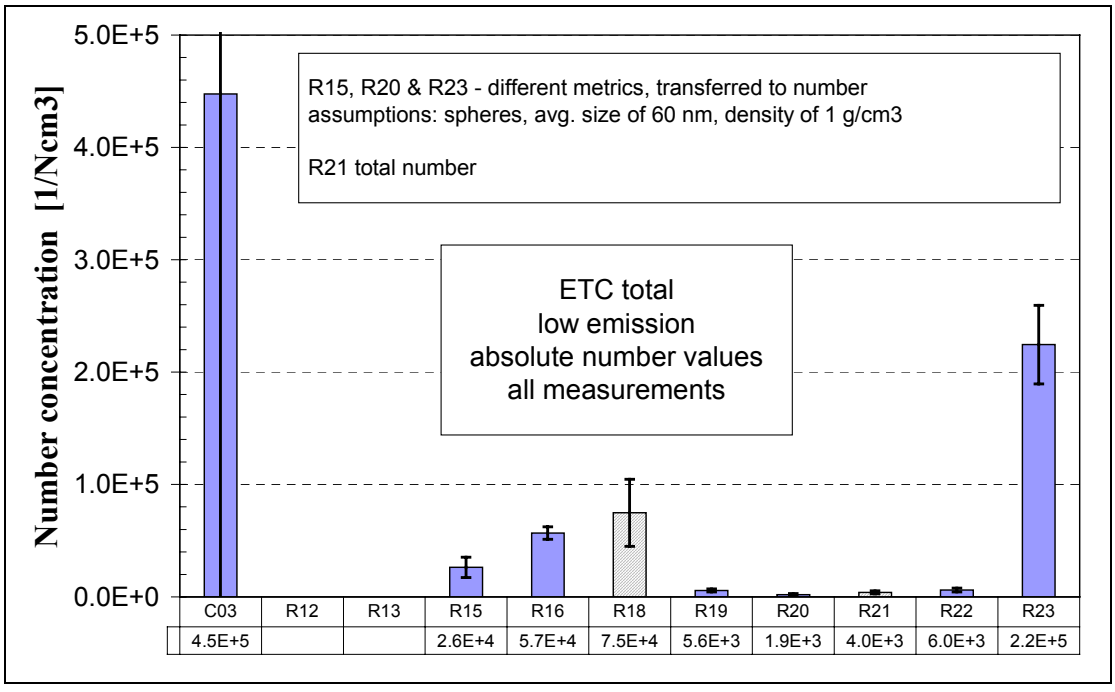


Figure 31: *Absolute value of total number concentration during ETC low-emission R21 fixed to 80 nm,R22 total number w/o filter stage*

Notes:

At least one outlier - was not taken into account for calculation

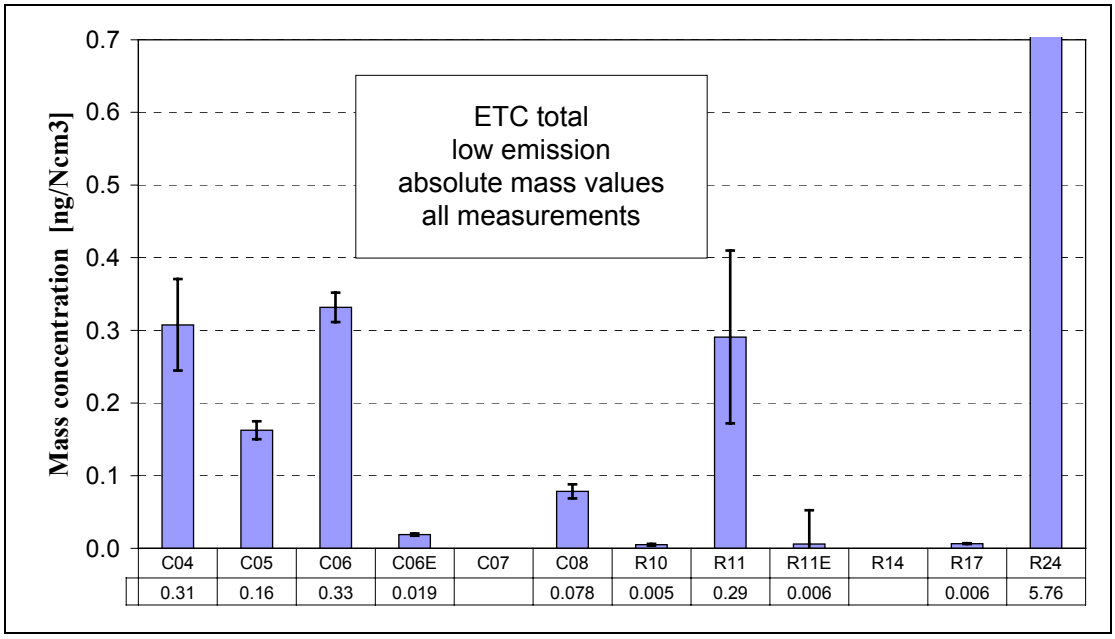


Figure 32: *Absolute value of total mass concentration on ETC low-emission*

9.1.7.1.3 Ratio of high to low-emission level

The ratio between the concentrations measured at the high and low-emission configuration gives a good indication of the sensitivity of the individual instruments. In the high-emission configuration, the exhaust flow was split into two branches, one past the trap, the other the bypass. For this reason, the comparison between the two configurations (high and low-emission) cannot be used to assess the trap efficiency.

In Figure 33, the ratios are plotted for the ETC. Large differences of about two orders of magnitude are observed between the mass-related and the number/length/surface-related instruments. The reason for this exceptionally large difference can be explained by the higher sensitivity of the instruments that are based on number, length or surface, as could already be seen from the ETC high/background ratios (Figure 20). The discrepancy in sensitivity between particle mass, determined by the filter method, and particle number had already been observed in earlier studies and has mainly been explained by collected condensed material on the filter for the post-filter sample. This explanation cannot be sufficient for the findings in this study as non-filter methods as well as methods sensitive only to EC show similarly low ratios.

Some instruments show different behaviour in comparison with the general observation, which can be explained in most cases. For DMS (C03), EDB (R16) and PM-300 (R18) significantly higher concentrations were observed for the low-emission configuration, resulting in a lower ratio. The MasMo (R10) shows a fairly high ratio compared to other mass instruments. The measurement method applied for MasMo is very similar to instruments C03, R15 and R20 and is based on electrical current measurements which are proportional to the Fuchs surface of the particles. Particle mass uses the density information which is also measured. On the basis of the measurement principle, the MasMo (R10) consequently belongs to the number/length/surface group. The ratio for DQL (R23) is similar to the mass-based

instrument, which can be explained by the fact that the principle of measurement is based on the metrics of volume.

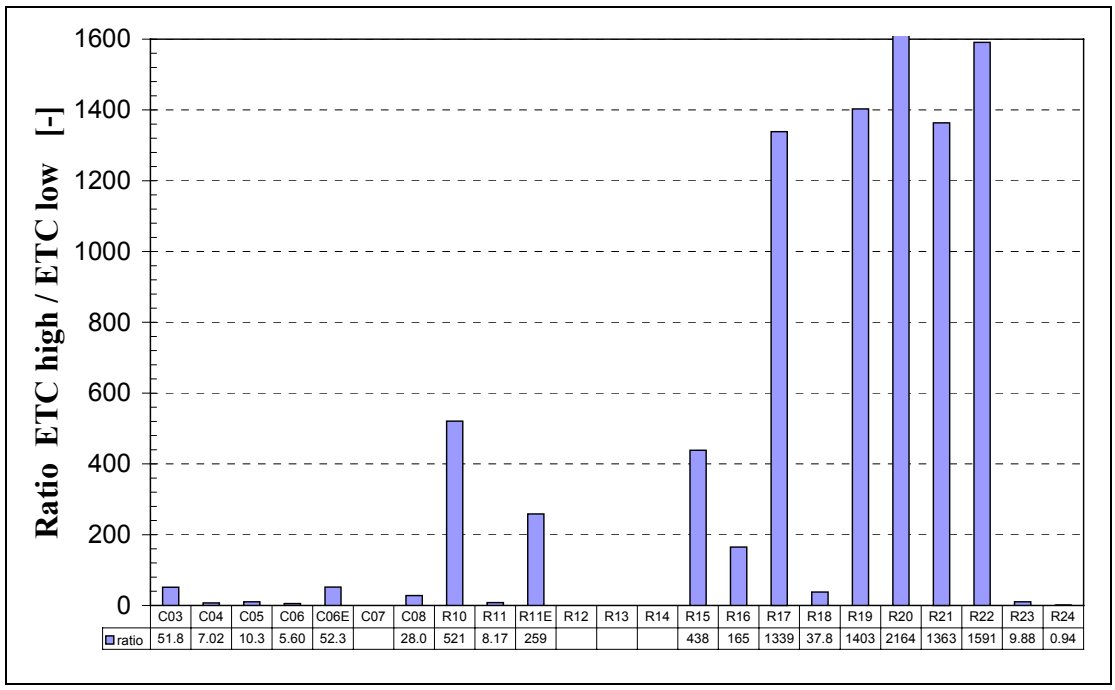


Figure 33: *Comparison between ETC high and ETC low-emission (R21: DMA fixed to 80 nm)*

Instrument	***Calibrated metrics***
C03, R16, R18, R19, R21, R22	particle number concentration [1/Ncm3]
C04, C05, C06, C06E, C08,R10, R11, R11E, R24	mass concentration [ng/Ncm3]
R15	surface concentration [µm2/Ncm3]
R17	EC-mass concentration [ngEC2/Ncm3]
R20	length concentration [mm/Ncm3]
R23	volume concentration [cm3/Ncm3]

9.1.7.2 European Steady-State Test (ESC)

9.1.7.2.1 High and low-emission

Figure 34 shows the absolute concentrations expressed in emission per output work [1/kWh] measured for the ESC at the high and low-emission levels.
In general, the figure of the absolute ETC values is quite similar to the figure of the absolute ESC values, for both emission levels. An exception is PM-300 (R18). Relative to other instruments, the concentration measured by R18 is two orders of magnitude lower in the ESC compared to the ETC, at both high and low-emission levels.
The high ratio for DMS (C03) is caused by a strong nucleation effect in the low-emission configuration.

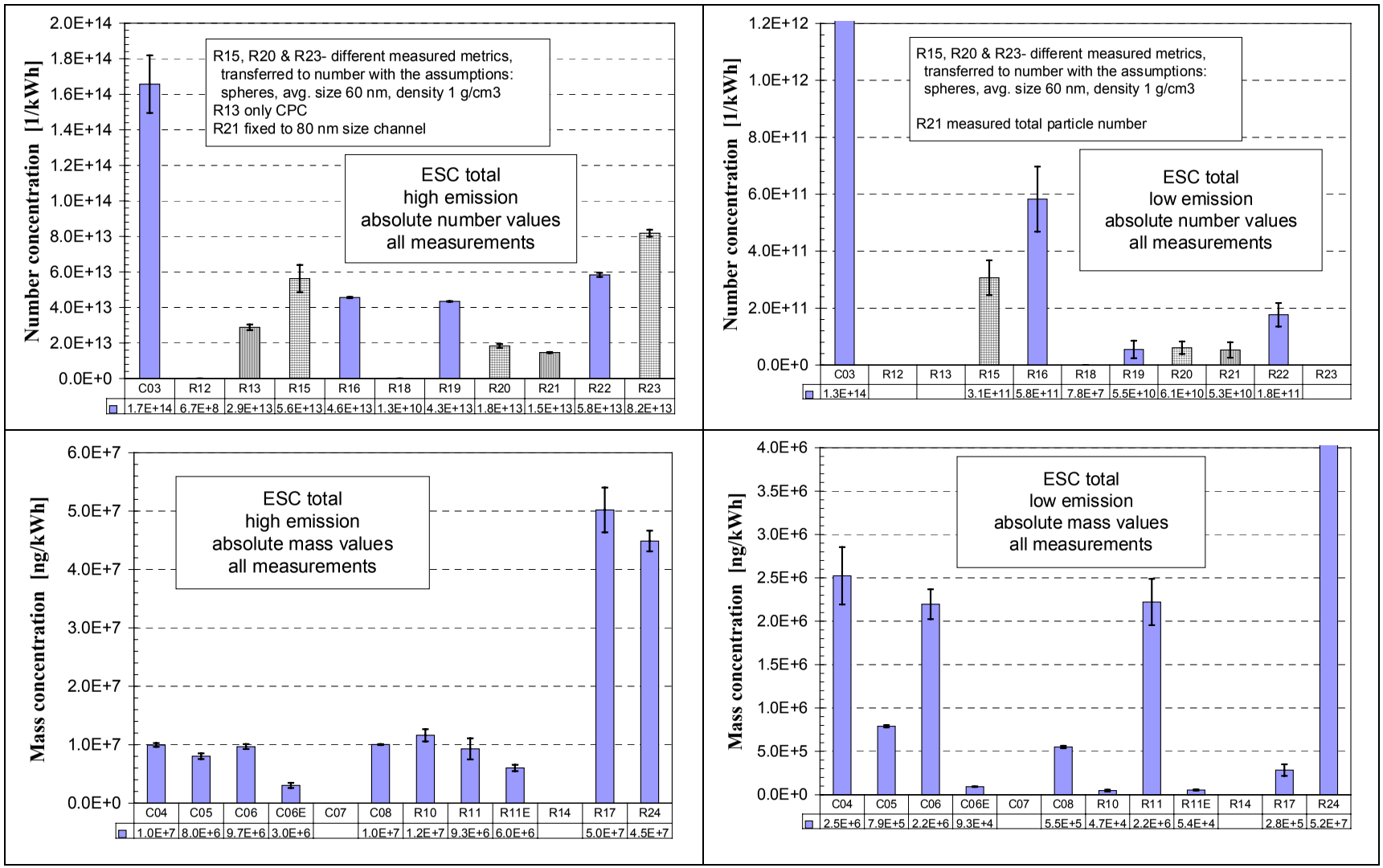


Figure 34: *Absolute number and mass results for ESC high and low-emissions / ESC high/low-emission*

9.1.7.2.2 Ratio of high to low-emission level

Figure 35 shows the ratios between the concentrations at ESC high and low-emission level. Compared to the ratio between the ETC cycles (Figure 33), the ratio for the number/length/surface related instruments is much lower, while the ratio of the mass-related instruments is not very different.

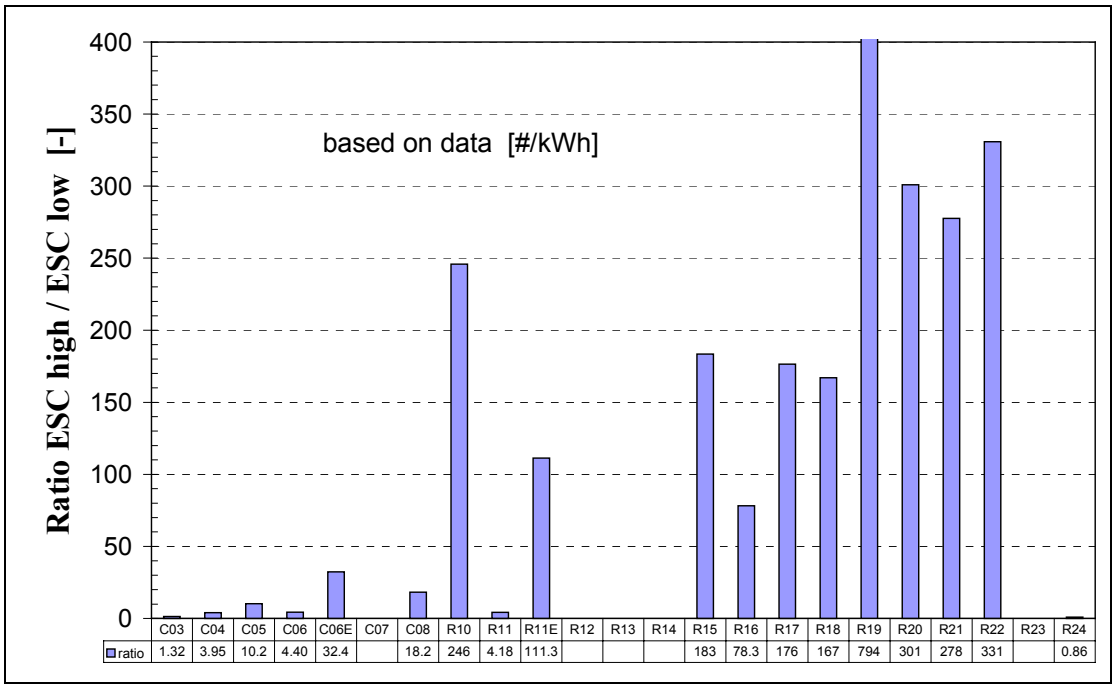


Figure 35: *Comparison between ESC high and ESC low-emission*

9.1.7.3 Steady-State Tests (SM)

9.1.7.3.1 High and low-emission

Figure 36 and Figure 37 show the results for the two selected single modes (C75 and B25) at the high and low-emission configurations respectively. The results for the other operating modes (idle, B100 and A50) can be found in the appendix. The concentrations are at a similar level to those for the ETC and ESC for almost all instruments. As for all steady-state tests, the concentrations measured by the PM-300 (R18) are exceptionally low compared to the ETC.
The total number concentrations of the R13 and R21 are calculated from the measured NSD (number size distribution) measurements.

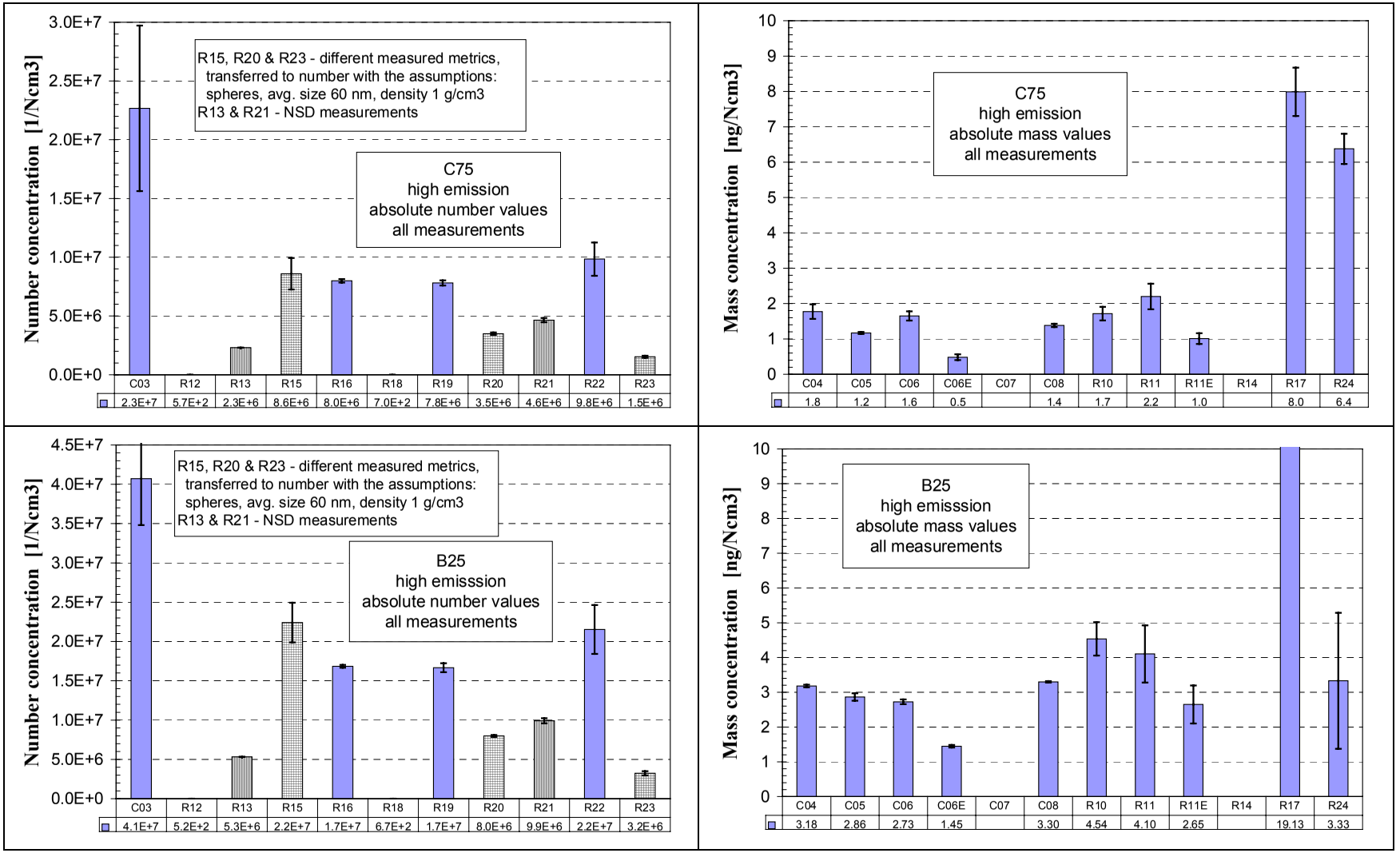


Figure 36: *Total number concentration / total mass concentration / SM high-emissions*

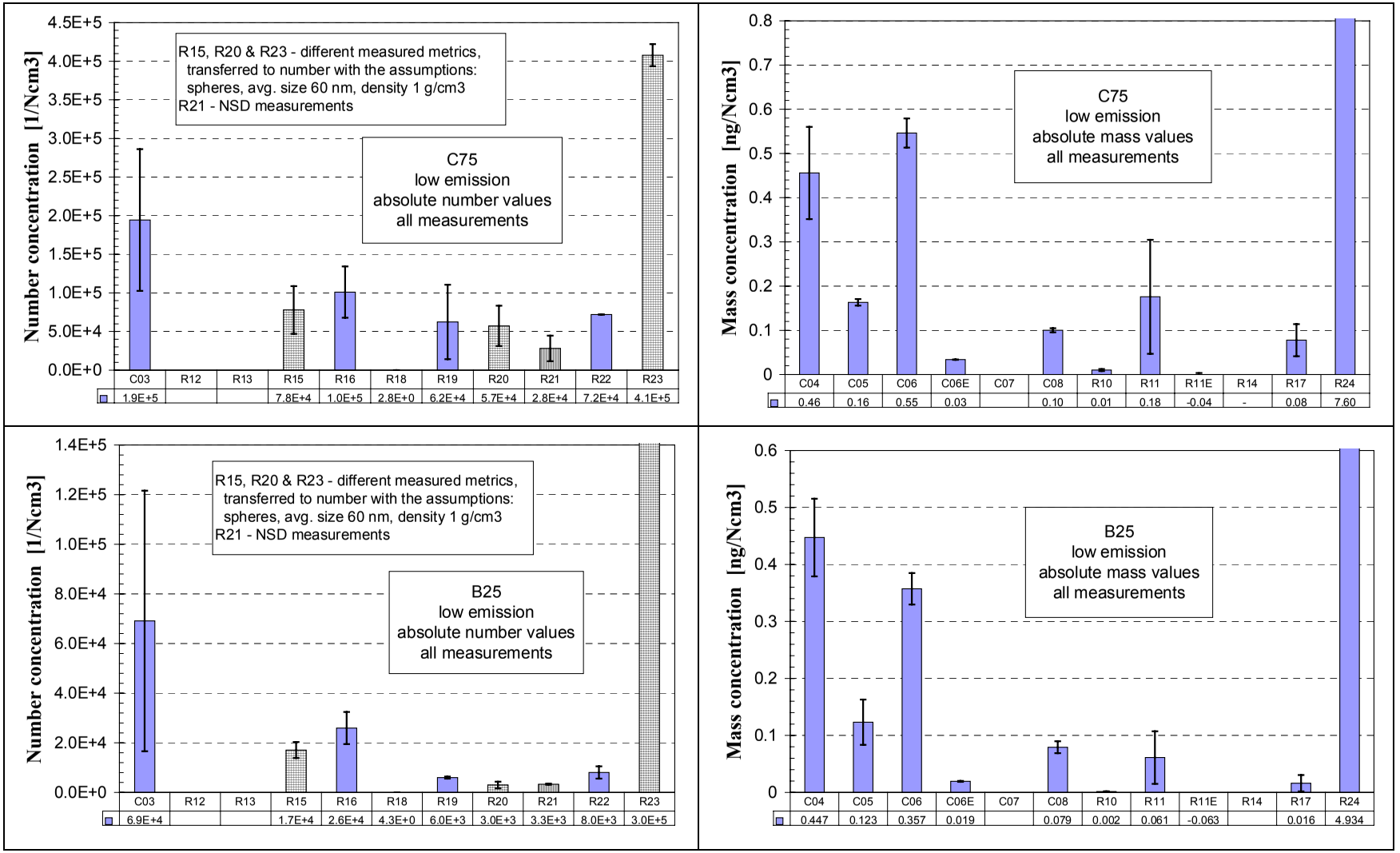
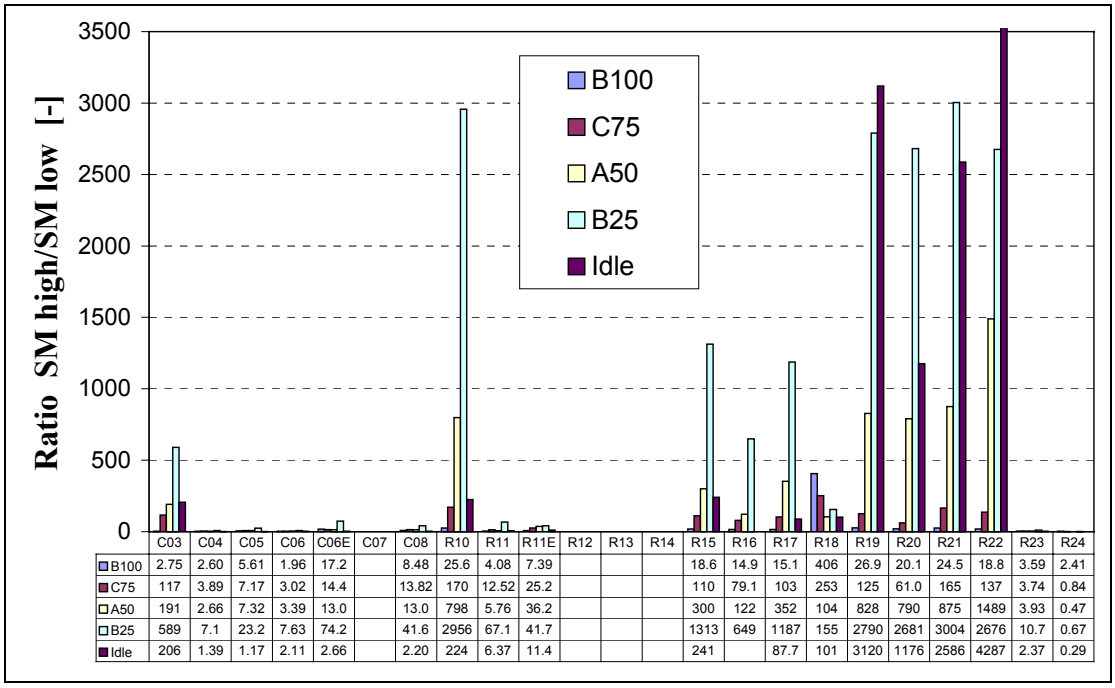


Figure 37: *Total number concentration / total mass concentration / SM low-emissions*

9.1.7.3.2 Ratio of high to low-emission level

Figure 38 shows the ratios between the high and low-emissions for the five single modes. Similar results are obtained to those for the ETC and the ESC. The clear difference between the individual modes is likely to be due to different flow splitting at the bypass for the high-emission set-up. The flow-splitting between bypass and trap varies depending on the backpressure due to the exhaust flow.



	C03	C04	C05	C06	C06E	C07	C08	R10	R11	R11E	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24
B100	2.75	2.60	5.61	1.96	17.2		8.48	25.6	4.08	7.39				18.6	14.9	15.1	406	26.9	20.1	24.5	18.8	3.59	2.41
C75	117	3.89	7.17	3.02	14.4		13.82	170	12.52	25.2				110	79.1	103	253	125	61.0	165	137	3.74	0.84
A50	191	2.66	7.32	3.39	13.0		13.0	798	5.76	36.2				300	122	352	104	828	790	875	1489	3.93	0.47
B25	589	7.1	23.2	7.63	74.2		41.6	2956	67.1	41.7				1313	649	1187	155	2790	2681	3004	2676	10.7	0.67
Idle	206	1.39	1.17	2.11	2.66		2.20	224	6.37	11.4				241		87.7	101	3120	1176	2586	4287	2.37	0.29

Figure 38: *Comparison between SM high and SM low-emission*

9.1.7.4 Particle composition

Only some of the instruments are able to distinguish between different components of the particles or their detection is based on a selective component, e.g. soot. Table 10 shows the list of instruments that provide information about at least one selective component. For clarity, and with the consequence of simplification, the components are grouped.

Code	*Instrument*	*Soot/EC*	*SOF/OC*	*Sulphate*
C05	LI2SA	✓		
C08	MEXA	✓	✓	✓
C08	PASS	✓		
R11	Coulometry	✓	✓	
R17	PAS	✓		

Table 10: *Particle components measured by the individual instruments*

In Figure 39, the results are presented for ETC high-emission configuration. The total mass concentrations measured by the gravimetric filter method (C04) and MasMo (R10) are added to the figure for comparison. Although the mass concentration determined by the individual instruments is similar (with the exception of PAS (R17)), the results for the single components are not consistent. This applies particularly to the soot/EC fraction.

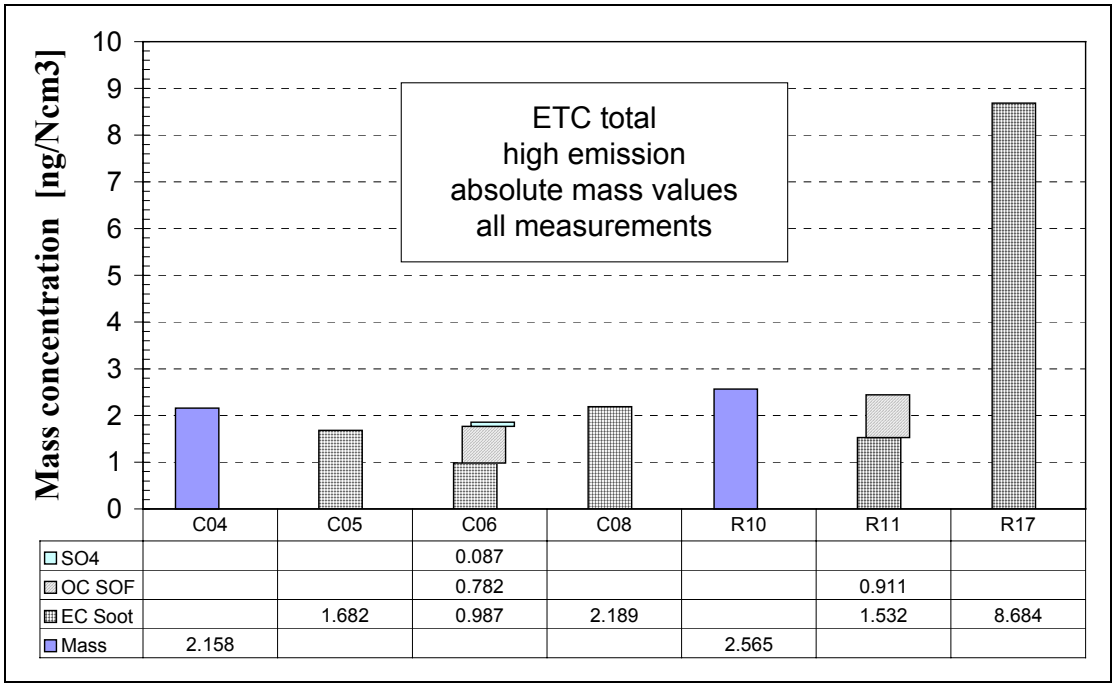


Figure 39: *Chemical composition / ETC high-emission*
(range bars are omitted in order to achieve better readability)

9.1.8 Correlation between instruments

The correlation between the instruments is shown in this section. To keep track of the measurements, each participating instrument is compared to three selected instruments, which are the gravimetric filter analysis (C04), the EC fraction of coulometry (R11E) and the condensation particle counter CPC 3022A (R19).
The correlation is made using all driven transient cycles and steady-state tests at high-emission level (H) as well as at low-emission level (L). The labelling used for the cycles is presented in Figure 40. Some additional comments on the correlation are given in note form for each instrument in the corresponding figure. Exceptionally high concentrations were measured for the gravimetric filter analysis (C04) in engine operating mode B100 and for the CPC 3022A (R19) at idle, most probably due to condensation/nucleation effects. In many cases, these items were excluded in the calculation of the correlation function.
Note that the quality of the correlations a priori is dominated by the high concentration measurements.

□ ETC H	□ ETC L	◇ SM B100 H	◇ SM B100 L
△ SM C75 H	△ SM C75 L	× SM A50 H	× SM A50 L
✳ SM B25 H	✳ SM B25 L	– SM Idle H	– SM Idle L
○ SCT H	○ SCT L	+ ESC H	+ ESC L

Figure 40: *Key to the following graphs (Figure 41 to Figure 60)*

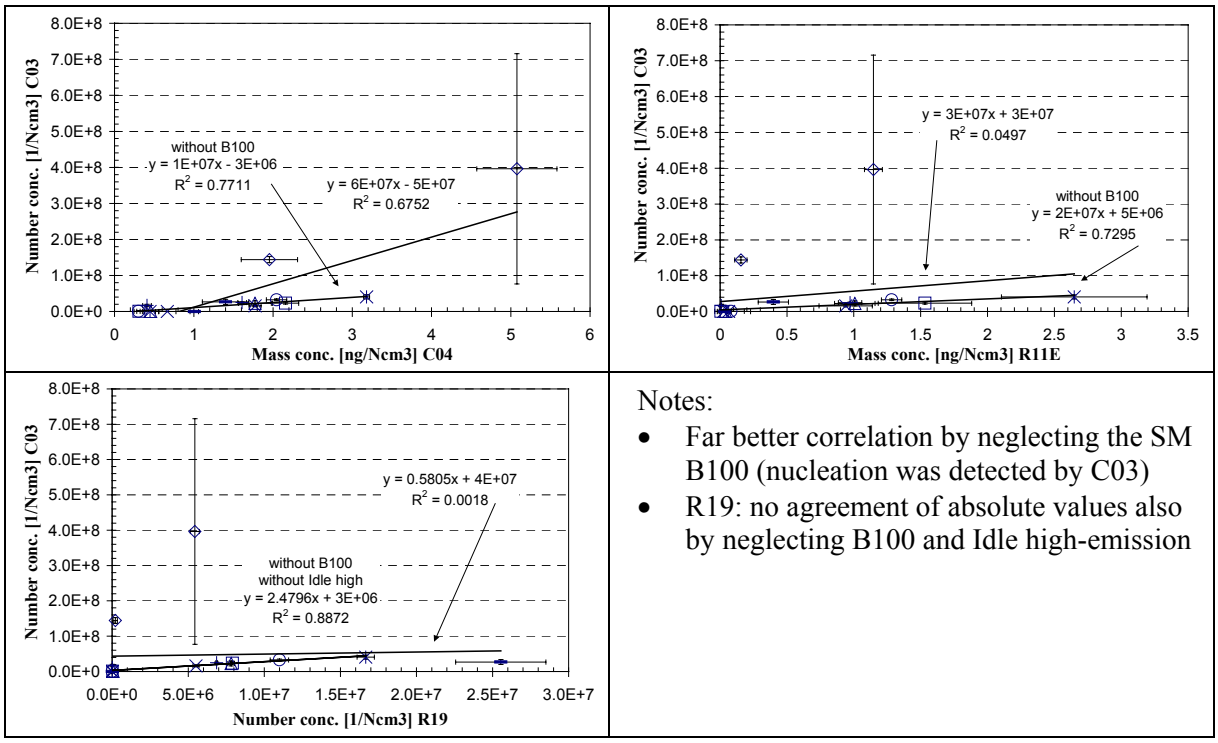


Figure 41: *Correlation between C03 and selected instruments / engine measurements*

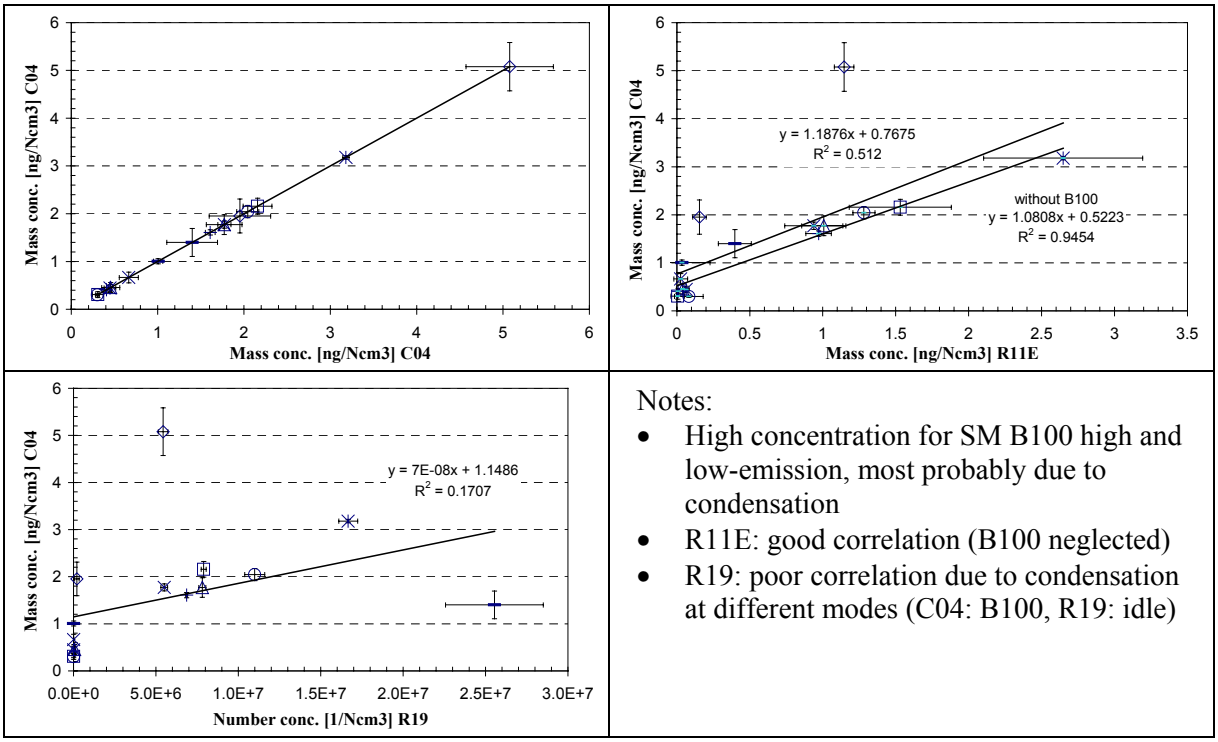


Figure 42: *Correlation between C04 and selected instruments / engine measurements*

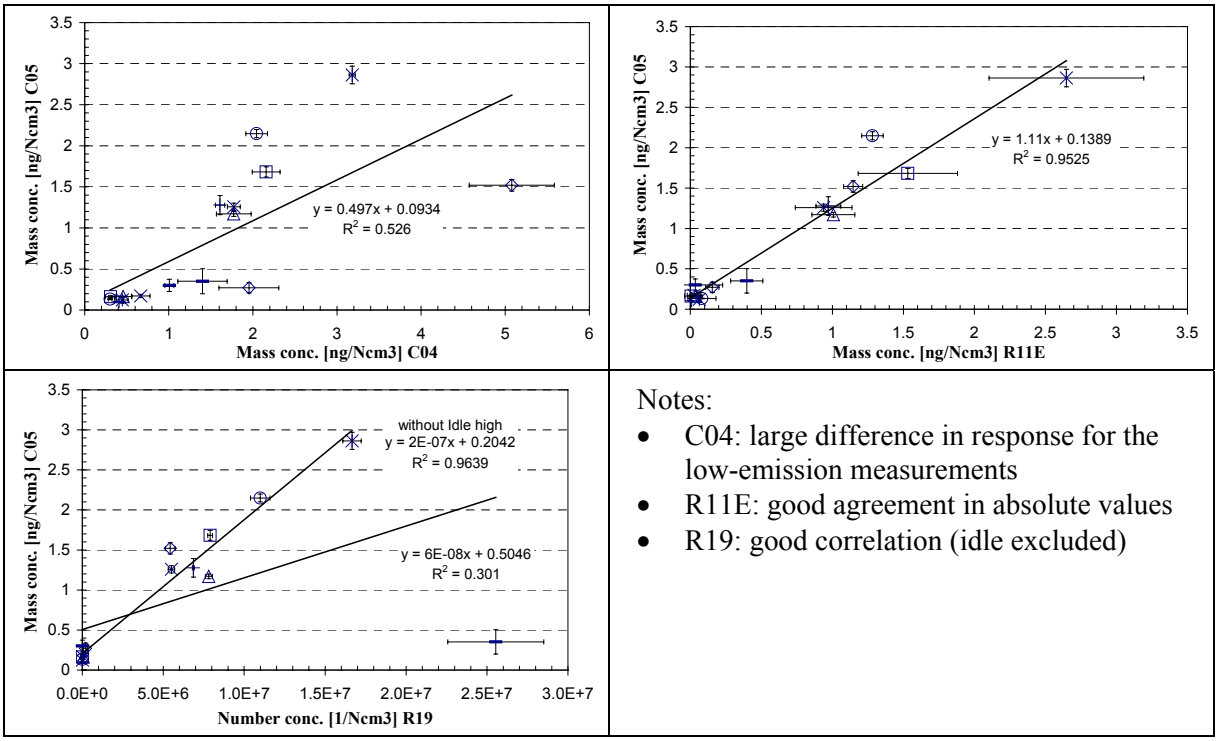


Figure 43: *Correlation between C05 and selected instruments / engine measurements*

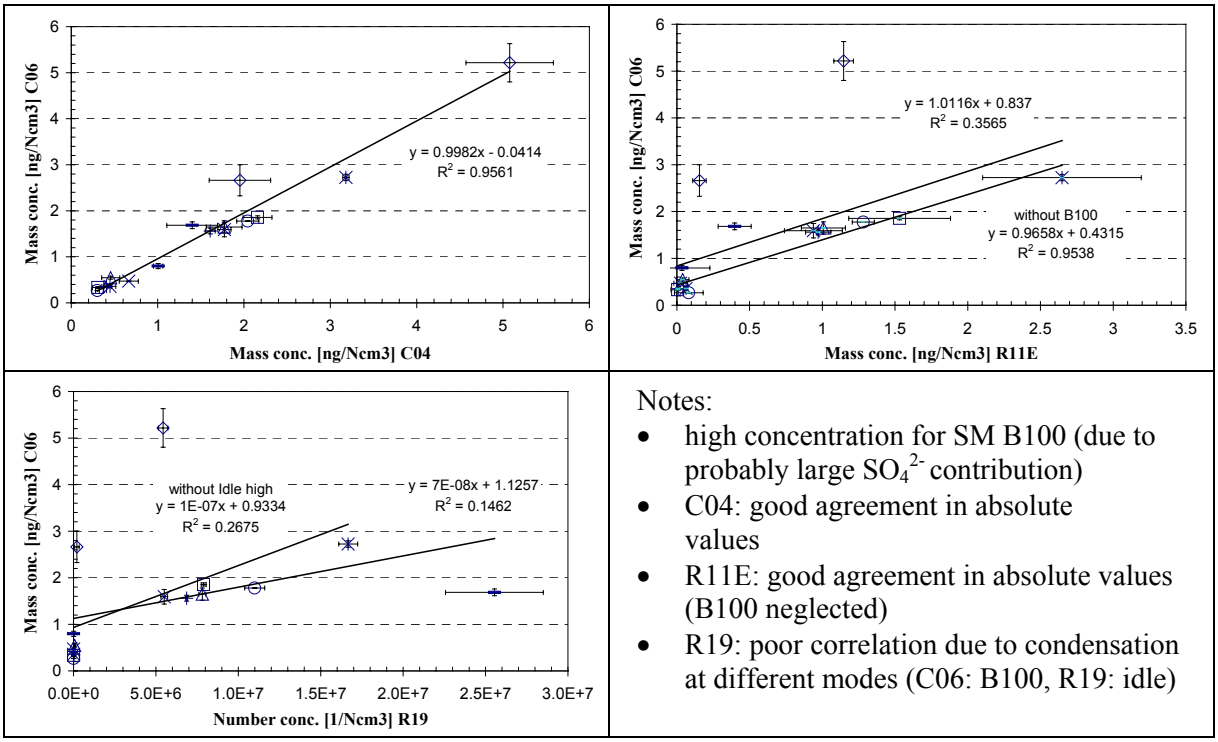


Figure 44: *Correlation between C06 and selected instruments / engine measurements*

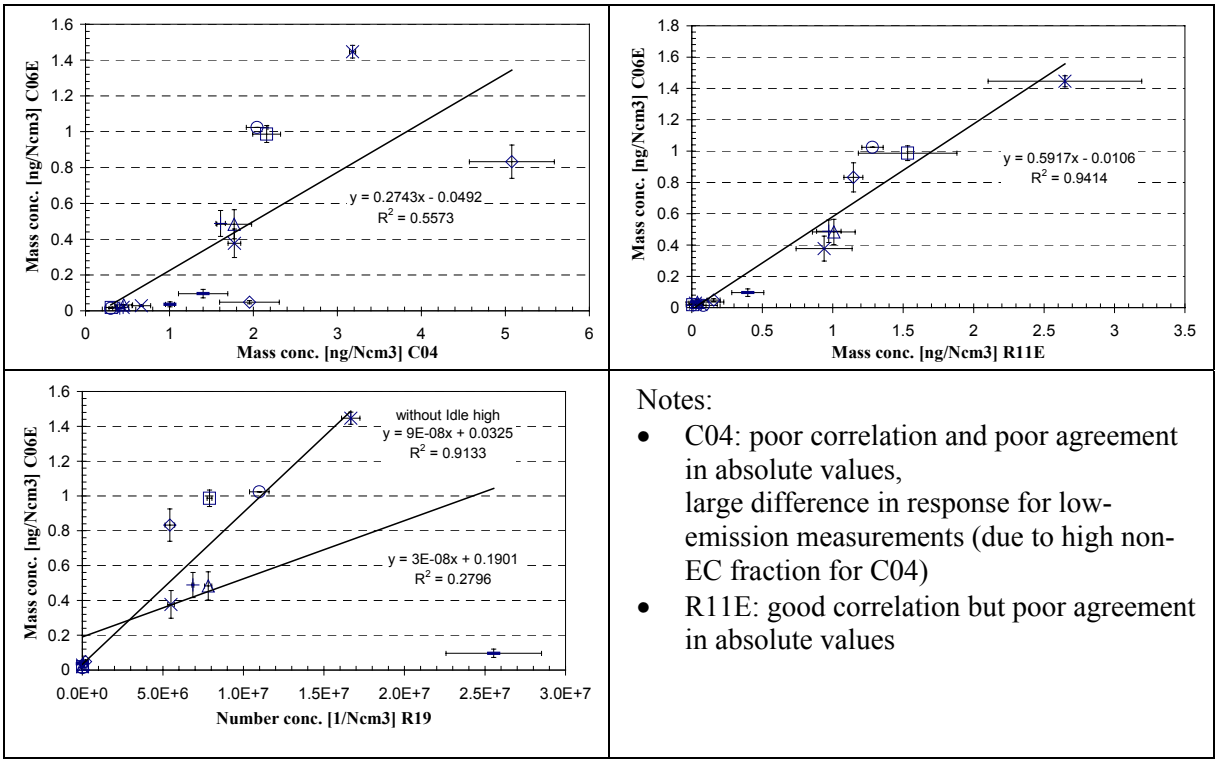


Figure 45: *Correlation between C06E and selected instruments / engine measurements*

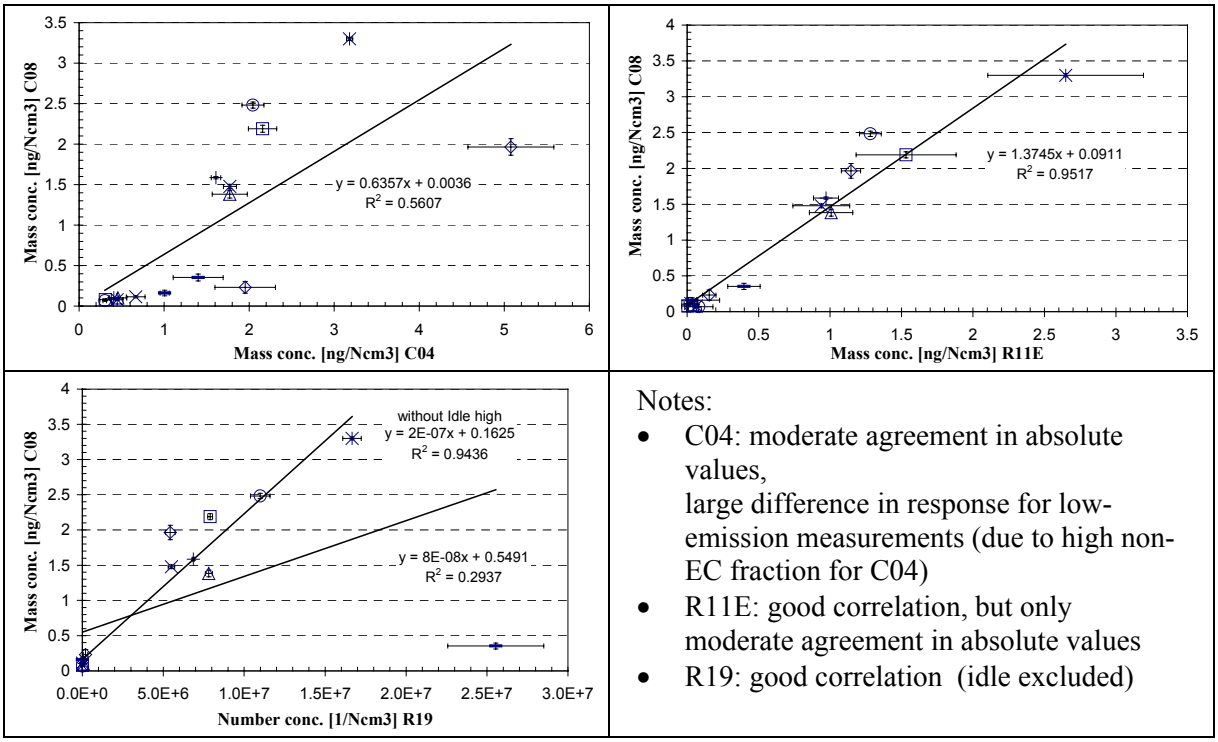


Figure 46: *Correlation between C08 and selected instruments / engine measurements*

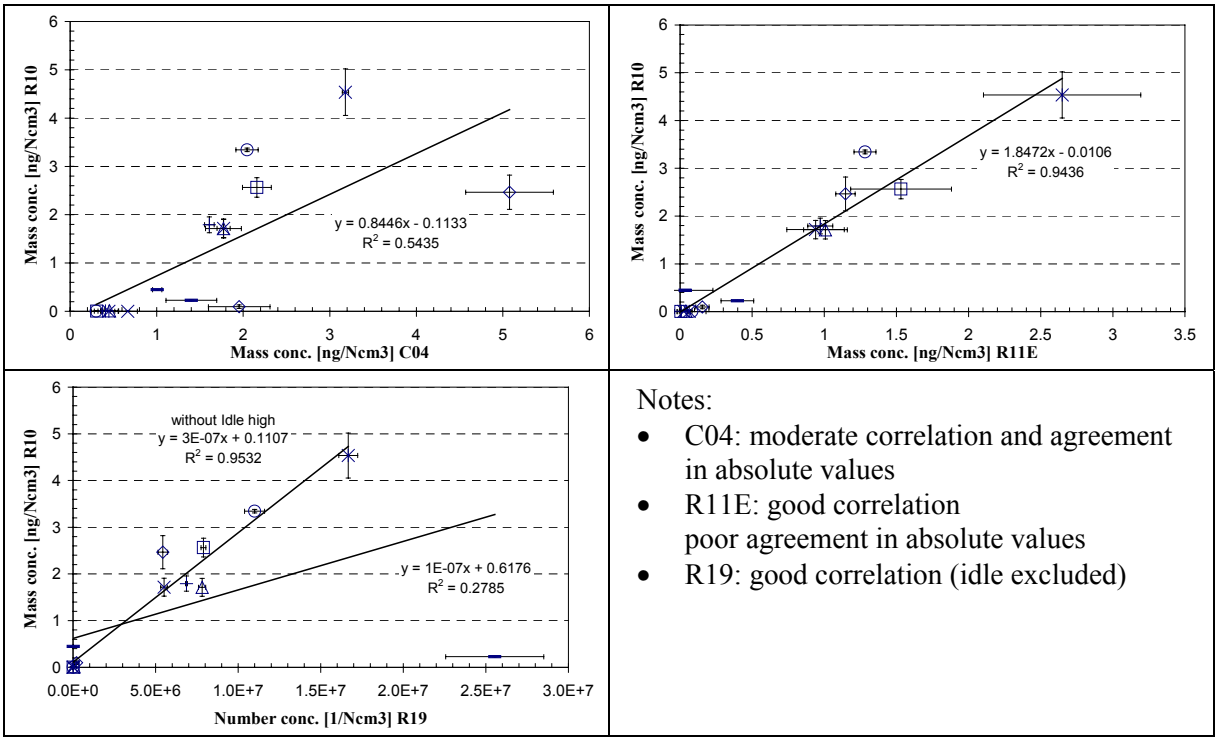


Figure 47: *Correlation between R10 and selected instruments / engine measurements*

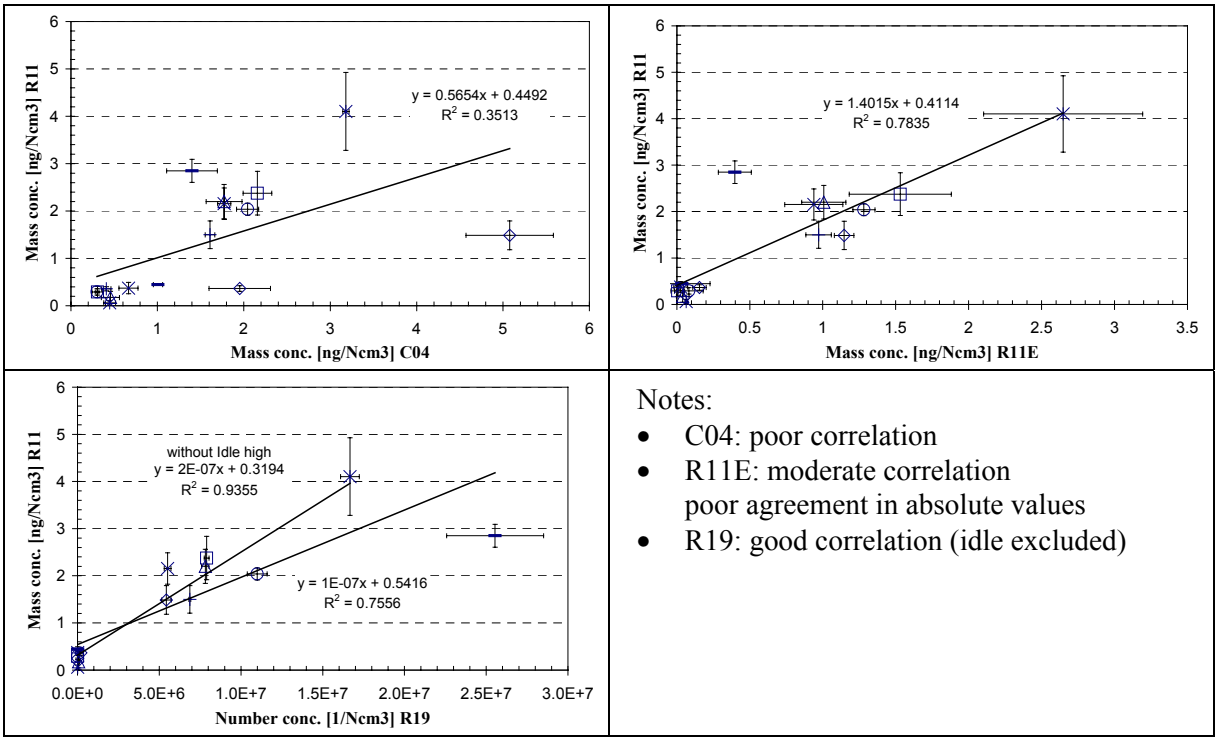


Figure 48: *Correlation between R11 and selected instruments / engine measurements*

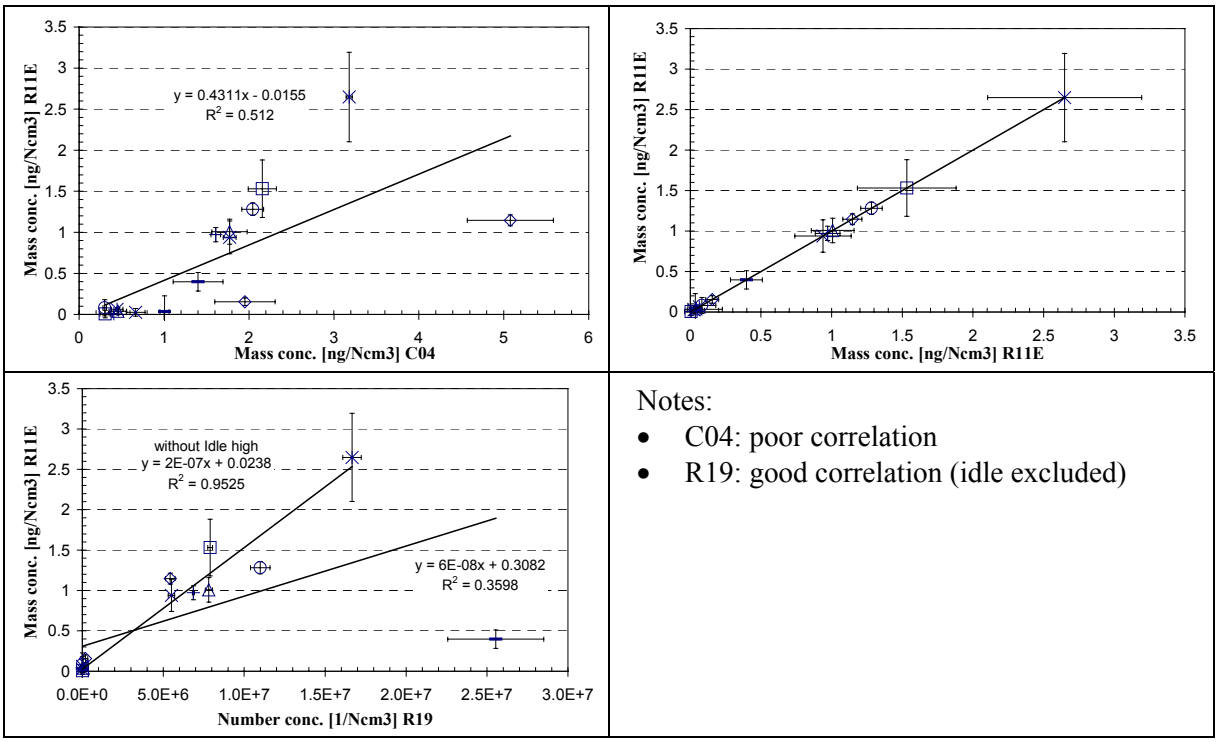


Figure 49: *Correlation between R11E and selected instruments / engine measurements*

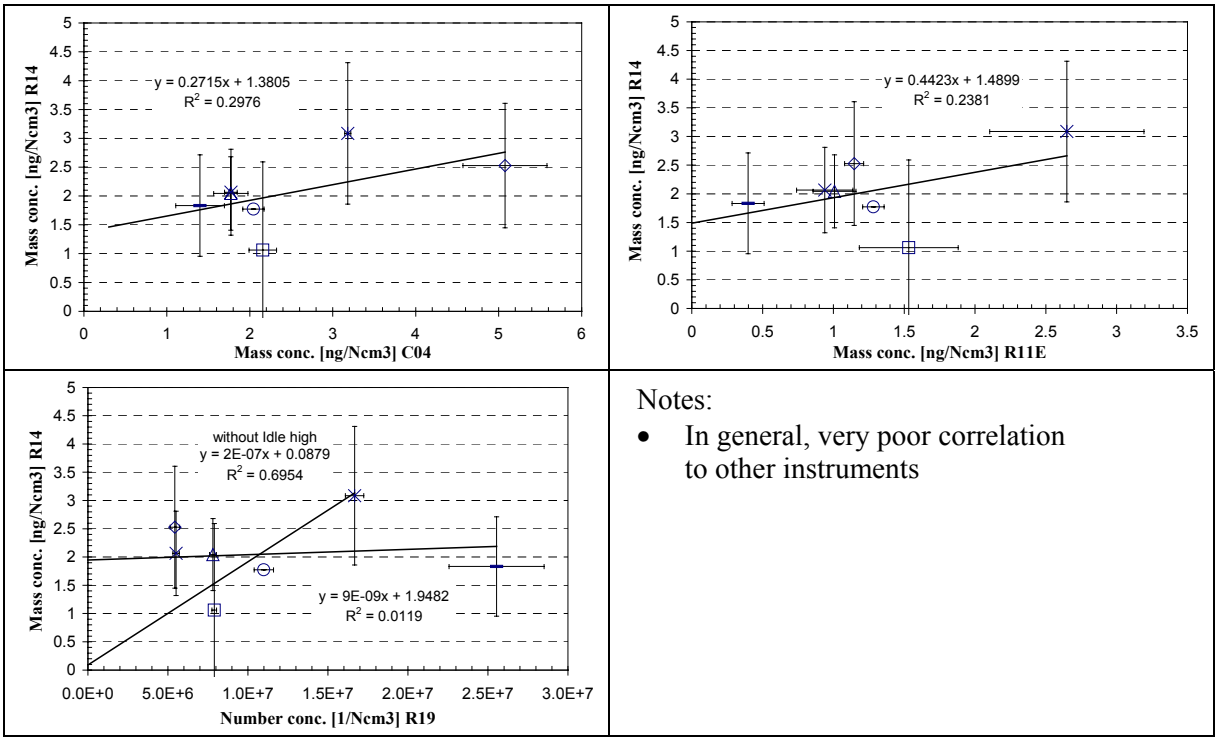


Figure 50: *Correlation between R14 and selected instruments / engine measurements*

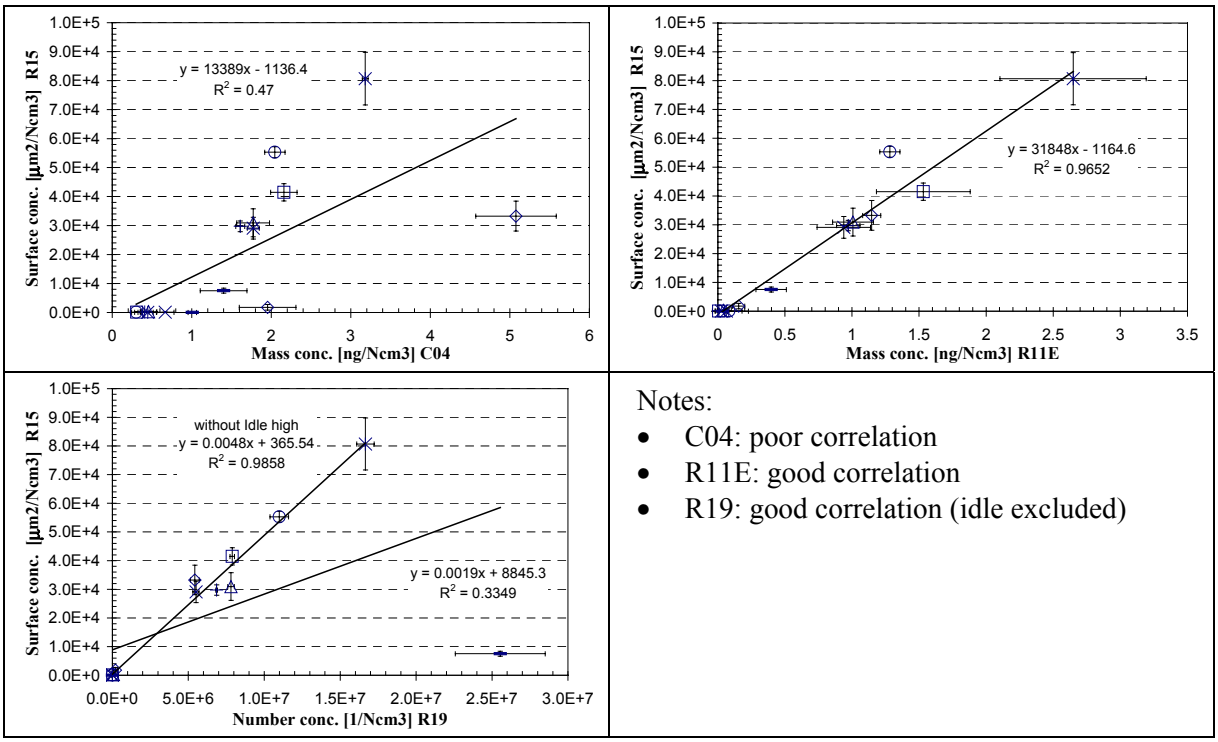


Figure 51: *Correlation between R15 and selected instruments / engine measurements*

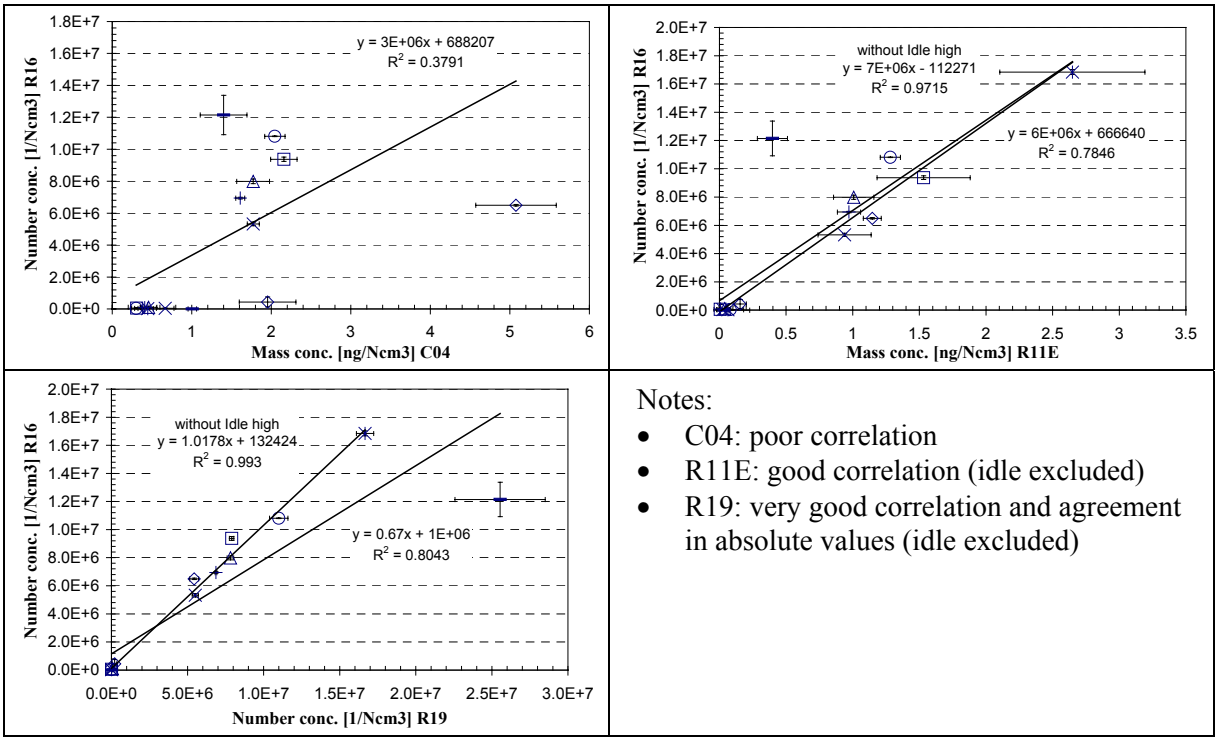


Figure 52: *Correlation between R16 and selected instruments / engine measurements*

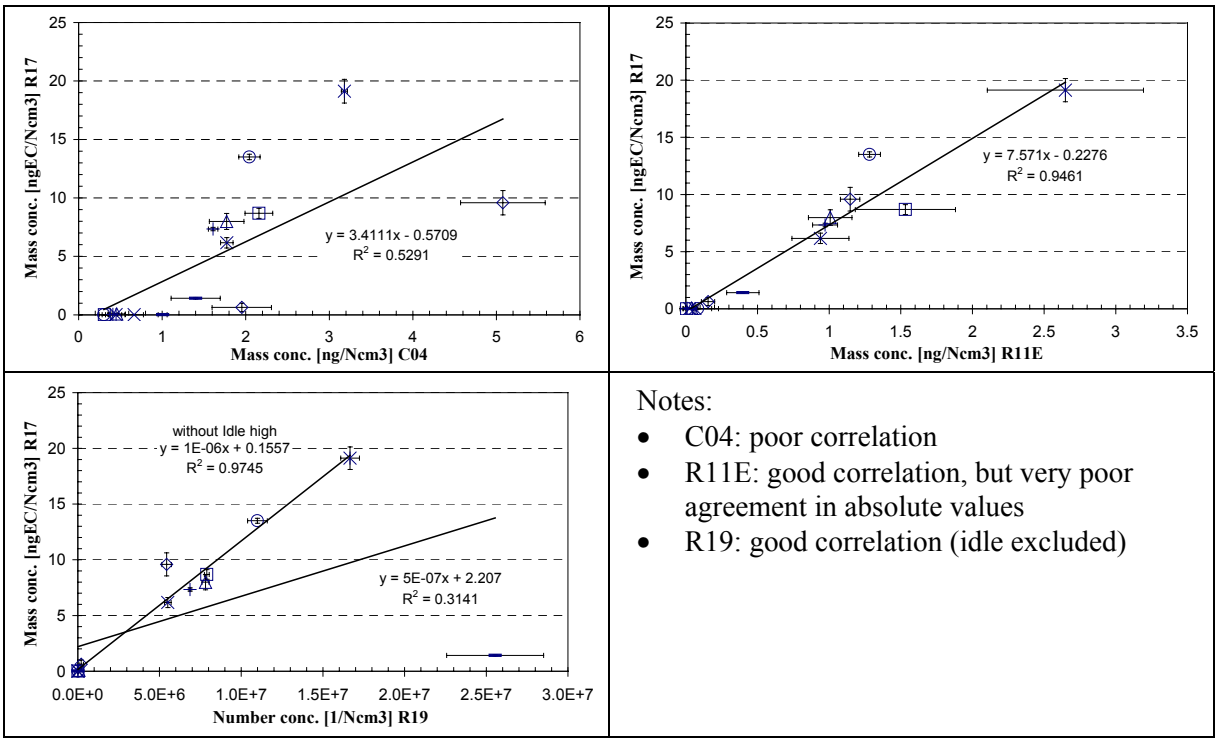


Figure 53: *Correlation between R17 and selected instruments / engine measurements*

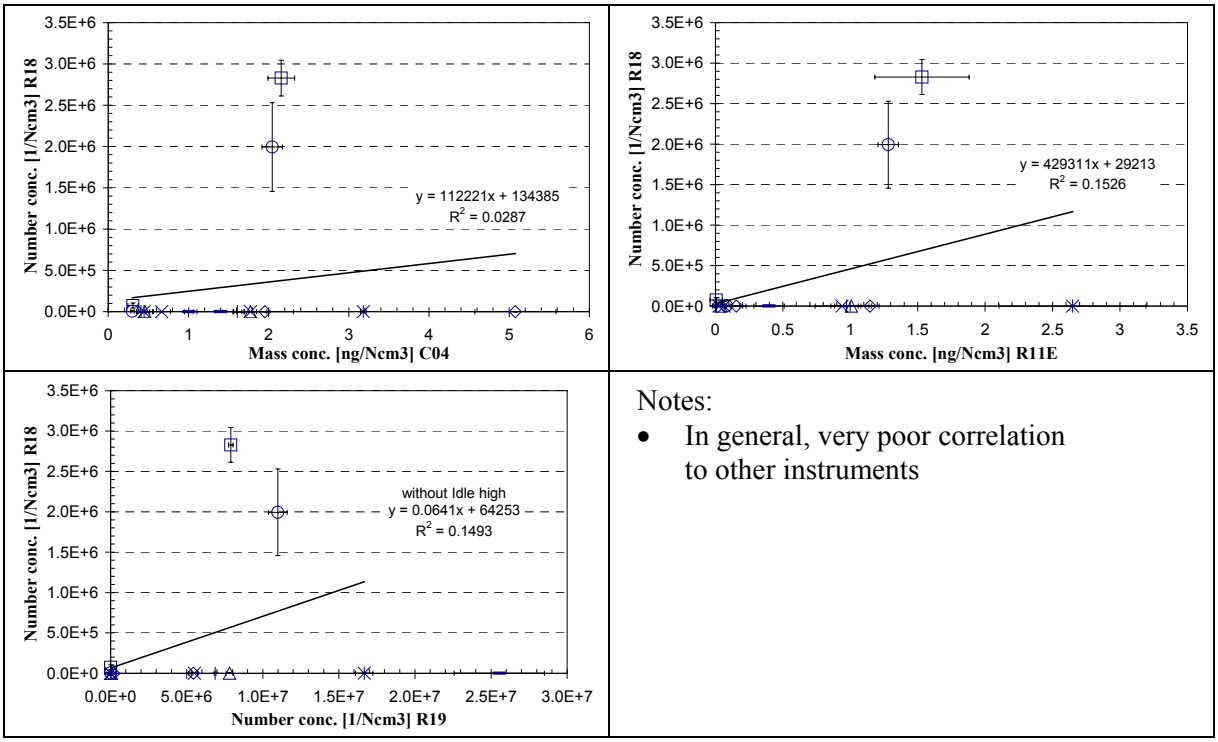


Figure 54: *Correlation between R18 and selected instruments / engine measurements*

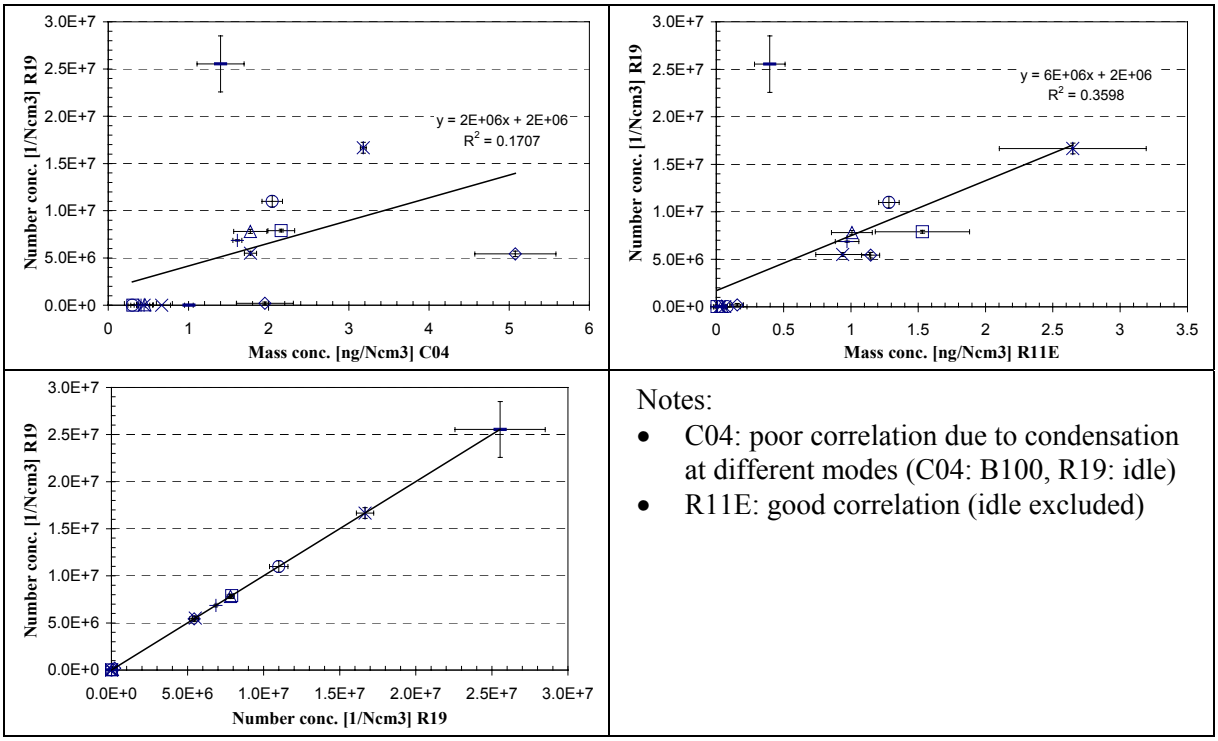


Figure 55: *Correlation between R19 and selected instruments / engine measurements*

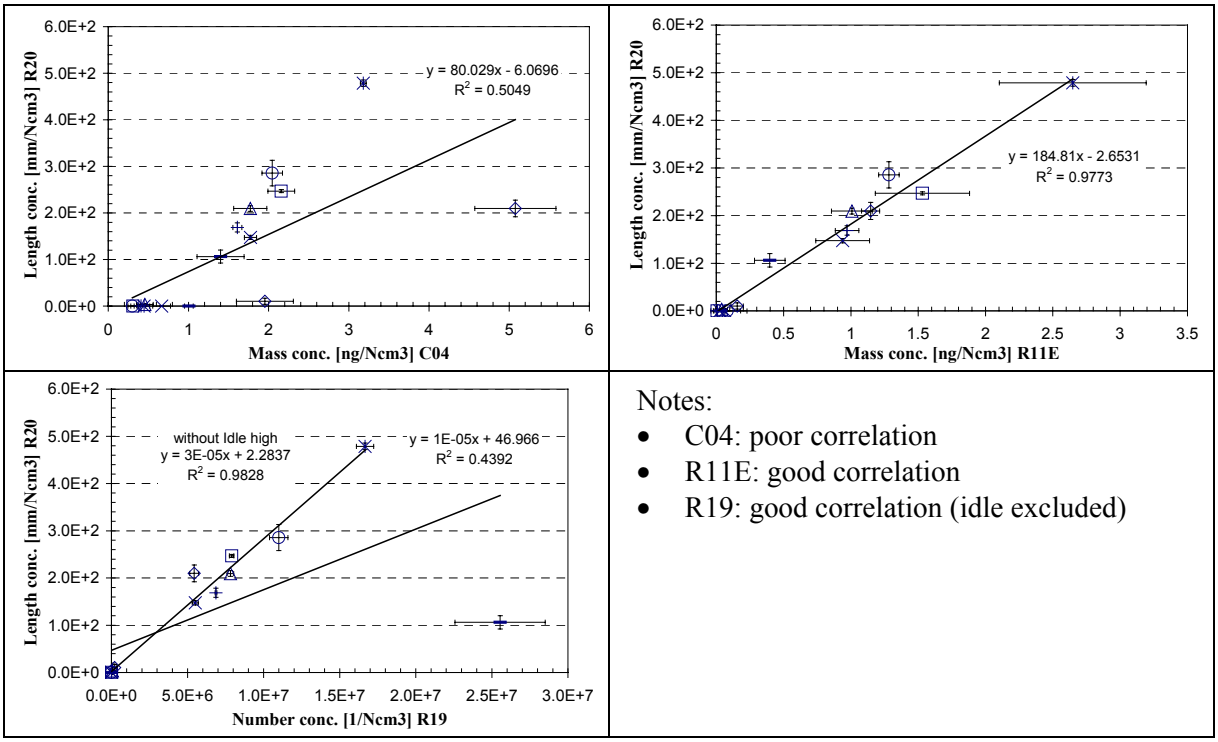


Figure 56: *Correlation between R20 and selected instruments / engine measurements*

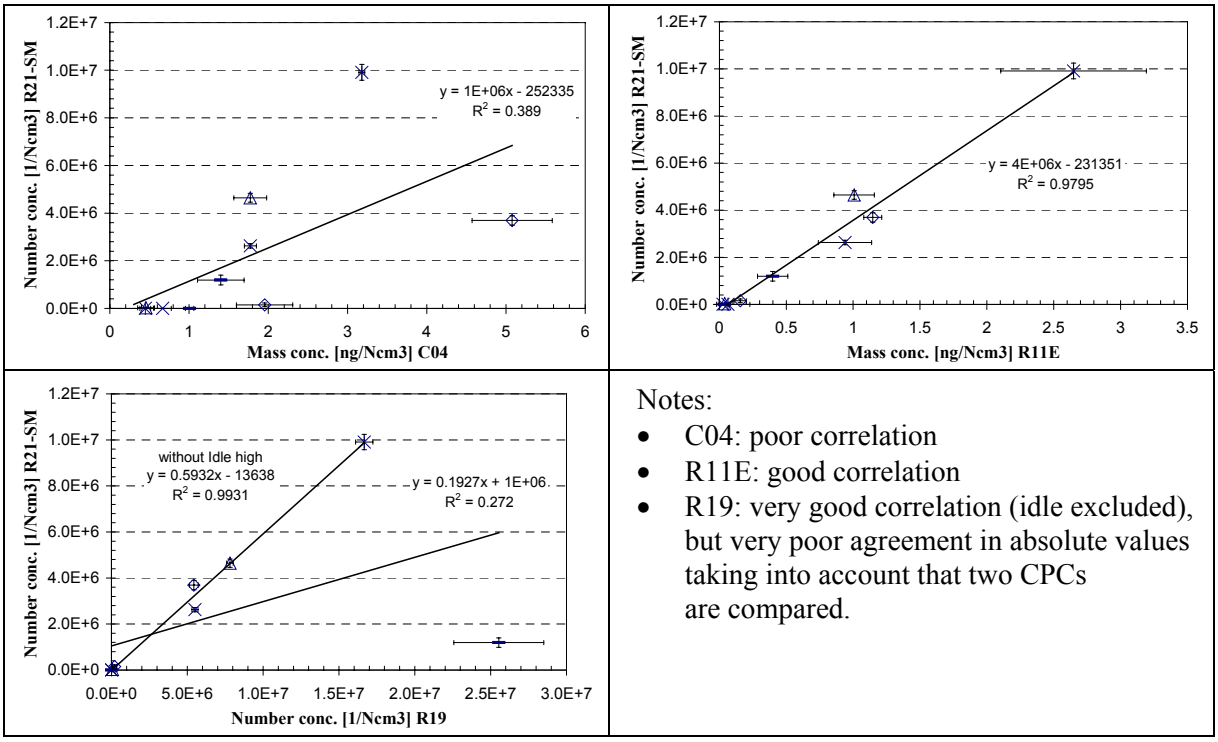


Figure 57: *Correlation between SMPS (R21) and selected instruments / only SM / engine measurements*

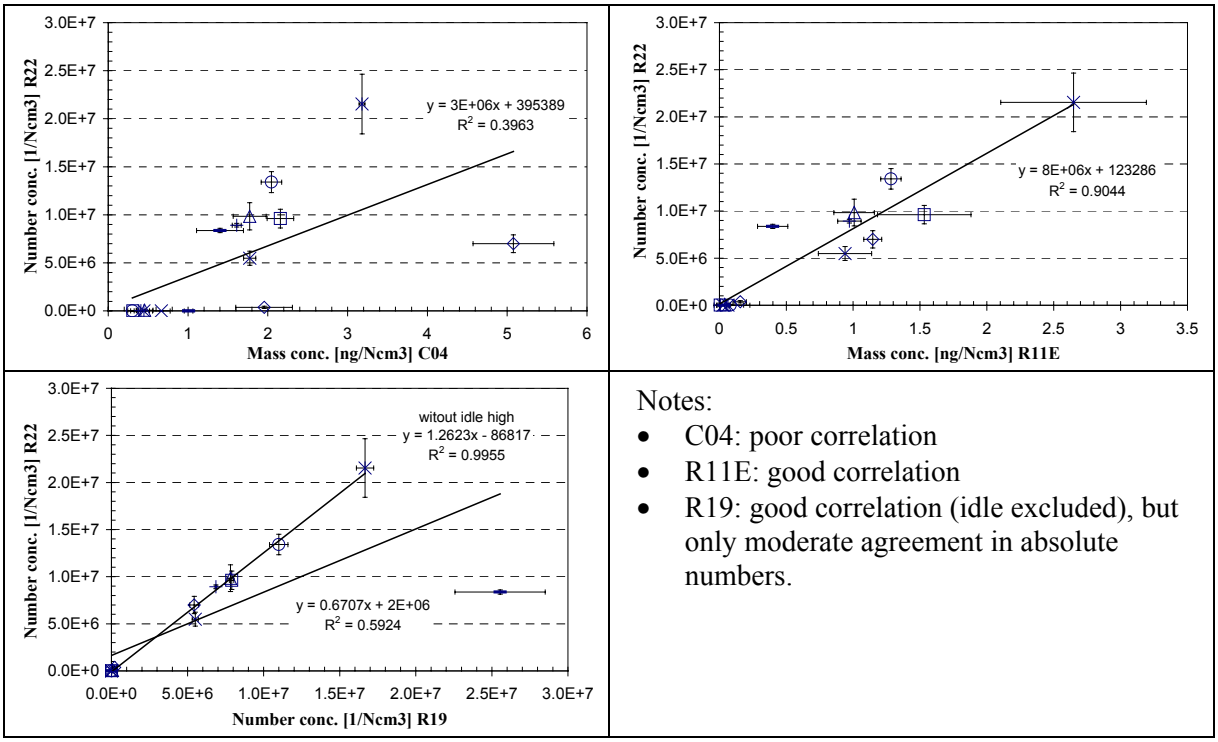


Figure 58: *Correlation between R22 and selected instruments / engine measurements*

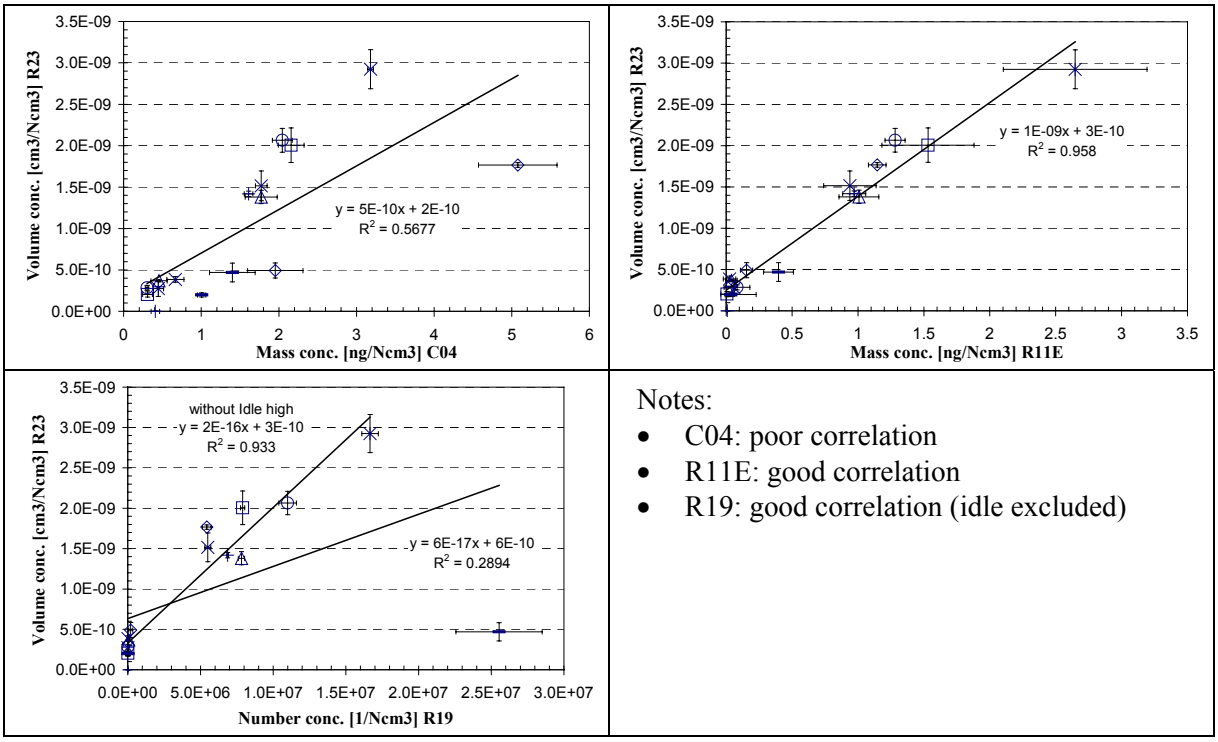
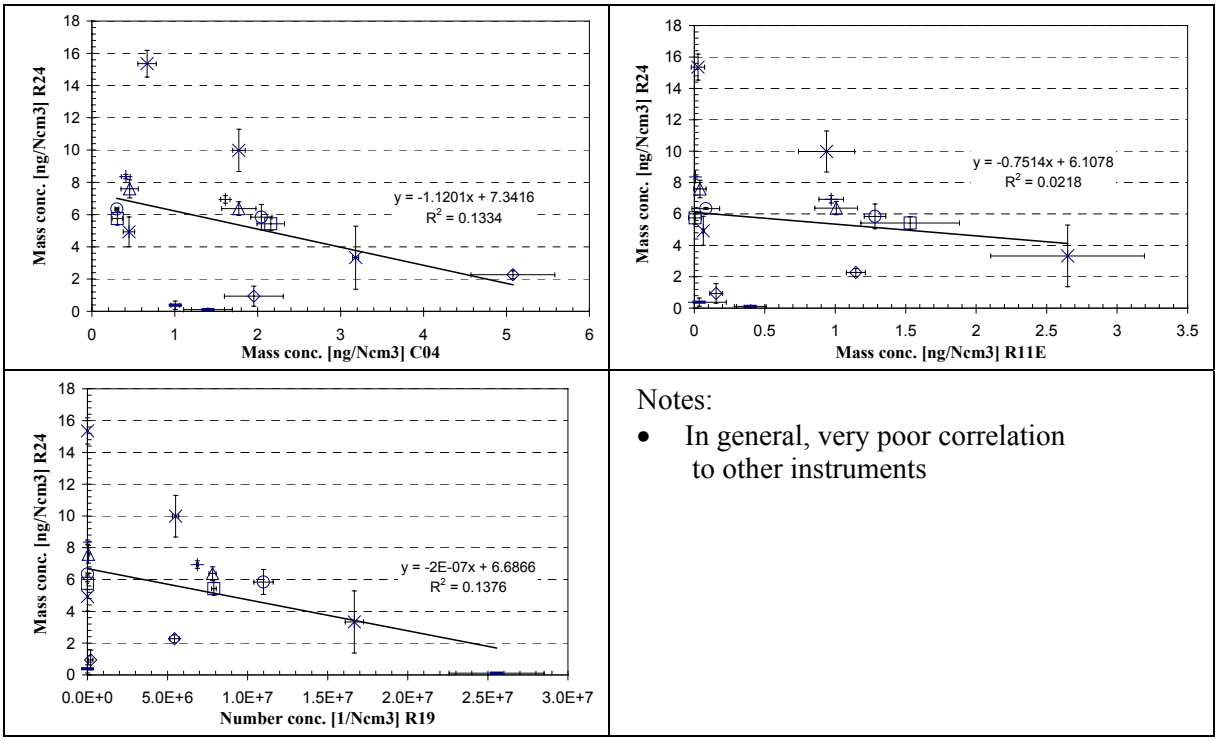


Figure 59: *Correlation between R23 and selected instruments / engine measurements*



Notes:

- In general, very poor correlation to other instruments

Figure 60: *Correlation between R24 and selected instruments / engine measurements*

9.1.9 Size Information

This section describes the measurements of particle sizes by some of the instruments. Out of the participating measurement systems, eight instruments are capable of providing size information. Most of them apply different measurement principles in determining an equivalent diameter, which depends on the measurement principle. This diameter is different from the geometric one, as the particles from combustion processes are agglomerated and therefore not spherical and vary in density. For this reason it is **not** possible to compare the instruments for a "correct" mean size or size distribution of the particles.
The two SMPS, the seq. SMPS+C (R13) and scanning SMPS (R21), are not capable of measuring transient cycles. Their results are only included for the steady-state tests (see section 9.1.9.3).
Table 11 gives the equivalent particle size property that is determined by the individual instruments. In order to obtain a better overview of the measured sizes, the distributions shown in Figure 61 to Figure 63 are normalised.

Code	*Instrument*	*Equivalent particle size property*	
C03	DMS	electrical mobility diameter of agglomerate	NSD
C05	LI2SA	transport surface (heat) of primary particle	mean
R10	MasMo	active surface area of agglomerate	median
R12	DustMonitor	light scattering diameter of agglomerate	NSD
R13	SMPS+C	electrical mobility diameter of agglomerate	NSD
R14	DPSO-1	light extinction diameter of primary particle	mean
R16	EDB	mechanical mobility diameter of agglomerate	NSD cal.
R18	PM-300	light scattering diameter of agglomerate	NSD
R21	SMPS	electrical mobility diameter of agglomerate	NSD
R22	ELPI	aerodynamic diameter of agglomerate	NSD
R23	DQL	light extinction diameter of primary particle	Mean

Table 11: *Particle size measured by the individual instruments*

9.1.9.1 Number size distribution and average size for ETC

Figure 61 shows the results for the ETC for the high and low-emission configurations. Looking at the high-emission measurements, the instruments DMS (C03), MasMo (R10), EDB (R16) and ELPI (R22) are in surprisingly good agreement. The ELPI (R22) detected a significantly higher concentration at its lowest size class (dp < 35 nm), for which a filter stage is used. LI2SA (C05) measures the primary particles and cannot be compared to others. For the light scattering instruments DustMonitor (R12) and PM-300 (R18), the midpoint diameter of the lowest size class is about 300 nm.
Wider differences between the instruments are observed for the low-emission measurements. Note that in this case the emission level was at the background level. Two additional modes can be seen for the DMS (C03). The mode below 10 nm is probably caused by nucleation. The second mode at about 500 nm measured in high-emission tests is most likely an artefact caused by the instrument.

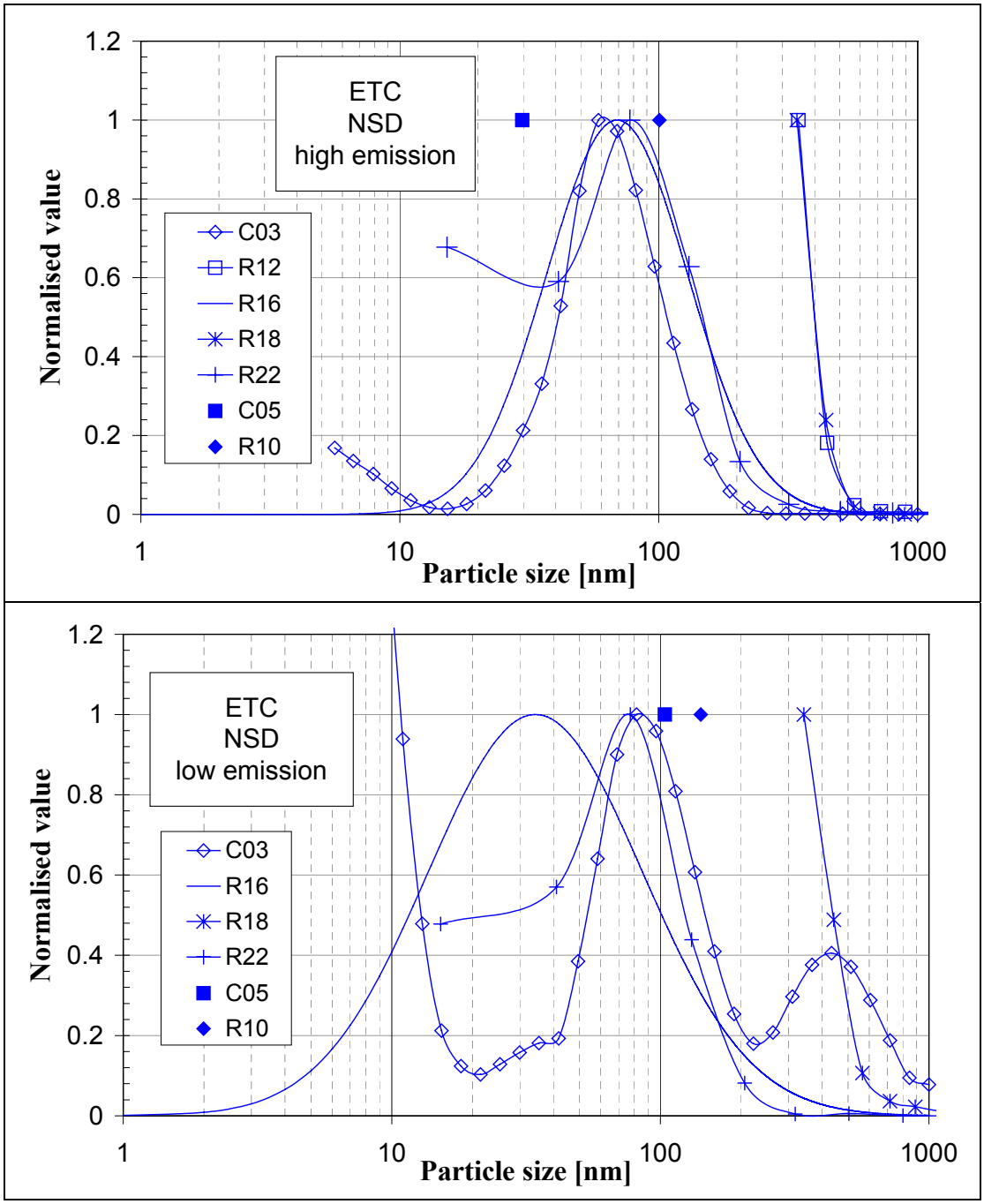


Figure 61: *Number Size Distribution (NSD) / ETC high/low-emission*

9.1.9.2 Number size distribution and average size for ESC

Figure 62 shows the results for the size measurements for the ESC for high and low-emission set-up. The NSD, mean and median represent the weighted average over the ESC. All instruments measure the particles in the same size range as for the ETC. DMS (C03) detects more nucleates for both emission levels for this test cycle. No data from LIS2A (C05) were available for the low-emission set-up.

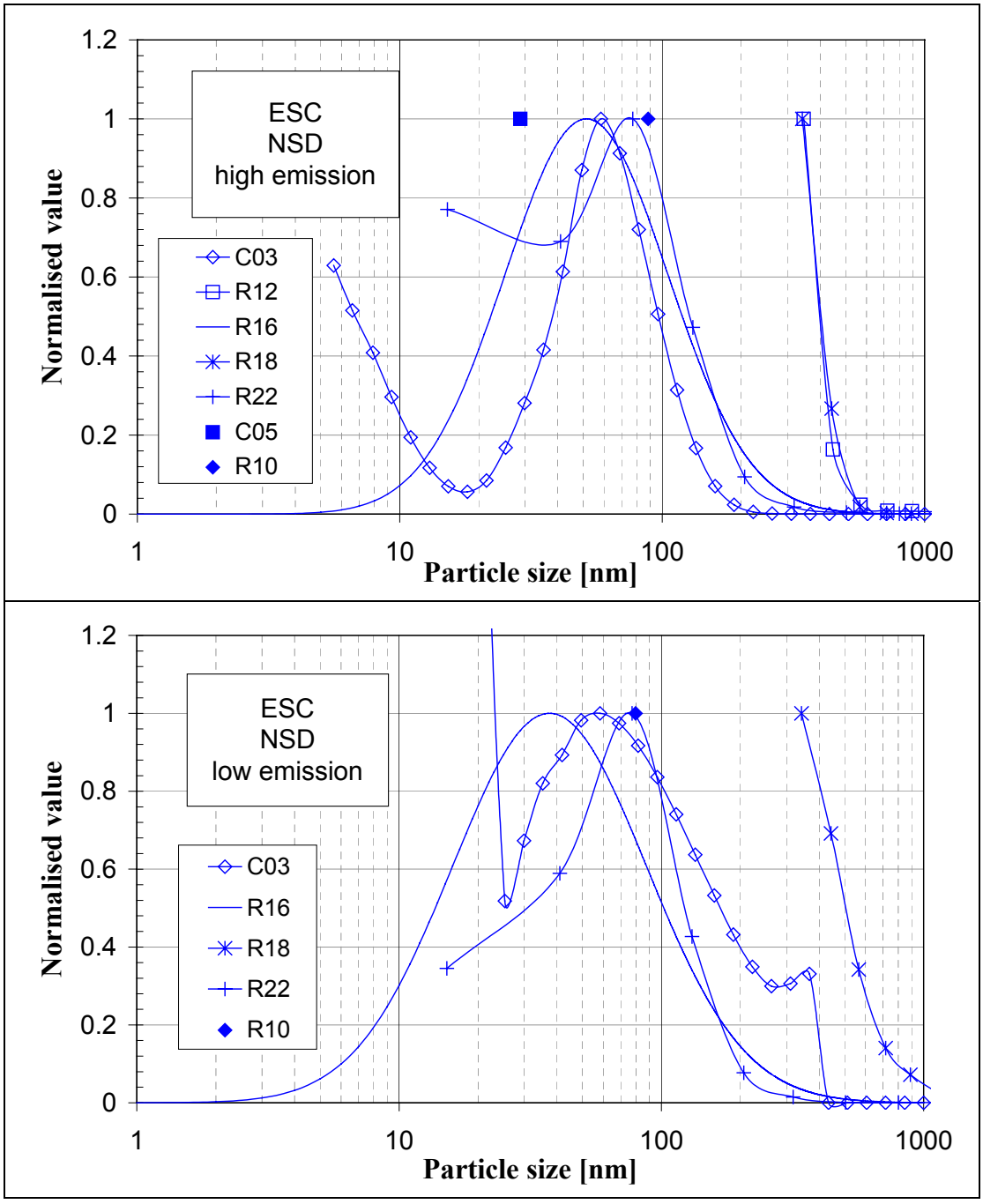


Figure 62: *Number Size Distribution (NSD) / ESC high/low-emission*

9.1.9.3 Number size distribution and average size for single modes

Figure 63 plots the number size distributions, mean and median as measured by the instruments during a high-load mode (C75) and a low-load mode (B25) of the engine. The results of the other single modes are shown in the appendix. The diagrams include data from the two mobility particle sizers (R13, R21). In general, good agreement between the instruments is observed with the exception of the optical instruments (R12, R18). It is notable that the DMS (C03) measures a significantly smaller width of the distributions than the other instruments. The seq. SMPS+C (R13) is the only instrument that shows a large particle mode at about 250 nm. This is in all probability an artefact originated by the instrument. For the full trap set-up single mode B25, the concentration is very low, resulting in wide scatter, especially for the DMS (C03). As already noted for the ETC and ESC, the ELPI (R22) measures fairly high concentrations with its filter stage for the high-emission set-up.

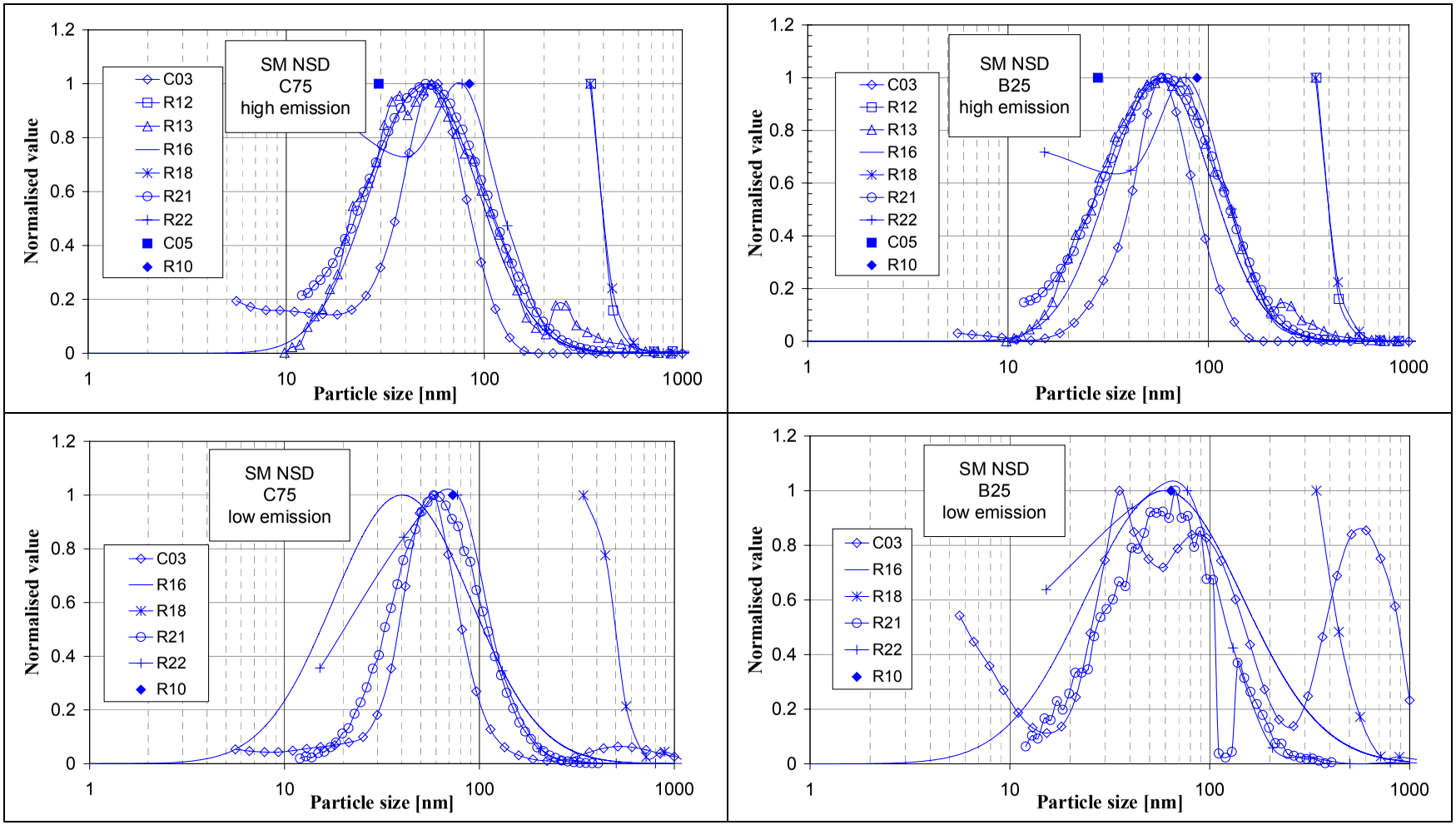


Figure 63: *Number Size Distribution (NSD) / SM high/low-emission*

9.2 CAST measurements

Using the aerosol generator CAST, tests were performed to obtain measurement data independent of the engine. The focus of the CAST measurement was to gather information on the linearity and detection limit of the instruments.
The following methods did not successfully participate in the CAST measurements for various reasons: gravimetric filter sampling (C04), MEXA (C06), Coulometry (R11), DustMonitor (R12), seq. SMPS+C (R13), DPSO-1 (R14), PM-300 (R18), DQL (R23), AVL437 (R24).

9.2.1 Calibration of CAST

Before the beginning of the measurement programme at EMPA, the CAST was calibrated using a scanning mobility particle sizer (SMPS 3934, TSI) at METAS. After the programme, i.e. 24 days later, the calibration was repeated at METAS. Figure 64 shows the result of the calibration measurements. All values with the exception of 90% at size A could be repeated with a drift of less than 10%. The mode of the size distribution showed a drift of about +5 nm for the particle size B and +2 nm at size A.

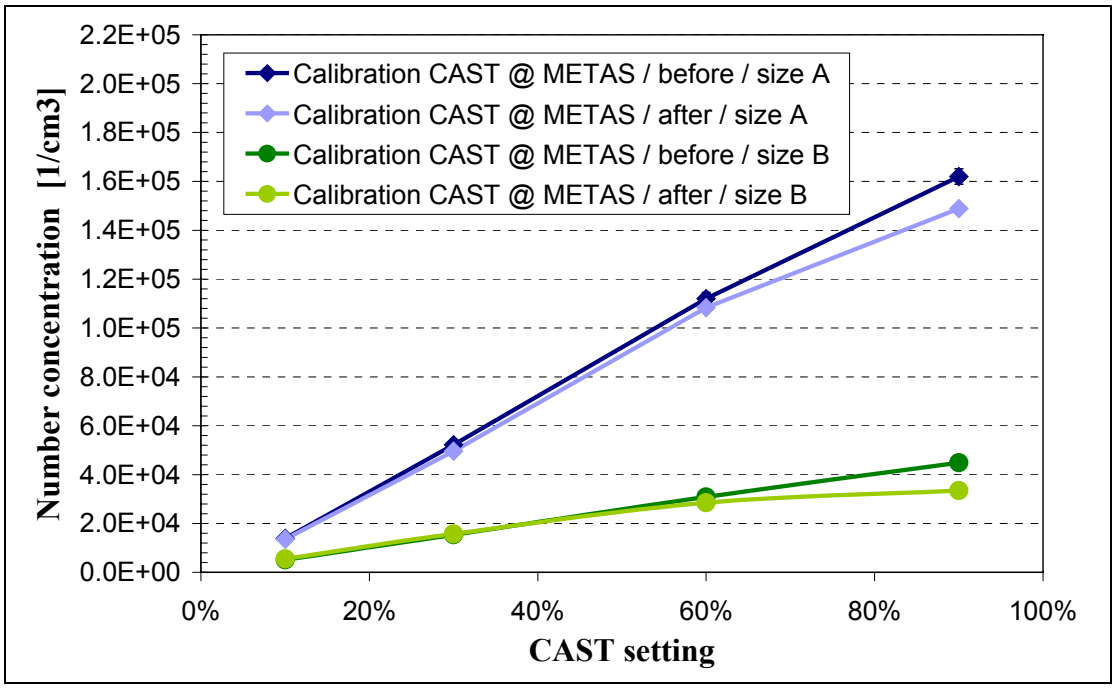


Figure 64: *Results of the CAST calibration at METAS before and after the measurement programme at EMPA*

9.2.2 Repeatability during the CAST measurements

Cast measurements were carried out before and after the engine test period.
For each instrument, the deviation between the measurement before (referred to as "before") and after the engine test (referred to as "after") relative to the measurement before were calculated. Figure 65 shows the deviation for CAST size A and in Figure 66 for CAST size B.

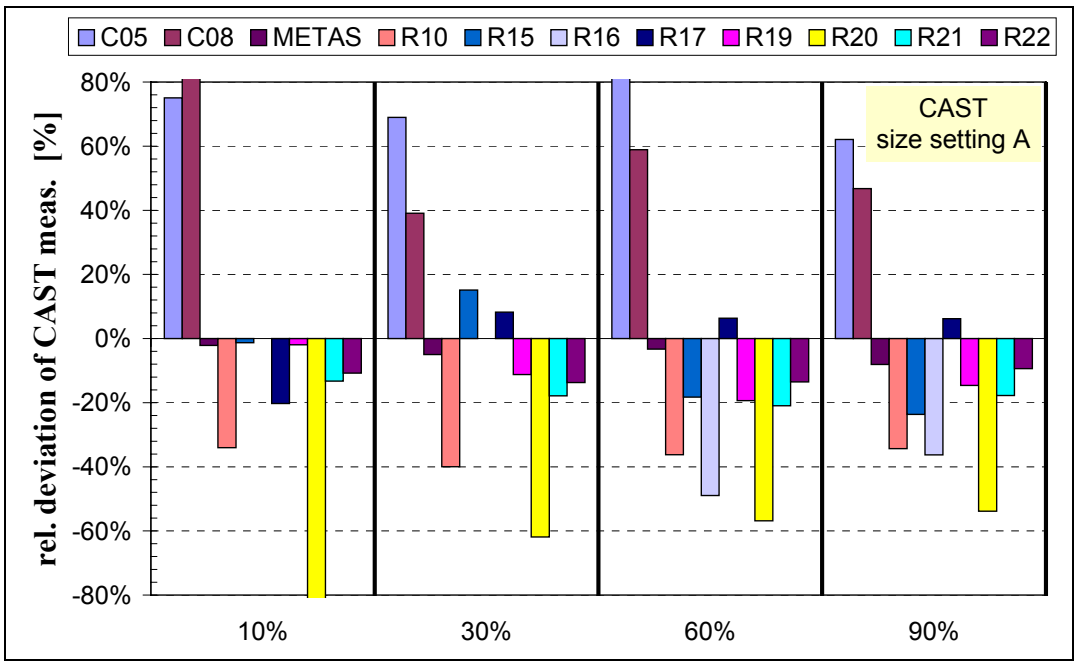


Figure 65: *Relative deviation on CAST measurements before & after the engine test period / CAST size A*

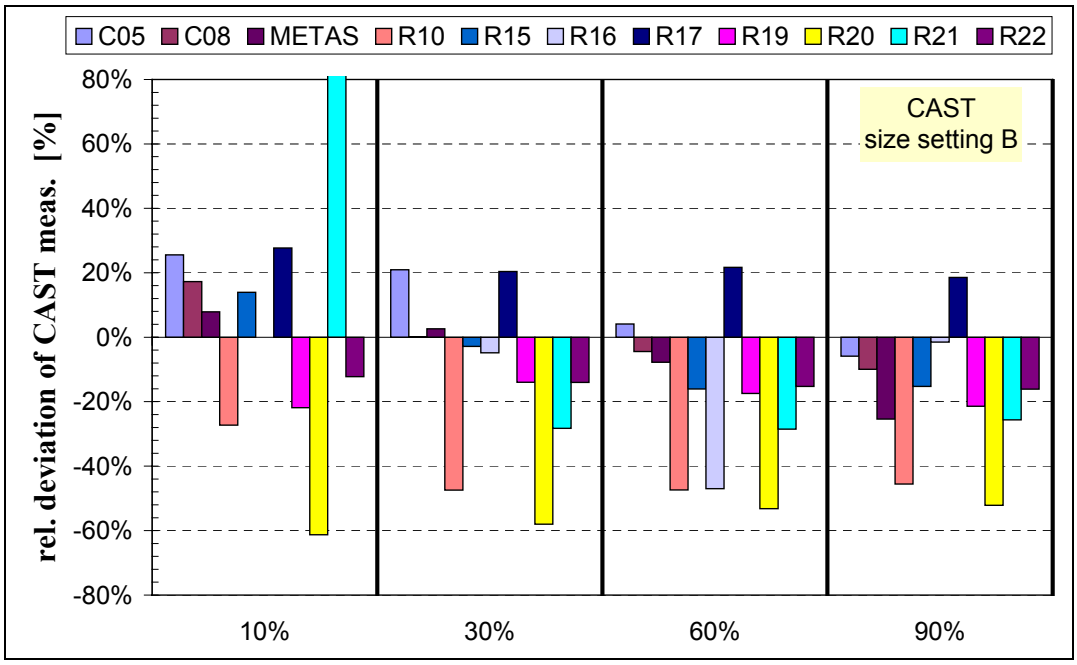


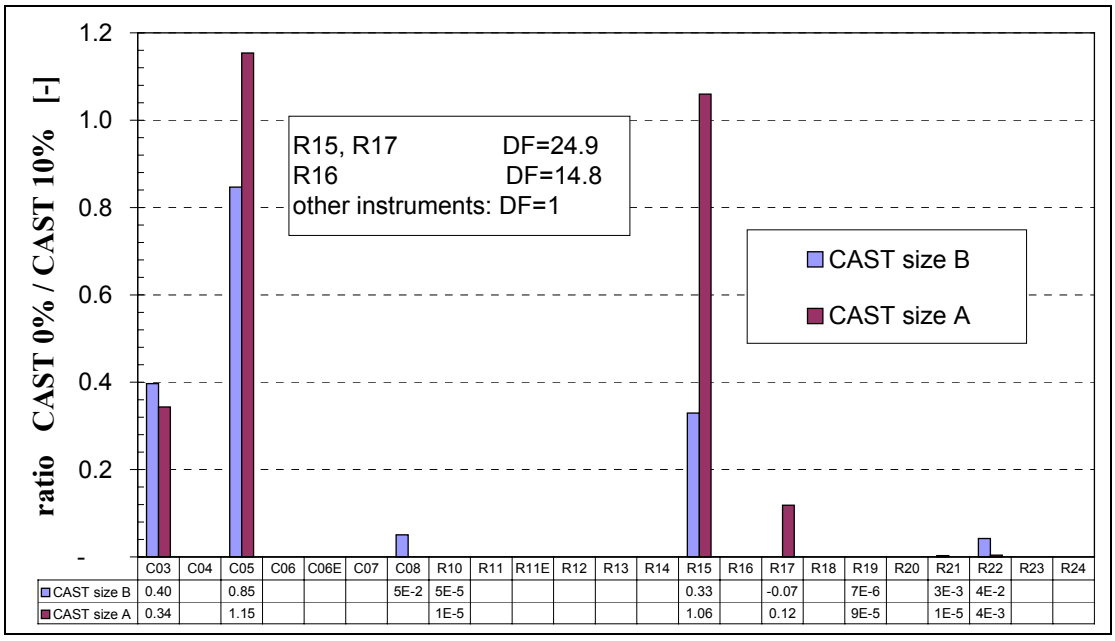
Figure 66: *Relative deviation on CAST measurements before & after the engine test period / CAST size B*

9.2.3 Noise level of instruments for CAST measurements

In a similar way to the engine tests, the results from the CAST measurements were analysed to obtain further information about the noise levels of the instruments. The noise-to-mean ratio was determined according to the definition described in section 8.2. The ratios were calculated for 10% and 90% concentrations for both CAST size settings (Figure 68 and Figure 69). In addition, a zero-check by setting the CAST at 0% concentration was carried out. This background test is compared to the measurements at 10% CAST setting in Figure 67.
Table 12 gives absolute values in number and mass measured by selected instruments. Figure 67 to Figure 69 show the noise/mean ratios for the individual instruments. It should be mentioned that only the instruments LQ1-DC (R15), EDB (R16) and PAS (R17) measured with their dilution unit upstream of the detection unit. This means that the actual measured concentration was lower by the dilution factor for these instruments in comparison with the other instruments. As can be seen from the results, the noise/mean ratios are significantly lower compared to the engine background measurements. This finding indicates that the higher noise for the engine test bench results is at least partly caused by the exhaust gas and dilution system.

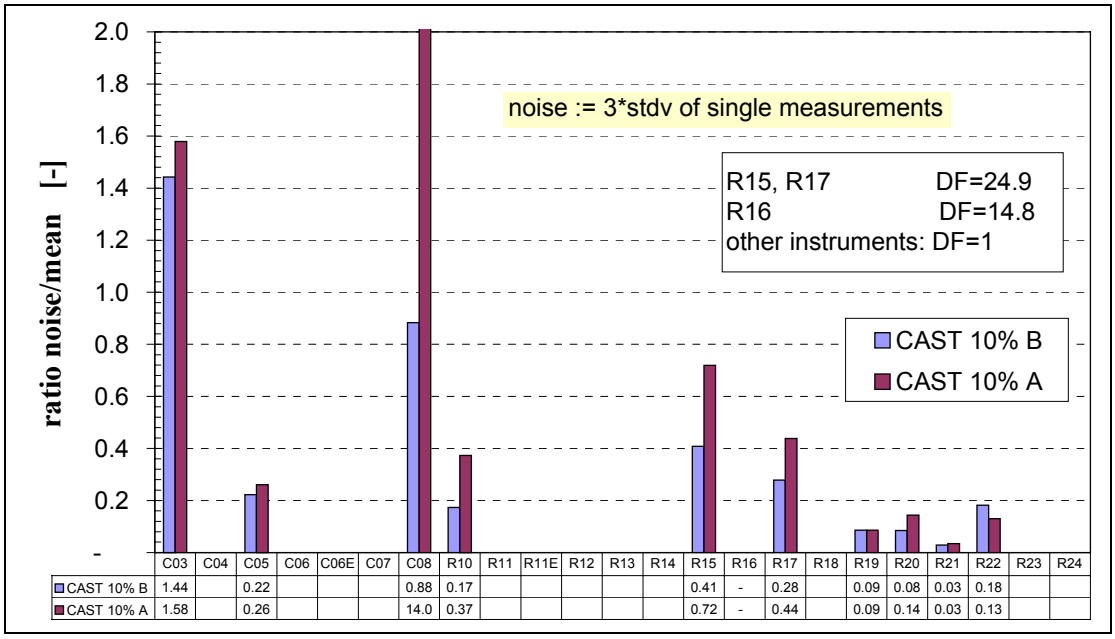
CAST setting	CPC (R19) [1/cm^3]	PASS (C08) [ng/cm^3]
conc. level 0%	6.8E-01	4.7E-04
conc. level 10% size B	4.96E+03	9.25E-03
conc. level 10% size A	1.51E+04	3.88E-04
conc. level 90% size B	5.19E+04	7.51E-02
conc. level 90% size A	1.80E+05	2.98E-03

Table 12: *Measured concentration of selected instruments for CAST settings*



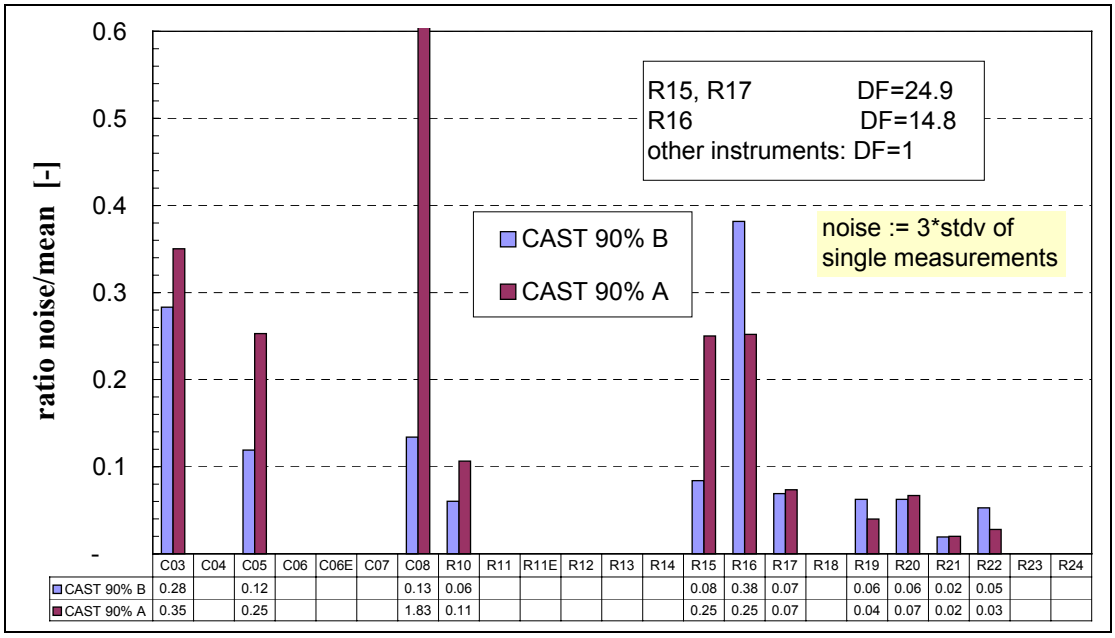
	C03	C04	C05	C06	C06E	C07	C08	R10	R11	R11E	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24
CAST size B	0.40		0.85				5E-2	5E-5						0.33		-0.07		7E-6		3E-3	4E-2		
CAST size A	0.34		1.15					1E-5						1.06		0.12		9E-5		1E-5	4E-3		

Figure 67: *Ratio on CAST measurements, Ratio between concentrations measured at 0% CAST setting (i.e. zero-check) and 10% CAST setting*



	C03	C04	C05	C06	C06E	C07	C08	R10	R11	R11E	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24
CAST 10% B	1.44		0.22				0.88	0.17						0.41	-	0.28		0.09	0.08	0.03	0.18		
CAST 10% A	1.58		0.26				14.0	0.37						0.72	-	0.44		0.09	0.14	0.03	0.13		

Figure 68: *Noise-to-mean ratio on CAST measurements, concentration setting: 10%*



	C03	C04	C05	C06	C06E	C07	C08	R10	R11	R11E	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24
CAST 90% B	0.28		0.12				0.13	0.06						0.08	0.38	0.07		0.06	0.06	0.02	0.05		
CAST 90% A	0.35		0.25				1.83	0.11						0.25	0.25	0.07		0.04	0.07	0.02	0.03		

Figure 69: *Noise-to-mean ratio on CAST measurements, concentration setting: 90%*

9.2.4 Linearity

Figure 70 shows the relative concentration measured by the instruments for the size setting A (mode of NSD at CAST size setting A) and B (mode of NSD at CAST size setting B). These two size ranges covered two different mass and number ranges. The measurements were carried out at EMPA before and after the engine test measurements. The data are normalised to the 90% value for each individual instrument. The range bars indicate the confidence interval of +/-1 stdv due to the variation within the 10 min measurement period.

Good performance in linearity is generally observed. There are some exceptions: LI2SA (C05) measured an almost constant concentration for the complete series of size A, for EDB (R16) the concentrations were too low for A30%, A10% and B10%, LQ1-DC (R15) showed rather high concentration for A10%.

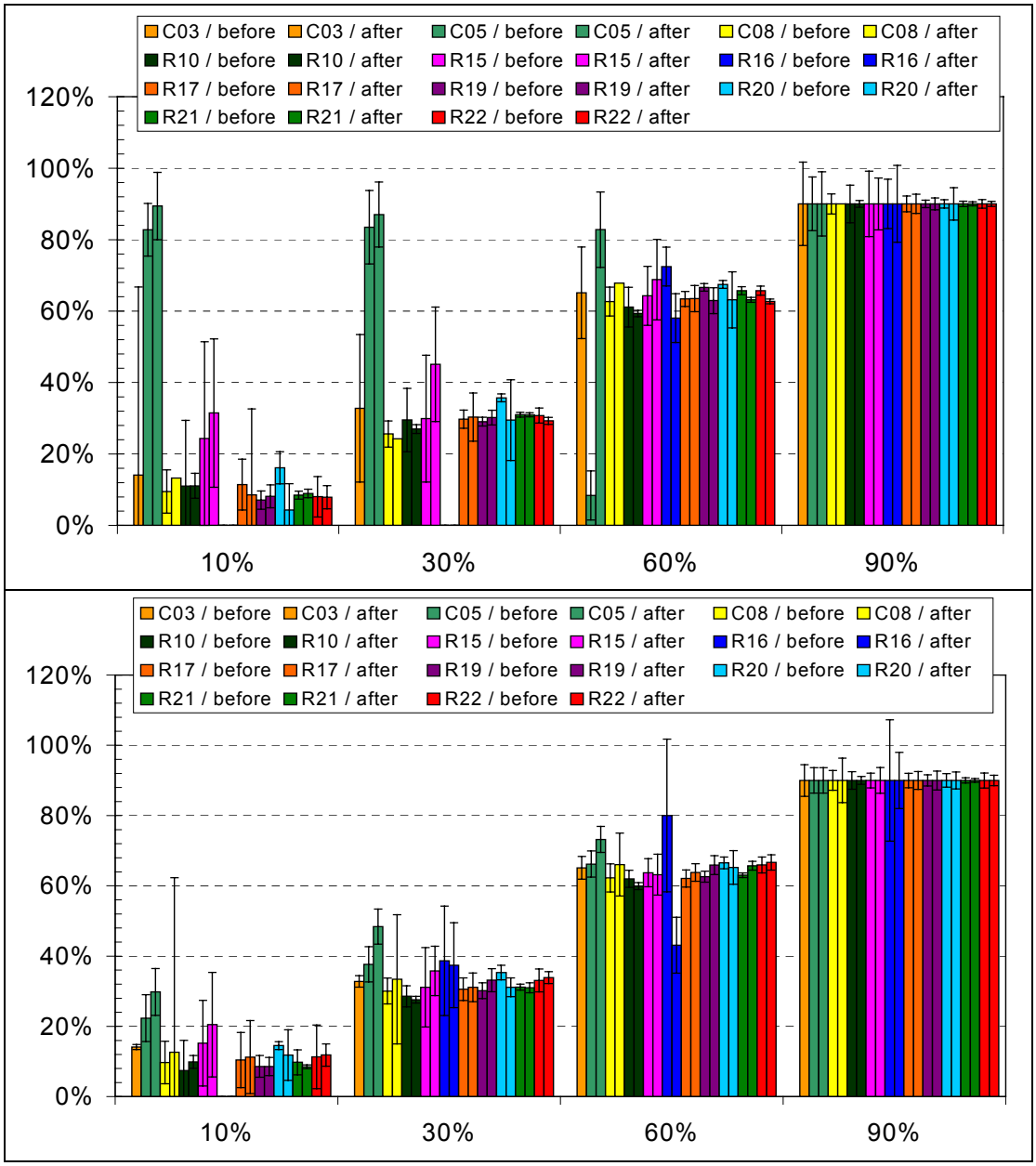


Figure 70: *Linearity of size A (upper figure) and size B (lower figure) measurements / CAST measurements*

The slightly higher values of LI2SA (C05) at CAST size B measurements can be explained by an offset of the instrument. This can also be seen in the correlation between LI2SA and other instruments (Figure 72).

9.2.5 Correlation between instruments

Figure 71 to Figure 81 show the concentrations measured by the individual instruments for the CAST measurements. For each instrument the results are correlated to three selected instruments, which are the CPC 3022A (TSI) operated by METAS, the LI2SA (C05) and coulometry (R11). Note that the measurements were **not** carried out simultaneously in most cases.

The filter sampling from the CAST for the coulometric analysis was carried out the day after the official measurements were finished. In order to achieve sufficient loading on the filters, only the 90% settings could be run and the duration of the single sampling was up to 2 hours. At least three runs per size setting were performed to quantify the measurement uncertainty, which is indicated by the range bars (+/- 1 stdv).

Some additional comments on the correlation are made in note form for each instrument in the corresponding figure.

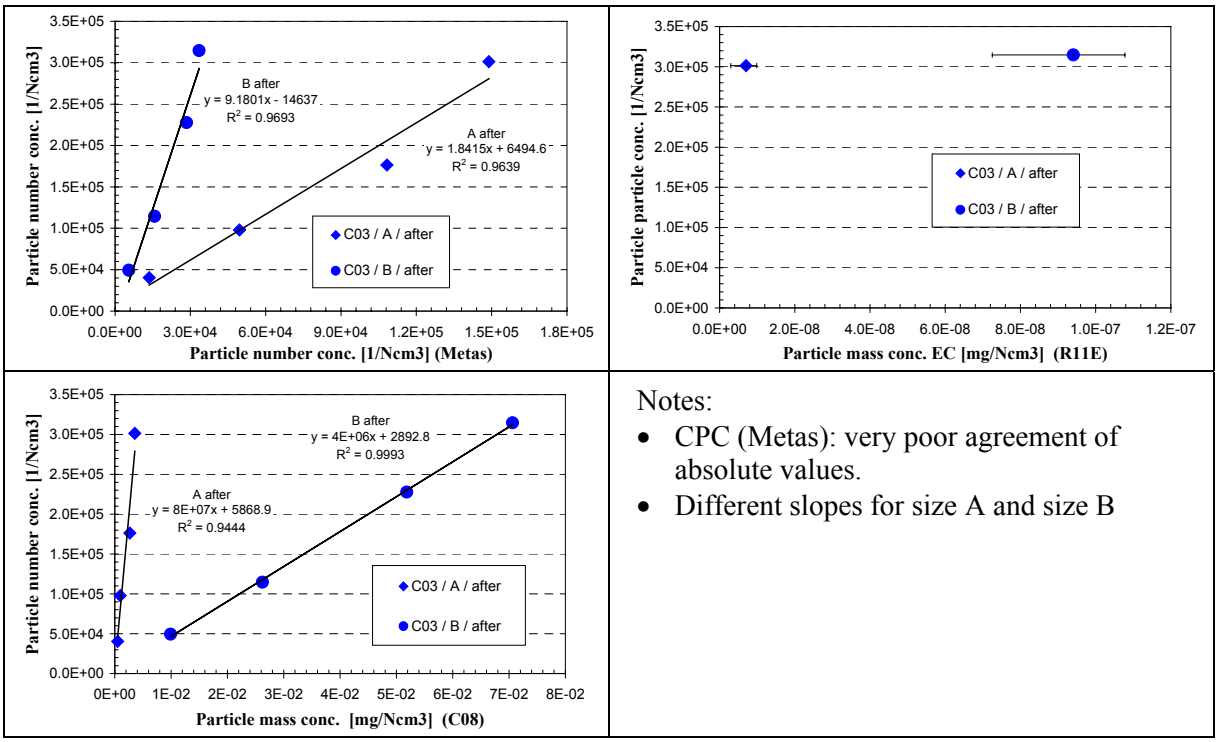
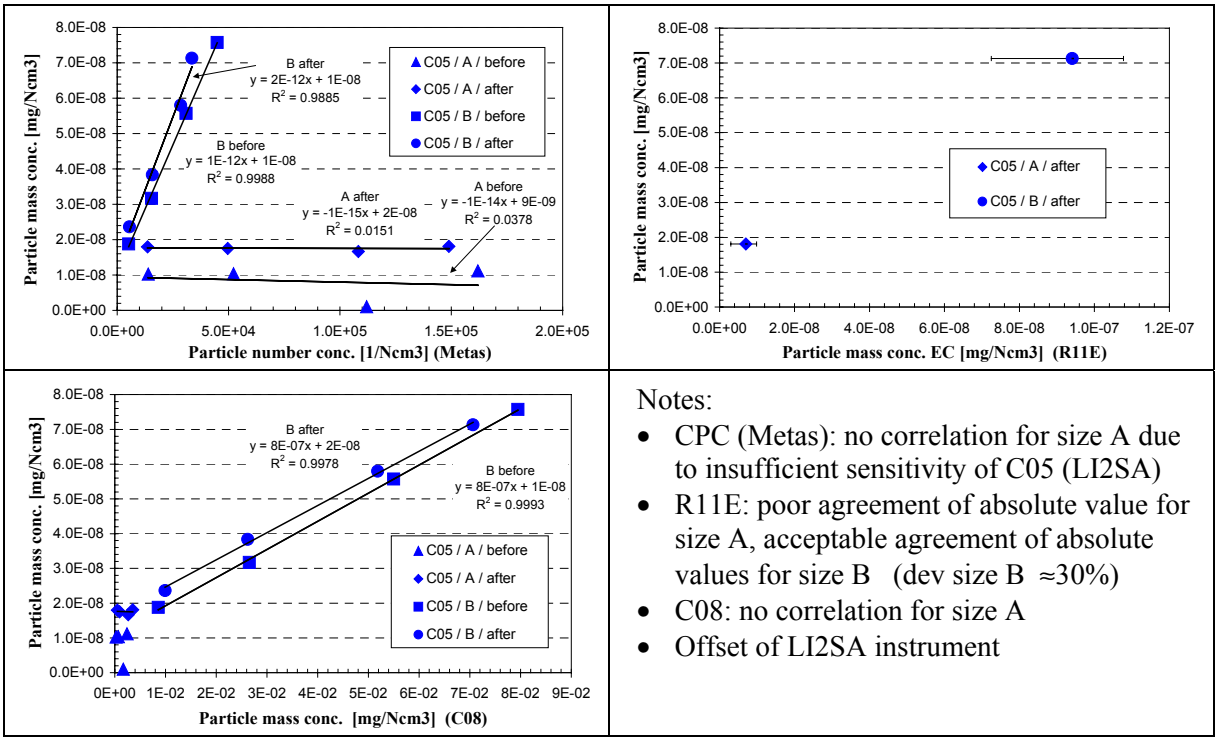


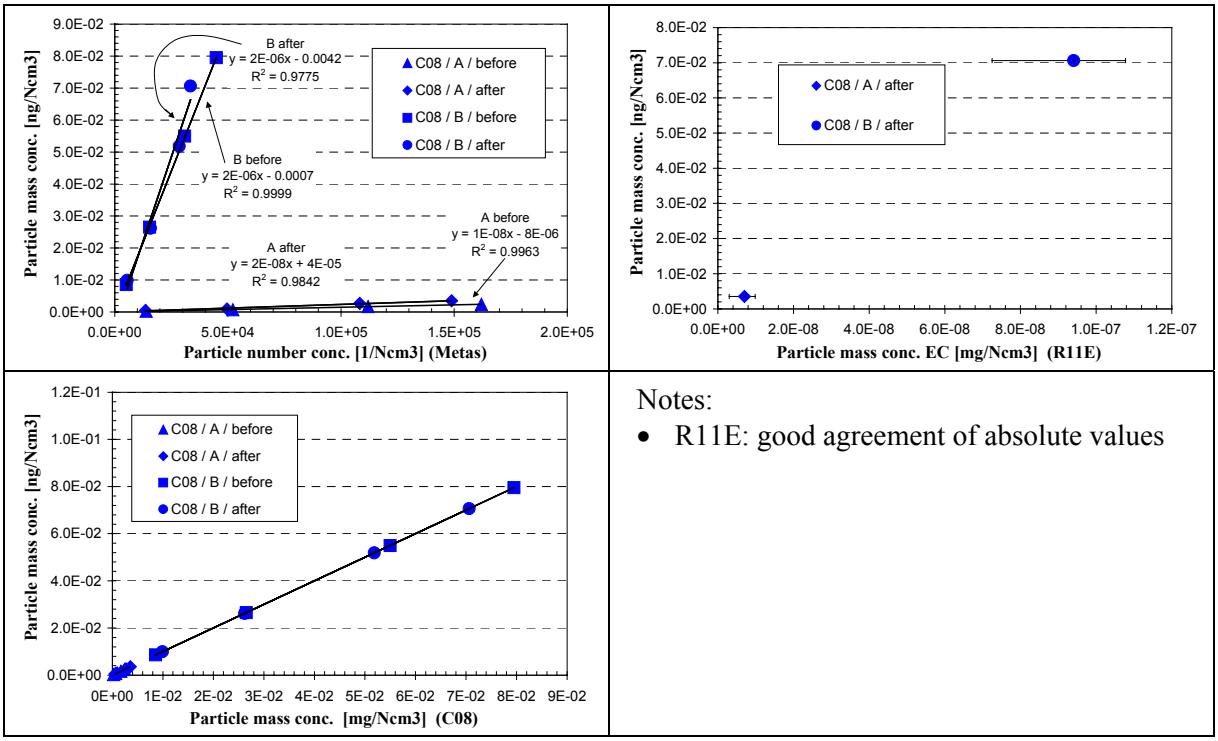
Figure 71: *Correlation between C03 and selected instruments / CAST measurements*



Notes:

- CPC (Metas): no correlation for size A due to insufficient sensitivity of C05 (LI2SA)
- R11E: poor agreement of absolute value for size A, acceptable agreement of absolute values for size B (dev size B ≈30%)
- C08: no correlation for size A
- Offset of LI2SA instrument

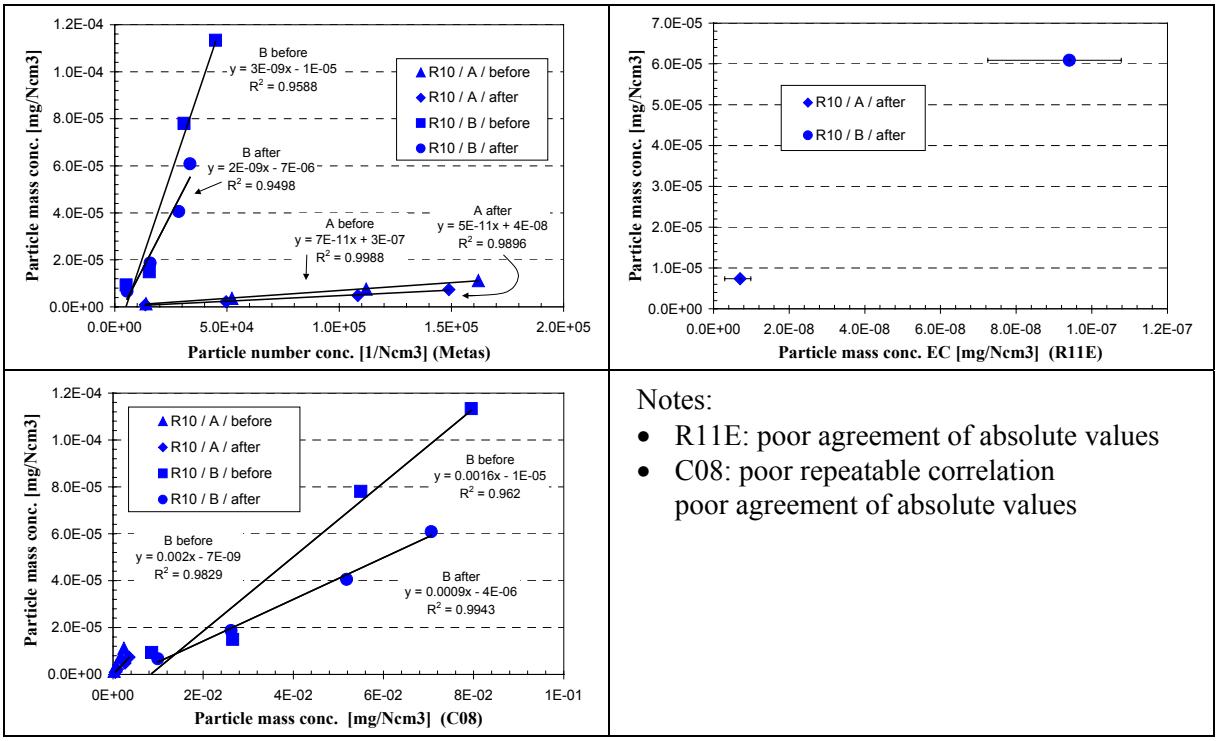
Figure 72: *Correlation between C05 and selected instruments / CAST measurements*



Notes:

- R11E: good agreement of absolute values

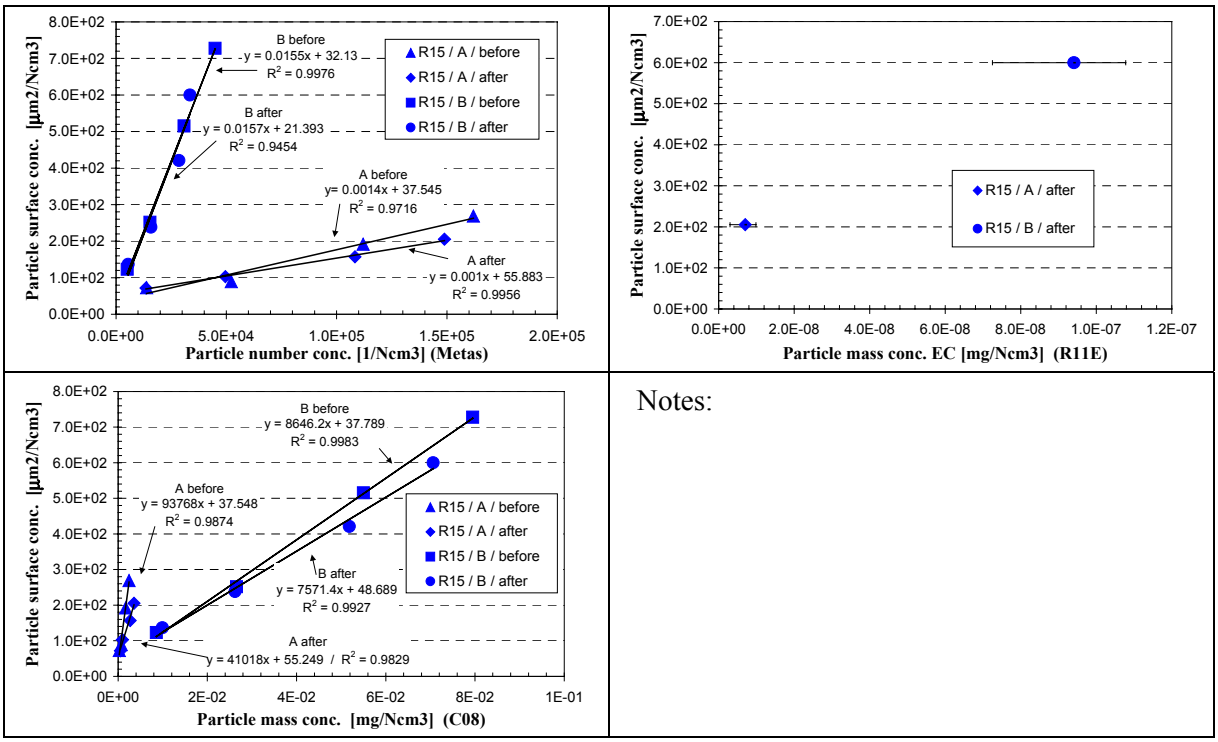
Figure 73: *Correlation between C08 and selected instruments / CAST measurements*



Notes:

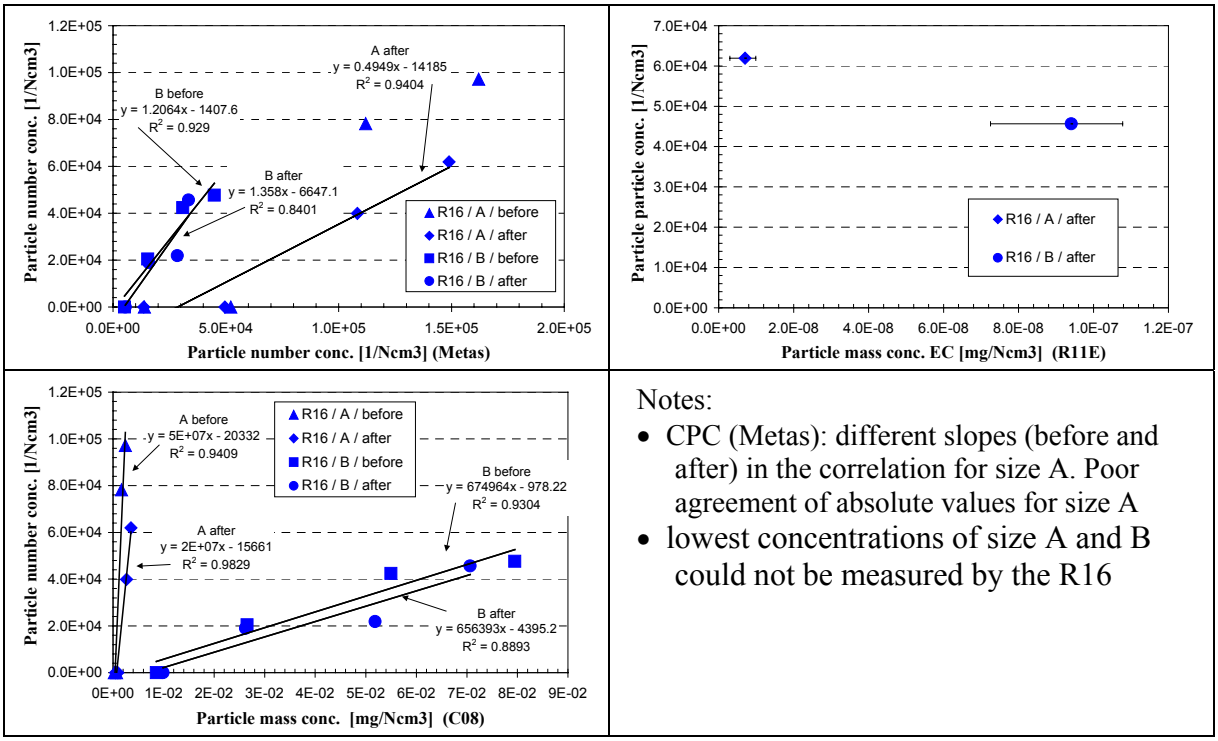
- R11E: poor agreement of absolute values
- C08: poor repeatable correlation
  poor agreement of absolute values

Figure 74: *Correlation between R10 and selected instruments / CAST measurements*



Notes:

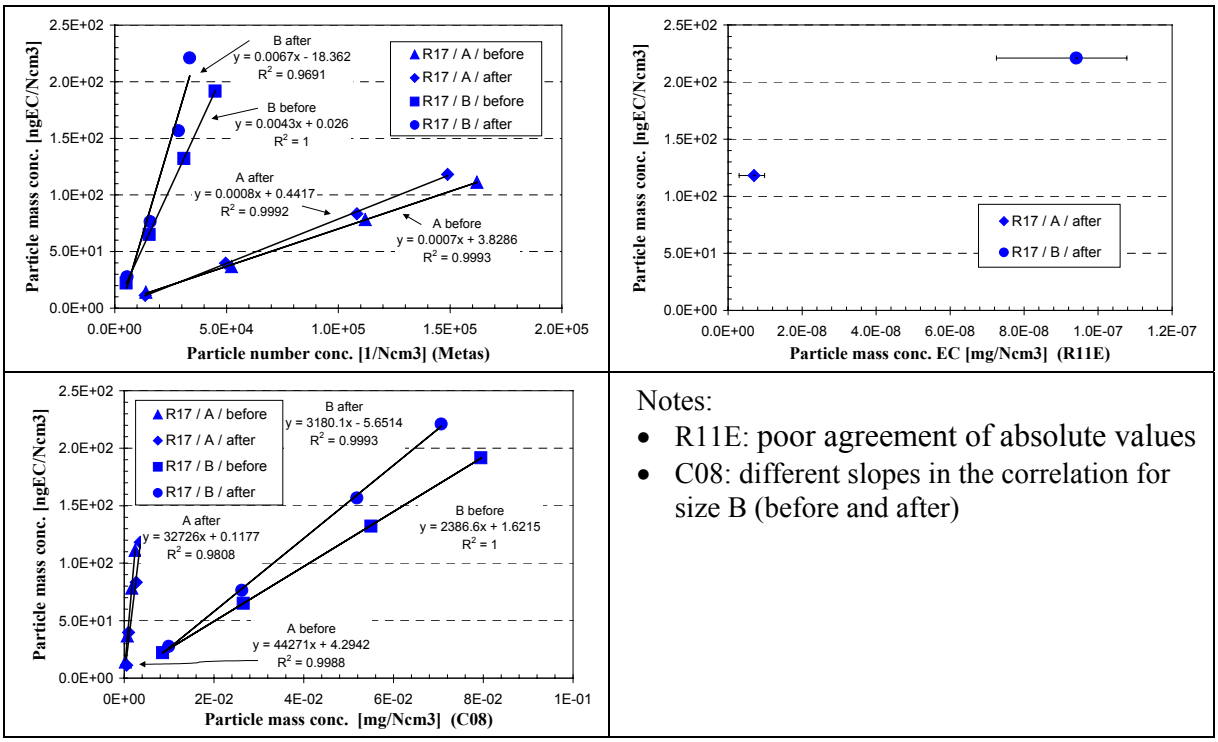
Figure 75: *Correlation between R15 and selected instruments / CAST measurements*



Notes:

- CPC (Metas): different slopes (before and after) in the correlation for size A. Poor agreement of absolute values for size A
- lowest concentrations of size A and B could not be measured by the R16

Figure 76: *Correlation between R16 and selected instruments / CAST measurements*



Notes:

- R11E: poor agreement of absolute values
- C08: different slopes in the correlation for size B (before and after)

Figure 77: *Correlation between R17 and selected instruments / CAST measurements*

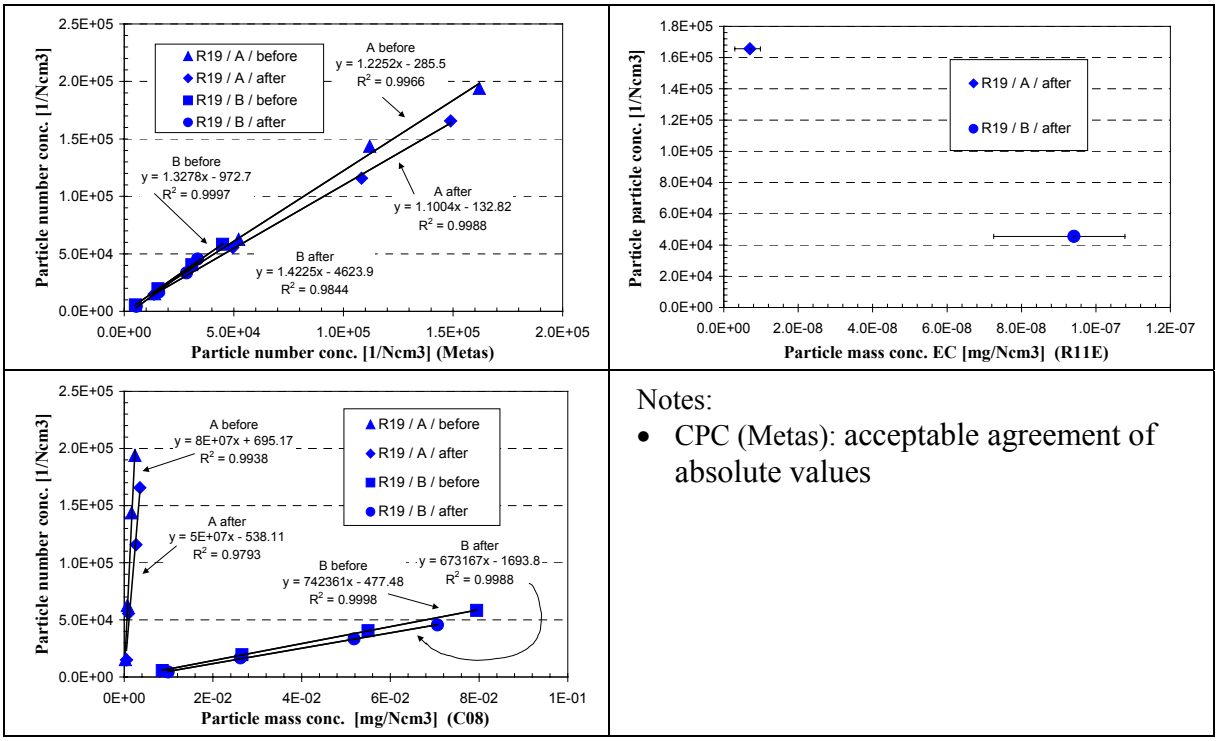


Figure 78: *Correlation between R19 and selected instruments / CAST measurements*

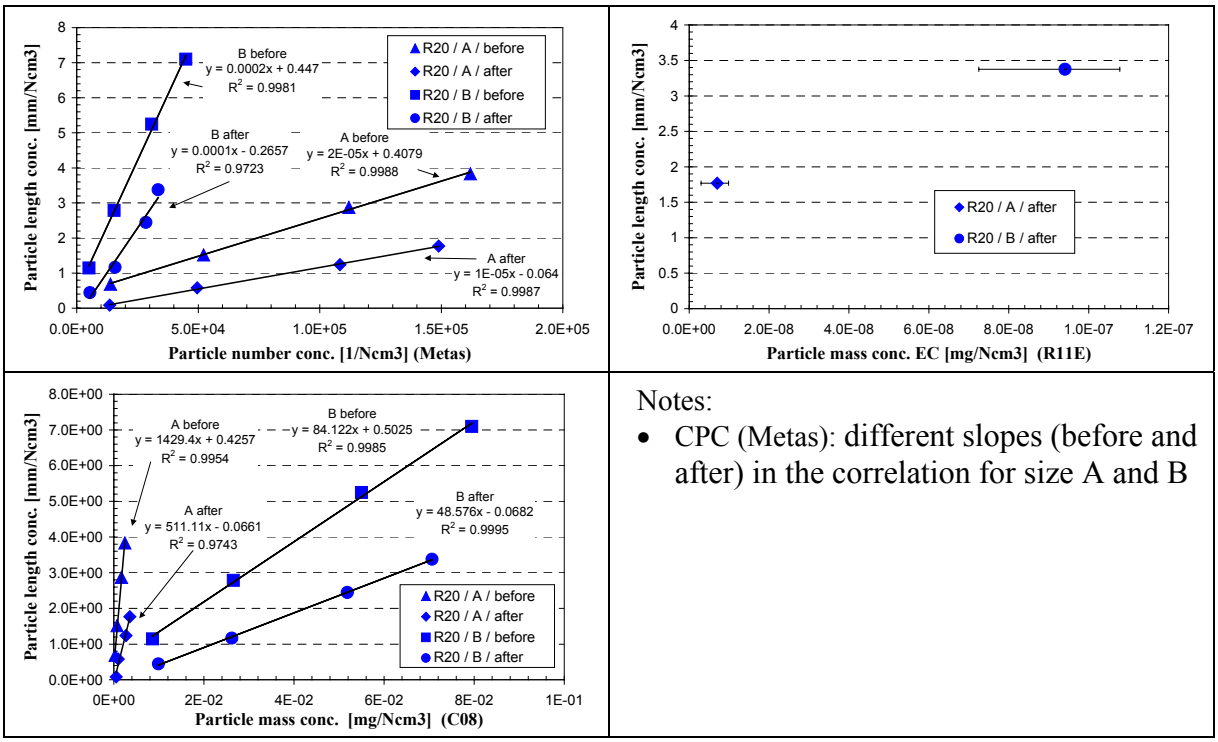


Figure 79: *Correlation between R20 and selected instruments / CAST measurements*

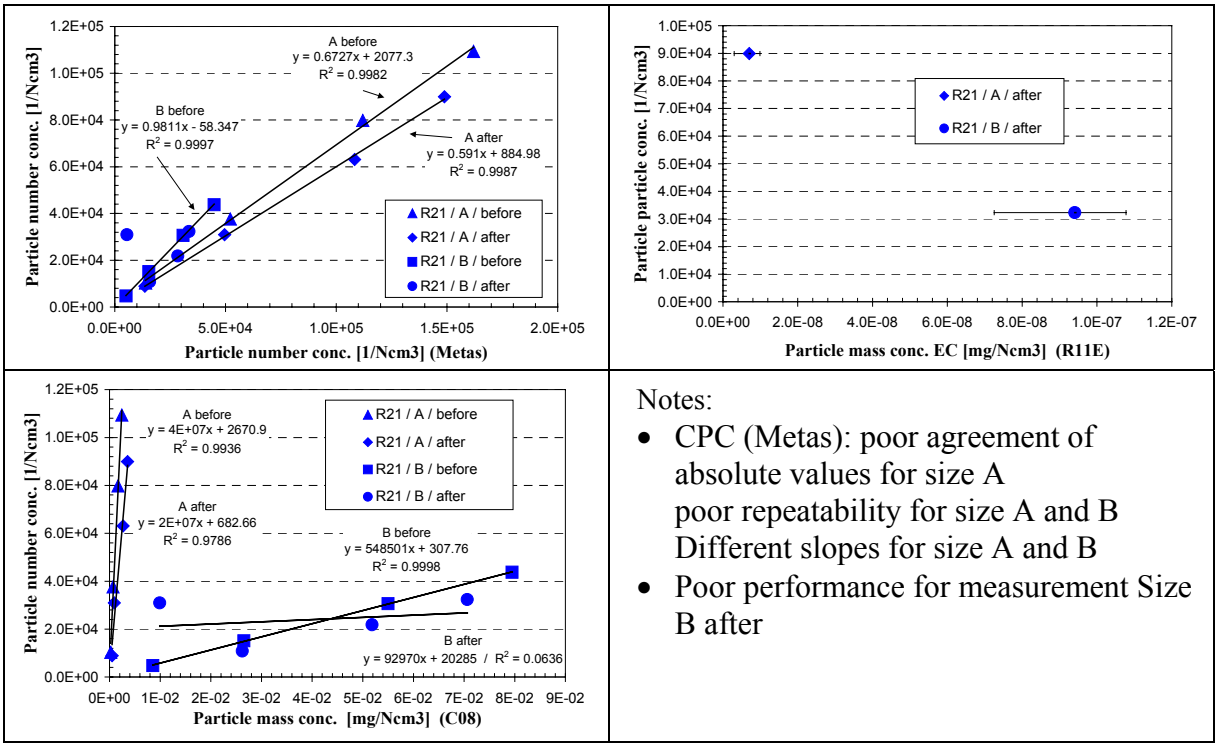


Figure 80: *Correlation between R21 and selected instruments / CAST measurements*

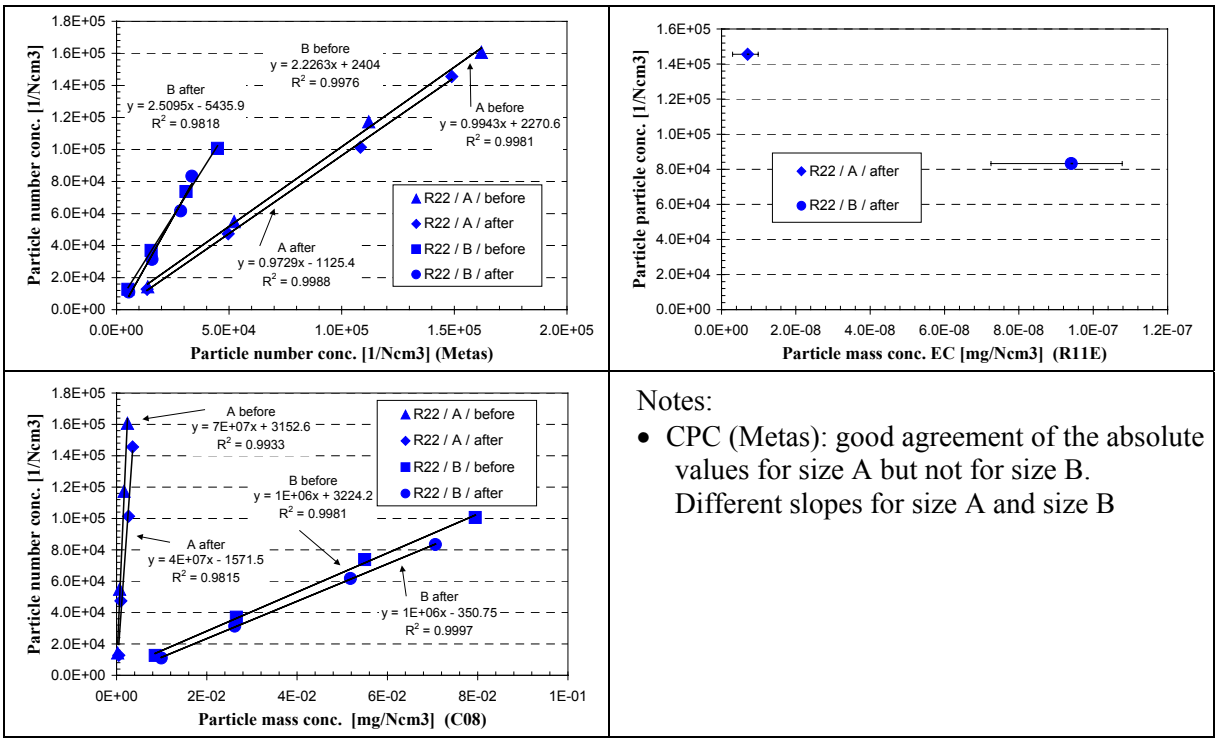


Figure 81: *Correlation between R22 and selected instruments / CAST measurements*

9.2.6 Size information

Two size settings were investigated with the CAST aerosol generator. Figure 82 plots the modes of the NSD's as measured by METAS in their laboratories before and after the measurement programme at EMPA. A scanning mobility particle sizer (SMPS 3934-C, TSI) was used for this calibration.

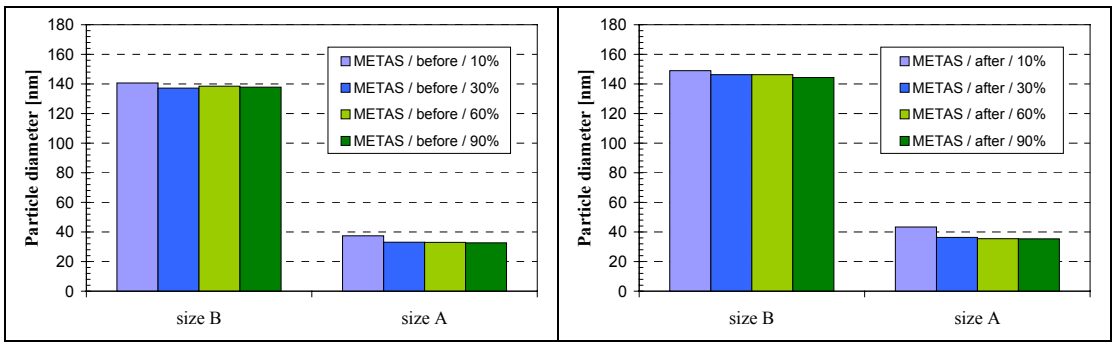


Figure 82: *Mode of NSD of the CAST measurements before and after EMPA measurement programme / measured by METAS*

Figure 83 to Figure 88 show the results of the particle size measurements of the individual instruments with the CAST. The purpose of the graphs is to show the stability of the measurements for the individual instruments. The absolute values cannot be compared between the instruments due to the fact that different measuring principles are applied.

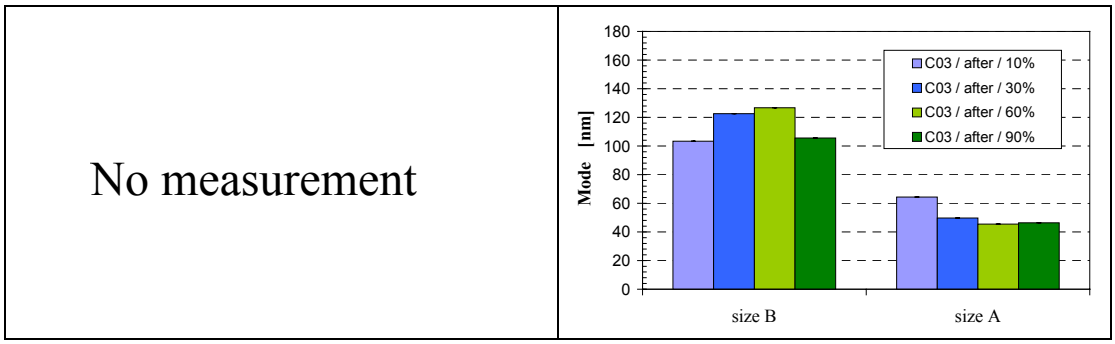


Figure 83: *Mode of NSD as measured by DMS (C03) on the CAST measurements*

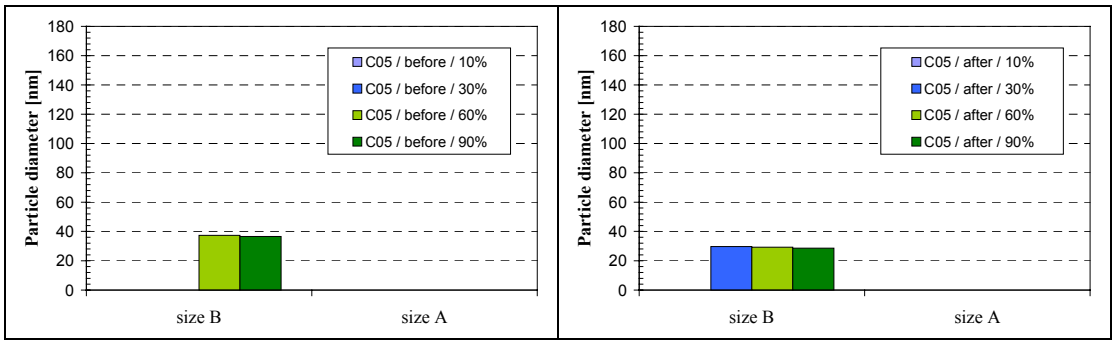


Figure 84: *Mean of primary particles as measured by LI2SA (C05) on the CAST measurements*

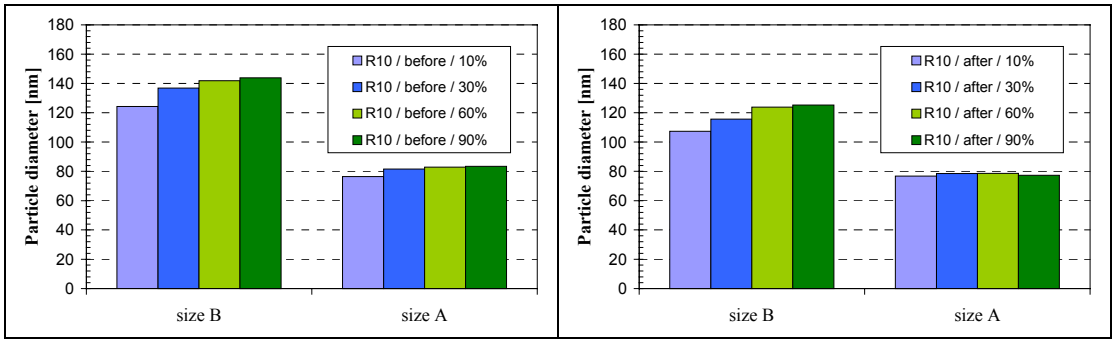


Figure 85: *Median of active surface distribution for the CAST measurements as measured by MasMo (R10)*

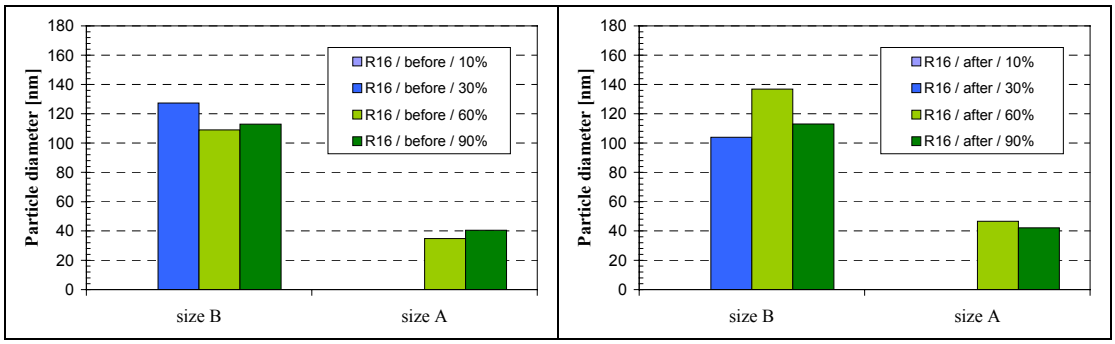


Figure 86: *Mode of NSD for the CAST measurements as measured by EDB (R16)*

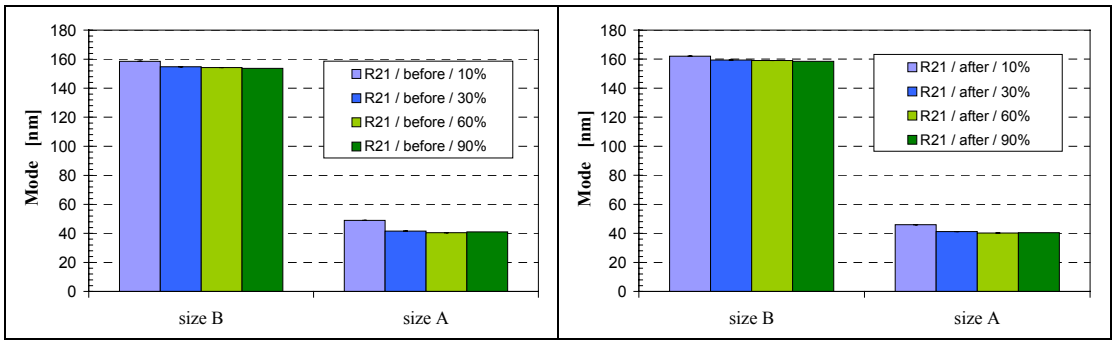


Figure 87: *Mode of NSD for the CAST measurements as measured by SMPS (R21)*

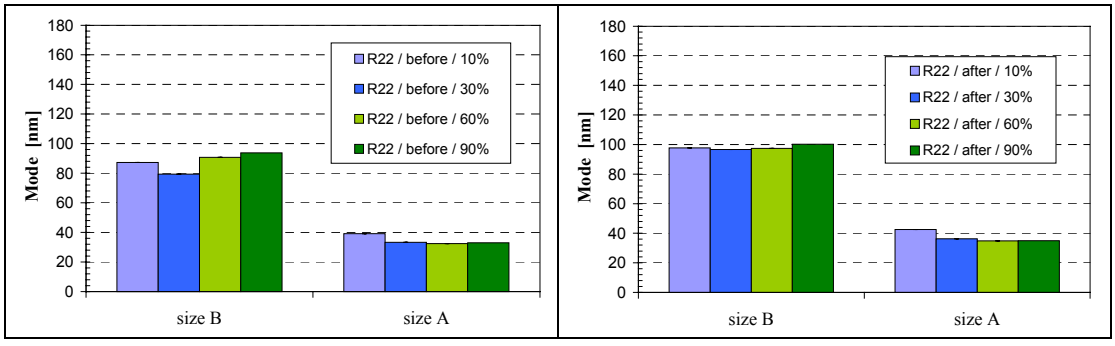


Figure 88: *Mode of NSD for the CAST measurements as measured by ELPI (R22)*

10 Discussion

At the time of completion of this report, there was as yet no detailed catalogue of criteria in existence within PMP for the assessment of the candidate systems. This fact affected the present experimental study in the following ways:

- The participating systems could not be optimised for this catalogue of criteria that will be defined in a later phase of PMP.
- The manufacturers applied their own individual strategy for their measurement set-up with the consequence of reduced comparability between the candidate systems.
- A clear assessment and ranking of the systems for the suitability for future legislation was not possible owing to the missing criteria.

Complete measurement systems were investigated in this study, consisting of sampling and a detection unit. Some of the instruments took their sample from the exhaust gas line, others from the primary full-flow CVS tunnel and a third group took it from the secondary dilution tunnel. The use of different sampling systems has to be taken into account by comparing the **instruments** only to each other.
In order to generate emission values (e.g. in units per kWh), the particle concentrations measured from raw gas exhaust line has to be multiplied by the time-synchronised exhaust gas flow that is measured separately. The separate procedure of exhaust flow measurement has not been taken into account for the assessment of the candidate systems as it is a general requirement for all applications of raw gas measurements.

For the assessment of the candidate systems, the following criteria were investigated in this study:

- Robustness
  - suitability for type approval tests
- Repeatability
  - transient tests
  - steady-state tests
- Time response
  - capability to follow a transient cycle
  - response on step changes in engine operation
- Linearity
- Sensitivity
  - Ratio between two emission levels
- Detection limit
  - Variation of several low concentration measurements
  - Noise-to-signal ratio
- Plausibility of absolute values
  - Correlation between instruments

Further aspects for the assessment were considered but were not investigated in this study

- Ease of calibration

- link to traceable references

Criteria that were not considered due to lack of data but should be considered in future studies

- Reproducibility
  - accuracy and precision (determined by measurement with different instruments of the same model for the same emission source)
- Response to variation in particle properties
  - composition of particles (soot, adsorbates, etc.)
  - morphology, density
- Response to variation in sampling conditions
  - temperature, humidity, pressure conditions, residence times, flow rates
- Concentration range
  - defines the demands on the dilution system

DMS (C03)

Robustness

The version of DMS that was tested at EMPA was a prototype. The instrument was still being optimised during the measurement programme with the result that some measurements were skipped. No fundamental problems in robustness were identified that would restrict use for type approval tests.

Repeatability

The conditioning of the sample for the DMS was not optimised as no additional dilution or thermal treatment was used downstream of the sampling from the primary CVS tunnel. As a consequence, the DMS measures significantly volatile particles more often and in a much higher concentration during the test runs compared to other measurement systems. The presence of nuclei particles had a detrimental effect on the repeatability of the results, mainly for the low post-trap set-up (i.e. low-emission configuration). In the few cases without nucleation, the DMS showed a COV in the range of 15% or better.

Response time

The response time (t_{50-10}) of the DMS to well-defined concentration changes was observed to be fast, within a few seconds. The t_{90-10} times showed slightly higher values in the range of 10 to 20 s, probably due to the non-stable contribution of volatile particles. The DMS was able to follow a transient test cycle and to detect individual peaks in particle concentration due to brief load peaks during the transient ETC.

Limit of detection (LOD)

The LOD of the DMS shows a rather high value caused by nucleation effects, resulting in a very low (about 15) ratio between ETC high-emission and LOD.
The LOD is larger than the concentration measured at ETC low-emission level. No proposition was therefore possible for the ETC low-emission configuration (post-trap).

Sensitivity

The results are affected by the frequently detected nucleation particles (very high LOD).
The use of an modified sampling system in order to get rid of the nucleation phenomena will greatly improve the sensitivity of the instrument.

Linearity

The DMS showed flawless performance in linearity during the CAST tests.

Comparison with other instruments

The frequent detection of nucleation particles again made it difficult to interpret the absolute values. Owing to this effect, the DMS measured significantly higher number concentrations than the other number-based instruments in most cases. But significant discrepancy is also observed for the CAST measurements between the absolute values measured by CPC (METAS) and those measured by the DMS, which cannot be explained by nucleation. Nevertheless, a rather close correlation between DMS and the CPC (R19) was observed (R^2=0.89) for the engine data when modes with obviously strong nucleation were excluded.

Calibration

The calibration procedure of absolute number concentration by a traceable standard is not yet fixed. The calibration of size can be carried out by means of standard reference particles (latex, gold).

Summary

The tested DMS was a prototype, and it is assumed that further development will improve the performance. The DMS provides time-resolved and size-discriminated data that most probably exceed the requirements for a future type approval test procedure. The benefit of the number-based instrument is the very high sensitivity and the ability to distinguish between different modes of particles by the size information.
The results obtained by the DMS were greatly affected by the detection of nucleation particles due to non-heated sampling. For this reason, the true performance of the DMS could not be evaluated. However, discrepancies in number concentration were also observed for the CAST measured where no nucleation took place.

Gravimetric filter method (C04)

Robustness

The application as the regulated method for type approval tests for more than twenty years proves the robustness of the gravimetric filter method. No detrimental effects was observed due to the adoption of some specifications of US 2007 Federal Register.

Repeatability

Good repeatability was observed for all test measurements. The COVs of the measurement results were found to be within 10% for the high-emission configuration and 20% for the post-trap (low-emission) configuration.

Response time

The method does not provide time-resolved results.

Limit of detection (LOD)

The LOD was found to be about 60% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission (about 60% of Euro 4) was about 11 times higher than the LOD.

Sensitivity

The gravimetric filter method showed comparatively small differences in concentration between the two investigated emission levels configuration with and without bypass. For all test cycles, the ratio between high (60% of Euro 4) and low-emission (post-trap) configuration was below 10.
The concentrations for the background and post-trap were measured in the same range as for most instruments.

Linearity

No tests for linearity were carried out with CAST due to the high flow rates required for the filter methods.

Comparison with other instruments

Rather poor correlation to other measurement systems was generally observed. For the single-mode B100, significantly higher concentrations were found in comparison with other instruments probably due to condensed material. Almost perfect correlation was found to the MEXA 1370 PM (C06) ($R^2 = 0.96$). The regression factor (R^2) for the correlation to the other instruments did not exceed 0.56.

Calibration

A calibration procedure is established for the regulated gravimetric filter method which is based on reference weights.

Summary

The gravimetric filter method as applied in this study is based on EU Directive 1999/96/EC. However some specifications of the US 2007 Federal Register were adopted. The main modifications affected the use of a pre-cyclone and filter holders for filters of 47 mm diameter, filters of different quality, the thermal insulation of the sampling system and the conditioning of the dilution air.
The gravimetric filter method performed very well in the repeatability tests. The relatively low sensitivity compared to number/surface-based systems has to be assessed less favourably. The poor correlation to most of the other instruments is probably due to the volatile fraction. Whereas most instrument detect only solid particles, the particle mass collected on the filter also includes volatile material due to the sampling conditions.

LI2SA (C05)

Robustness

Although the LI2SA is a fairly new measurement instrument, it gave the impression of being very robust during the measurement programme.

Repeatability

Very good repeatability was observed for most test cycles. The COVs of the measurement results were found to be within 4% for the high-emission configuration (60% Euro 4) and 8% for the post-trap (low-emission) configuration of the transient ETC. A higher variation up to 30% was only found for some single modes at the low-emission level..

Response time

The response of the LI2SA to concentration changes were observed to be fast and stable within a few seconds ($t_{90-10} < 4$ s). The LI2SA was able to detect individual peaks in particle concentration during the transient ETC test cycle due to brief load peaks.

Limit of detection (LOD)

The LOD was found to be about 22% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission was about 45 times above the LOD.

Sensitivity

The LI2SA showed comparatively low differences in concentration between the two investigated emission levels with and without bypass. The ratio between high (60% Euro 4) and low-emission (post-trap) configuration did not exceed 15 for any test cycle.
The concentration for the background and post-trap were measured in the same range as for most instruments.
At the CAST measurements the LI2SA showed insufficient sensitivity for the low-mass settings.

Linearity

During the CAST tests, the LI2SA showed a flawless performance in linearity for the larger size setting (CAST size B). For the size setting (CAST size A), LI2SA did not show any response at all, as the mass concentrations of these samples with smaller particles were too low according to the specification of the instrument (see Appendix).

Comparison with other instruments

Good agreement to other mass-based methods was generally observed for the high-emission configuration. Very good correlation was found to EC mass-based instruments (C06E: R^2 = 0.97, C08: R^2 = 0.99) and to the MasMo (R10: R^2 = 0.99). Moreover, the LI2SA showed good correlation to the CPC 3022A (R19) (R2 = 0.96). For the high-emission configuration, the agreement of the absolute values was within 12% of the EC values measured by coulometry (R11E) and 25% for PASS (C08). Significantly higher concentration compared to coulometry (R11E) and MEXA (C06E) were measured for the post-trap configuration. Poor performance was observed in the CAST measurements at CAST size setting A (lower mode of the number size distribution). Here, the LI2SA did not show any response, in contrast to most other instruments.

Calibration

The LI2SA can be calibrated for EC mass by the coulometric reference method.
With regard to the primary particle size, no calibration method is as yet available to the authors' knowledge.

Summary

The LI2SA provides time-resolved real mass data including information on the mean size of the primary particles. The instrument performed very well in relation to repeatability and showed good correlation to other instruments. However, the sensitivity is low in comparison with number-based instruments and was not sufficient for some very low concentration settings. It should be mentioned that the LI2SA is able to measure from the raw gas line, which would have increased the sensitivity by the dilution factor. According to the manufacturer, the sensitivity has been improved in the latest version of the instrument.

MEXA 1370 PM (C06)

Robustness

The filter sampling and its analysis by the instrument were found not to pose any problems during the measurement programme.

Repeatability

Good repeatability was observed for all test measurements. For the ETC, the COV of the measurement results was found to be within 2% for the high-emission configuration (60% Euro 4) and 6% for the post-trap (low-emission) configuration. For the steady-state tests a higher COV of up to 20% was observed for both configurations. Looking at all cycles performed at high-emission level, the COV values of EC tend to have higher values.

Response time

This method does not supply time-resolved results.

Limit of detection (LOD)

The LOD was found to be about 20% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission (about 60% of Euro 4) was about 31 times higher than the LOD.

Sensitivity

The MEXA 1370 PM showed comparatively small differences in total mass between the two investigated emission levels with and without bypass. For all test cycles, the ratio between high (60% Euro 4) and low-emission (post-trap) configuration was below 10. Higher ratios of between 13 and 70 were determined by looking only at the EC fraction. For both, total mass and EC mass, the values were measured in the same range for the background and post-trap as for most instruments.

Linearity

No tests for linearity were carried out by CAST due to the high flow rates required for the filter methods.

Comparison with other instruments

The MEXA showed almost perfect agreement to the gravimetric filter method (C04). The deviation of the slope of regression line was within 1% with $R^2 = 0.96$. This is also a result of the identical sampling procedure applied for both filters. With regard to correlation to other instruments, a good result was found for the EC mass (R11E: $R^2 = 0.94$, C05: $R^2 = 0.97$). However, the MEXA detected about 60% of the EC mass measured by coulometry.

Calibration

The instrument is calibrated by CO_2 and SO_2 calibration gas.

Summary

The MEXA 1370 PM is a filter-based method where weighing is replaced by gas analysis after vaporisation. The method performed very well in the repeatability tests. The very good agreement compared to the gravimetric filter method (C04) was due to the identical sampling procedure.
The MEXA shows low sensitivity similar to the gravimetric filter method (C04) and most other mass-based instruments in comparison with the number-, length-, surface-based instruments. Because the method is able to distinguish between different species of particles, the sensitivity can be improved by taking only the EC mass into account for the quantification.

TEOM (C07)

The TEOM participated in the measurement programme, but EMPA has never received any measurement results for further data evaluation. For this reason, no assessment of the instrument is possible.

PASS (C08)

Robustness

The PASS tested at EMPA was a prototype, but proved to be very robust during the measurement programme.

Repeatability

A very good repeatability was observed for most test cycles. The COVs of the measurement results were found to be within 2% for the high-emission configuration (60% Euro 4) and 13% for the post-trap configuration of the transient ETC. A higher variation of up to 32% was only found for some single modes at the low-emission level.

Response time

The response of the PASS to a defined concentration changes was found to be fast and stable within a few seconds ($t_{90\text{-}10} < 4$ s). The PASS was able to follow a transient test cycle and to detect individual peaks in particle concentration due to brief load peaks during the transient ETC.

Limit of detection (LOD)

The LOD was found to be about 40% of the measured ETC low-emission concentration. The concentration for the ETC high-emission (about 60% of Euro 4) was about 74 times higher than the LOD.
The PASS showed fairly high noise-to-signal values for the CAST measurements.

Sensitivity

The PASS showed comparatively small differences in the ratios between high (60% Euro 4) and low-emission (post-trap) configuration. Ratios between 8 and 41 were determined for the different test cycles (ETC: 28). These results are significantly lower than for most number /length/surface-based instruments.

Linearity

During the CAST tests the PASS showed flawless performance in linearity for both size settings studied.

Comparison with other instruments

Good agreement with other mass-based methods was generally observed for the high-emission configuration. Very good correlation was found to EC mass-based instruments (C06E: $R^2 = 0.95$, C05: $R^2 = 0.99$). Moreover, the PASS showed good correlation with the CPC (R19) (R2 = 0.94). Looking at the high-emission level, the agreement of the absolute values compared to the EC values measured by the coulometry is within 37%, and agreement in comparison with LI2SA (C05) is about 25%. Significantly higher concentrations compared with coulometry (R11E) and MEXA (C06E) were measured for the post-trap configuration.

Calibration

The PASS can be calibrated for EC mass by comparison with the coulometric reference method.

Summary

The PASS provides time-resolved real mass data. The instrument performed very well in repeatability and showed good correlation with other instruments. However, the sensitivity is low in comparison with number-based instruments. Some discrepancy in absolute values was found for very low concentration compared to EC values. Although the PASS tested at EMPA was a prototype, the instrument showed convincing performance.

MasMo (R10)

Robustness

Although the MasMo is a fairly new measurement instrument, it proved to be very robust during the measurement programme.

Repeatability

Good repeatability was observed for most test cycles. The COV of the measurement results was found to be within 8% for the high-emission configuration (60% Euro 4) and 24% for the post-trap (low-emission) configuration of the transient ETC. Only for some single modes at the low-emission level was a higher variation of up to 52%.

Response time

The response to a defined concentration change was observed to be fast and stable within a few seconds ($t_{90-10} < 8$ s). The MasMo was able to follow a transient test cycle and to detect individual peaks in particle concentration due to brief load peaks during the transient ETC.

Limit of detection (LOD)

The LOD was found to be about 72% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission (about 60% of Euro 4) was about 715 times higher than the LOD, which is somewhat high for a mass-based instrument.
The MasMo showed a rather low noise-to-signal value within single CAST measurements.

Sensitivity

Relatively high differences between high (60% Euro 4) and low-emission (post-trap) configuration were measured by the MasMo. Ratios between 25 and 3000 were determined for the different test cycles (ETC: 520). The MasMo showed high sensitivity in comparison with other mass-based instruments.
In contrast to most other instruments, the MasMo measured a significantly higher mass concentration for the background than for the post-trap configuration.

Linearity

The CAST tests exhibited flawless performance in linearity for the MasMo.

Comparison with other instruments

Good agreement with other mass-based methods was generally observed for the high-emission configuration. Very good correlation was found to EC mass based instruments (C06E: $R^2 = 0.95$, C05: $R^2 = 0.99$). The agreement of the absolute values was within 37% compared to the EC values measured by the coulometry (R11E) and 25% in correlation to the LI2SA (C05).
The MasMo also benefited from the use of a heated sampling line and the heated dilution unit.

Calibration

A calibration by a traceable standard would be a problem as the mass is calculated from a surface-related size distribution. The calibration of absolute surface area concentration by a traceable standard has not yet been solved.

Summary

The MasMo provides time-resolved mass concentrations including some size information. The mass and size information is calculated using size distribution for the active surface and the particle density. The reliability of the median active surface area diameter was not investigated in this study. The mass median diameter will be calculated in the updated software version.
The instrument performed very well in repeatability and showed good correlation with other instruments for mass concentration. The sensitivity was found to be high in comparison with other mass-calibrated instruments. Although the MasMo is a very new measurement technique, the instrument showed convincing performance. As the algorithms assume a monomodal symmetric distribution of the measured aerosol, more experience has to be gained with aerosols that do not fulfil this condition, e.g. aerosol downstream of a trap, bimodality by additives.

Coulometry (R11)

Filter sampling using the partial flow system AVL Smart Sampler was found to operate without any problems during the measurement programme.

Repeatability

In view of the fact that the coulometry is a reference method, the results for the repeatability were not very satisfactory. The COV of the EC+OC mass was found to be within 19% (EC: 23%) for the high-emission configuration (60% Euro 4) and 41% (EC: >700%) for the post-trap configuration of the transient ETC. For some single modes higher variation up to 180% was found for the low-emission configuration. The high variation for the EC mass at the close-to-zero level indicates offset instability of the instrument.

Response time

The method does not provide time-resolved information.

Limit of detection (LOD)

For both, EC+OC and EC, the LOD was found to be about 120% of the measured ETC low-emission concentration. The concentration for the ETC high-emission (about 60% of Euro 4) was about 6.6 times higher than the LOD.
For the EC measurements (R11E), the ratio between ETC low-emission and LOD is about 0.04, while the ratio between ETC high-emission and LOD is about 11.

Sensitivity

The coulometry showed comparatively low differences in concentration between the ratio between high (60% Euro 4) and low-emission (post-trap) configuration for EC+OC. Ratios between 4 and 60 were determined for the different test cycles (ETC: 8). EC alone revealed a significantly higher sensitivity. The values for the ratios between high and low were found to be between 7 and 260 (ETC: 260). Only slightly lower sensitivity was consequently determined for EC mass measured by coulometry than for the number/length/surface-based instruments.
Significantly higher EC+OC and EC mass concentration was measured for the background than for the post-trap configuration.

Linearity

No tests for linearity were carried out with CAST due to the high flow rates required for the filter methods.

Comparison with other instruments

Acceptable agreement to other mass-based methods was generally observed for the high-emission configuration. For the ETC post-trap measurements, the absolute PM values measured by the coulometry, by the gravimetric filter sampling (C04) and by the MEXA 1370 (C06) showed less than 10% variation in total mass. Better correlation with other instruments was found for the EC mass fraction (C06E: $R^2 = 0.94$, C05: $R^2 = 0.95$, $R^2 = 0.95$, R10: $R^2 = 0.94$, R19: $R^2 = 0.95$) than for OC+EC (C04: $R^2 = 0.51$). The agreement of the absolute EC concentrations was within about ±40% to the PASS (C08), LI2SA (C05) and MEXA (C06E).

Calibration
Coulometry is a reference method for the quantification of elemental carbon (EC).

Summary
Coulometry provides real mass concentrations for elemental carbon (EC) and organic bound carbon (OC). Due to the sampling, no time-resolved data is obtained. The principle is widely used for the regulation of EC exposure at workplaces in many countries. The measurements carried out in this study did not show very good repeatability, but good correlation of the EC concentration with many other instruments. However, the sensitivity is low compared to number-based instruments.

Dust Monitor (R12)
As the instrument took part in a very limited number of measurements, only a very reduced assessment of the system is possible.

Robustness
The number of measurements was too low for an assessment to be made.

Repeatability
The very limited number of measurements available for the instrument did not allow an evaluation of repeatability to be made.

Response time
For the DustMonitor, the characteristic times (response values) could not be determined as the instrument responded to load changes during the SCT in the opposite way . The DustMonitor was able to follow the transient ETC but it is questionable whether the signal was related to the particle emission.

Limit of detection (LOD)
The LOD could not be determined because the instrument did not measure at engine low-emission level.
The DustMonitor showed a rather high noise-to-signal value within single measurements for the engine background.

Sensitivity
No findings about the sensitivity of the DustMonitor could be obtained as the instrument did not participate in the measurements with the post-trap (low-emission) configuration.

Linearity
No measurements with the CAST were carried out for linearity tests.

Comparison with other instruments
The DustMonitor showed a concentration about three orders of magnitude lower than other number-based instruments.

Calibration

Calibration of absolute number concentration by a traceable standard has not yet been solved. The calibration of size can be carried out using standard reference particles (latex, gold).

Summary

The DustMonitor is based on a light scattering method and provides time-resolved particle number concentrations. In this study, the instrument measured much far low particle concentrations in comparison with other instruments. Due to the principle of measurement, the instrument is focused on the detection of particles in a far higher size range than the typical emissions level of a modern diesel engine. This version of the DustMonitor proved not to be suitable for future type approval purposes.

Seq. SMPS+C/UPC (Ultrafine Particle Counter) (R13)

As the instrument took part in a very limited number of measurements, only a very reduced assessment of the system is possible.

Robustness

The number of measurements was too low for an assessment to be made.

Repeatability

The very limited number of measurements available for the instrument did not allow an evaluation of repeatability to be made.

Response time

A measurement with the seq. SMPS+C requires a stable aerosol for a few minutes. For this reason SMPS+C is not able to perform transient measurements, and a stand-alone CPC was therefore used for these tests. The UPC showed fairly long response times ($t_{90-10} > 15$ s, $t_{10-90} > 60$ s). The long response times are probably caused by the low flow rate through the UPC and/or by the non-stable contribution of volatile particles. The UPC was able to follow a transient test cycle and to detect individual peaks in particle concentration due to brief load peaks during the transient ETC.

Limit of detection (LOD)

The LOD could not be determined because the instrument did not measure at low engine emission level.

Sensitivity

No findings on the sensitivity of the seq. SMPS+C could be obtained as the instrument did not take part in the measurements with the post-trap (low-emission) configuration.

Linearity

No measurements with the CAST were carried out for linearity tests.

Comparison with other instruments

Only a few measurements were available for the comparison with other instruments. With the reservation that different dilution systems were used, the comparison of the SMPS+C (R13) to the SMPS3936-L10 (R21) revealed significant discrepancies in number concentrations up to a factor of 2. A deviation of up to 35% was observed for the stand-alone CPCs. For both set-ups the Grimm instrument (R13) measured the lower concentration.

Calibration

Calibration of absolute number concentration by a traceable standard has not yet been solved. The calibration of size can be carried out using standard reference particles (latex, gold).

Summary

The SMPS+C provides detailed number size distributions. The advantage of particle size information is offset by the inability to follow a transient test cycle, as constant particle emission for several minutes is needed for the measurement. Due to the very short period of participation in the programme, performance could not be properly evaluated. The few results obtained by the SMPS+C indicated a significant discrepancy in concentration compared with other number-based instruments. A stand-alone CPC was able to measure transient cycles with high sensitivity, but any size information became lost. As the CPC is very susceptible to nucleation particles, the removal of such particles (e.g. by a thermodesorber) is highly recommended for repeatable results to be obtained.

DPSO-1 (R14)

Robustness

The instrument proved to operate very robustly during the measurement programme.

Repeatability

Due to the strong NO_2 sensitivity, only the data measured at the high-emission level could be evaluated. The DPSO-1 showed poor repeatability for the ETC cycles (COV = 144%) and for the single modes, repeatability being in the range of 40%. However, it is not known to what extent these results are also affected by the NO_2 concentration.

Response time

Characteristic times (response values) could not be determined for the DPSO-1 because the instrument showed opposite behaviour in relation to load changes during the SCT compared to other instruments. The DPSO-1 was able to follow the transient ETC, but it is questionable whether the signal was related to the particle emission.

Limit of detection (LOD)

Due to the strong NO_2 interference, it was not possible to determine a limit of detection for particle measurement.

Sensitivity

The sensitivity of the instrument was too low and the NO_2 interference was too high for reliable measurements at low-emission level.

Linearity

The particle concentration provided by the CAST was too low for linearity tests with the DPSO-1.

Comparison with other instruments

It was difficult to relate the interpretation of the results to particle concentration because of the strong NO_2 interference of the instrument. It was therefore not possible to make a comparison of absolute values. Poor correlation with other instruments was generally found.

Calibration

The DPSO-1 is calibrated for the extinction coefficient by zero & span check. There is no generally valid relationship between k-value and particle mass.

Summary

The DPSO-1 is an opacimeter that uses sensors at three different wavelengths. Although the multiple sensors allow the interference of NO_2 to be reduced, the instrument had serious problems in measuring reliable particle concentrations in this study.
The cross-sensitivity of NO_2 was dominant, especially at low-emission level. This version of the DPSO-1 was found not to be suitable for future type approval purposes.

LQ1-DC (R15)

Robustness

This instrument was found to operate very robustly during the measurement programme.

Repeatability

Good repeatability was observed for most test cycles. The COV of the measurement results was found to be within 7% for the high-emission configuration (60% Euro 4) and 34% for the post-trap configuration of the transient ETC. Higher variation up to 56% was only observed for some single modes for the low-emission configuration.

Response time

The response time (t_{50-10}) of the LQ1-DC to well-defined concentration changes was observed to be fast, within a few seconds. The t_{90-10} times showed slightly higher values in the range of 15 to 20 s, probably due to the non-stable contribution of volatile particles. The LQ1-DC was able to follow a transient test cycle and to detect individual peaks in particle concentration due to short load pulses during the transient ETC being limited.

Limit of detection (LOD)

The LOD was found to be in the same range as the measured ETC low-emission concentration. The concentration for the ETC high-emission (about 60% of Euro 4) was about 430 times higher than the LOD.
The LQ1-DC showed fairly low noise-to-signal values within single measurements on CAST measurements.

Sensitivity

The LQ1-DC showed comparatively large differences in the ratio between high (60% Euro 4) and low-emission (post-trap) configurations. Ratios between 19 and 1300 were determined for the different test cycles (ETC: 440). The results demonstrate high sensitivity.
The concentration for the background and post-trap were measured in the same range as for most instruments.

Linearity

The tests with the CAST tests revealed flawless performance in linearity for the LQ1-DC for both investigated size settings.

Comparison with other instruments

The absolute values measured by the LQ1-DC could not be compared to other instruments as the LQ1-DC is the only instrument calibrated on active surface area. However, a cross-check by the transfer to number, applying very simple assumptions gave reasonable results. Very good correlation was obtained to some number (R19: $R^2 = 0.99$) and mass-based instruments (C05: R^2: 0.99, R11E: $R^2 = 0.97$). The correlation to the EAD (R20), which is based on the same principle of diffusion charging, showed a correlation with $R^2 = 0.98$.

Calibration

The calibration of absolute surface concentration by a traceable standard is not yet available.

Summary

The LQ1-DC is based on diffusion charging and provides time-resolved data on an integral surface area. The instrument performed very well in repeatability and showed very good correlation to most other instruments. The sensitivity of the instrument is very high. The measurement is susceptible to nucleation particles, but less pronounced than number-based methods. Nevertheless, the removal of volatile particles (e.g. by thermal treatment) is highly recommended in order to obtain more repeatable results. The rotating disc dilution unit (heated to T = 393 K), as used for the LQ1-DC (and R16, R17, R12, R13), gave no indication of significant interference by volatile particles. Calibration is found to be very difficult as the integral active surface area has to be calculated by means of the number concentration of a monodisperse aerosol.

EDB (R16)

Robustness

The EDB tested at EMPA was a prototype but proved to be very robust during the measurement programme.

Repeatability

A very good repeatability was observed for most test cycles. The COV of the measurement results were found to be within 2% for the high-emission configuration (60% Euro 4) and within 10% for the post-trap configuration of the transient ETC cycle. A higher variation of up to 70% was only observed for some single modes at the low-emission level.

Response time

The response time of the EDB to defined concentration changes was observed to be fast and stable within a few seconds ($t_{90-10} < 3$ s). The EDB was able to follow a transient test cycle. The detection of individual peaks in particle concentration due to short load pulse during the transient ETC cycle was limited.

Limit of detection (LOD)

The LOD was found to be about 30% of the measured ETC low-emission concentration. The concentration for the ETC high-emission (about 60% of Euro 4) was about 560 times higher than the LOD. The EDB was not able to measure the engine background concentration.

Sensitivity

The EDB showed only moderate ratios between the high (60% Euro 4) and low-emission (post-trap) configurations. Ratios between 15 and 650 were determined for the different test cycles (ETC: 165).

Linearity

The tests with the CAST showed moderate linearity performance for the EDB for both investigated size settings. It should be noted that the concentration of the test aerosol was lower by a factor 15 than most other instruments because of using an additional dilution unit.

Comparison with other instruments

The EAD showed agreement in total number with the CPC (R19) and the ELPI (R22) within 20% for the ETC high-emission configuration. For the post-trap configuration, the measured concentration was about 10 times higher than with other instruments. Very good correlation was obtained to the CPC (R19: $R^2 = 0.99$) and mass-based instruments (R11E: $R^2 = 0.97$).

Calibration

Calibration of absolute number concentration by a traceable standard has not yet been solved. The calibration of size can be carried out using standard reference particles (latex, gold).

Summary

The EDB provides time-resolved real number concentrations, including some size information. The instrument performed very well in repeatability and showed good correlation to other instruments for the high-emission configuration (about 60% of Euro 4). Measurements at post-trap emission level showed wide discrepancies in number concentrations and lack of sensitivity for this early-stage prototype instrument. It is expected that further development will overcome these shortcomings. As the algorithms assume a monomodal lognormal distribution of the measured aerosol, more experience has to be gained on aerosols that do not fulfil this condition, e.g. post-trap aerosols. The calibration for number concentration is found to be difficult as the instrument applies size-dependent diffusion charging and the size channels of the diffusion battery are very wide..

PAS (R17)

Robustness

The instrument was found to operate without any problems during the measurement programme.

Repeatability

Very good repeatability was observed for many test cycles. The COV of the measurement results was found to be within 5% for the high-emission configuration (60% Euro 4) and 10% for the post-trap (low-emission) configuration of the transient ETC cycle. The variation was observed to be larger than 50% for the low-emission configuration for all single modes.

Response time

The response time of the PAS to well-defined concentration changes was observed to be fast and stable within a few seconds ($t_{90\text{-}10} < 7$ s). The PAS was able follow a transient test cycle. Detection of individual peaks in particle concentration was limited due to short load peaks during the transient ETC.

Limit of detection (LOD)

The LOD was found to be about 30% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission (about 60% of Euro 4) was about 4400 times higher than the LOD.

Sensitivity

The PAS showed comparatively small differences in concentration between high (60% Euro 4) and low-emission (post-trap) configurations. Ratios between 15 and 1440 were determined for the different test cycles (ETC: 1440). The results demonstrate good sensitivity of the instrument.
The concentrations for the background and post-trap were measured in the same range as for most instruments.

Linearity

The tests with the CAST revealed flawless performance in linearity of the PAS for both investigated size settings.

Comparison with other instruments

The PAS showed very poor agreement in the absolute values compared to other instruments. For the ETC high-emission configuration, the measured EC mass concentration exceeded by a factor 3 to 5. According to the manufacturer, the instrument was not correctly calibrated. Very good correlation was observed to the CPC (R19: $R^2 = 0.97$) and coulometry (R11E: $R^2 = 0.95$).

Calibration

In principle, the PAS can be calibrated for EC mass by comparison to the coulometric reference method.

Summary

The measurement principle of PAS is based on the photoelectric charging of the particles. The instrument provides time-resolved data calibrated on EC mass concentration. A large

discrepancy in the absolute values with other instruments was observed, giving an indication of poor calibration of the instrument. The instrument performed very well in repeatability and showed good correlation to other instruments. Generally applicable mass calibration is found to be very difficult as charging is highly sensitive to the properties and is related to the surface area. This means that changes in size distribution, morphology or slight adsorption processes can significantly affect the result. From our point of view, these major difficulties significantly restrict the suitability of the method for type approval applications.

PM-300 (R18)

Robustness

The PM-300 operated stably during most of the project, but some measurements had to be skipped due to problems with a mass flow controller for the dilution unit.

Repeatability

For the transient test cycle ETC, good repeatability with a COV of 8% was observed for the high-emission configuration (60% Euro 4). For the post-trap configuration, a COV of 40% was measured. The absolute concentration for the steady-state tests were exceptionally low compared to other instruments, so there was no point in evaluating repeatability.

Response time

For the PM-300 the characteristic time response values could not be determined as the instrument reacted to load changes during the SCT in the opposite way. The PM-300 was able to follow a transient test cycle and to detect individual peaks in particle concentration due to short load pulses during the transient ETC.

Limit of detection (LOD)

The LOD could not be evaluated for the PM-300 due to inconsistent results.

Sensitivity

With reservation for inconsistency, the PM-300 showed comparatively moderate differences in concentration between high (60% Euro 4) and low-emission (post-trap) configurations. Ratios between 40 and 400 were determined for the different test cycles (ETC: 40).

Linearity

The particle concentration provided by the CAST was too low for the linearity check of the PM-300.

Comparison with other instruments

The concentrations measured for the different cycles by the PM-300 are not consistent in comparison with all other instruments. The concentrations of the transient cycles ETC and the SCT were measured as about four orders of magnitude higher compared to the steady-state-cycles SM and ESC. This is in clear contrast to all other instruments, which measured the concentration of SM and ETC in the same range. This inconsistency is observed for the high and low-emission configurations. Concerning the ETC, the values for the absolute concentration are in the same range as for most other number-calibrated instruments. But the

reliability of these results is questionable in view of the very low concentrations as measured for the steady-state tests.

Calibration

Calibration of absolute number concentration by a traceable standard has not yet been solved. The calibration of size can be carried out using standard reference particles (latex, gold).

Summary

The PM-300 is based on the light-scattering method and provides time-resolved particle number concentrations. Inconsistent results were obtained in this study.
The particle concentrations of the steady-state test measured by this instrument were far too low compared to other instruments. Due to the principle of measurement the instruments are focused on the detection of particles in a size range that is higher than the typical emissions from diesel engines. From our point of view, the PM-300 has little potential for future type approval application.

CPC 3022A (R19)

Robustness

The instrument was found to operate without any problems during the measurement programme.

Repeatability

The CPC showed very good repeatability for all tests in the high-emission configuration (60% Euro 4) (ETC: 2%, SM: 5%). Higher variation was determined at the low-emission level with a COV of 24% for ETC and up to 77% for SM. The high variation is probably caused by nucleation effects due to the inadequate performance of the heated dilution system.

Response time

The response time ($t_{50\text{-}10}$) of the CPC to well-defined concentration changes was observed to be fast within a few seconds. The $t_{90\text{-}10}$ times showed larger values up to 60 s. Significantly longer times were observed for the down-steps compared to the up-steps. The long response times are probably due to an error in the data read-out software. The CPC was able to follow a transient test cycle and to detect individual peaks in particle concentration due to short load pulses during the transient ETC.

Limit of detection (LOD)

The LOD was found to be about 70% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission (about 60% of Euro 4) was about 1950 times higher than the LOD.

Sensitivity

The CPC showed high differences in the ratios between high (60% Euro 4) and low-emission (post-trap) configuration. Ratios between 27 and 3100 were determined for the different test cycles (ETC: 1400). The results demonstrate very high sensitivity for the instrument.
The concentrations of the background and post-trap measurement were measured in the same range as for most instruments.

Linearity

The tests with the CAST showed flawless performance in linearity for both investigated size settings. For most of the concentration settings, the instrument operated in the photometric mode.

Comparison with other instruments

In general, acceptable agreement with other number-based methods was found with few exceptions. For the ETC, very good agreement in absolute values was found in comparison with the ELPI (R22) and EAD (R20) within 20%. A surprisingly wide difference of 30% was observed in comparison with the CPC3010 (R21) for the ETC post-trap (low-emission) measurements. This could be explained by the lower cut size of 7 nm for the CPC 3022A (R19), compared with 12 nm for the CPC 3010, which was used for the SMPS (R21).
In general, the CPC showed good correlation to most other instruments but not to filter methods (C04, C06) and some optical instruments (R14, R18). For the EC mass-based instruments (C06E, C08, R11E, C05) values for R^2 were always higher than 0.94. Even better results for R^2 were found for the relationship to number/length/surface-related instruments (e.g. R22: 0.99, R15: 0.99,: R10: 0.95).

Calibration

Calibration of absolute number concentration by a traceable standard has not yet been solved.

Summary

The stand-alone CPC provides time-resolved total number concentrations. The instrument performed very well in repeatability and showed very good correlation to most other instruments. The sensitivity of the instrument is very high, but is very susceptible to nucleation particles which can completely distort the measurement of solid particles concentration. The CPC showed unusually long relaxation times. According to the manufacturer, the long relaxation were caused by an error in the data read-out software. Removal of volatile particles (e.g. by a thermal treatment) is highly recommended for repeatable results. The heated double ejector-based dilution as applied for the CPC (and R22, R10) proved not to be sufficient to eliminate all nucleation particles during all engine operation modes.

EAD 3070A (R20)

Robustness

The EAD 3070A was found to operate without malfunction but had a zero drift problem throughout the measurement programme. According to the manufacturer, the problem was due to an insufficiently long warm-up period before zeroing the instrument.

Repeatability

The EAD showed very good repeatability for all tests of the high-emission configuration (ETC: 2%, SM: 9%). Significantly higher variation was determined for the low-emission configuration with a COV of 53% for the ETC and up to 63% for the SM. The high variation is probably caused by nucleation effects due to the inadequate performance of the heated dilution system.

Response time

The response of the EAD to well-defined concentration changes was observed to be fast and stable within a few seconds ($t_{90-10} < 4$ s). The EAD was able to follow a transient test cycle and to detect individual peaks in particle concentration due to short load pulses during the transient ETC test cycle.

Limit of detection (LOD)

The LOD was found to be about 160% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission (about 60% of Euro 4) was about 1370 times higher than the LOD.

Sensitivity

The EAD showed high differences in the ratios between high (60% Euro 4) and low-emission (post-trap) configuration. Ratios between 20 and 2700 were determined for the different test cycles (ETC: 2200). The results demonstrate very high sensitivity for the instrument.
The concentration for the background and post-trap were measured in the same range as for most instruments.

Linearity

The tests with the CAST revealed flawless performance in linearity of the EAD for both investigated size settings.

Comparison with other instruments

The absolute values measured by the EAD could not be compared to other instruments as the EAD is the only instrument calibrated on integral particle length. However, a cross-check by transferring the length to number applying very simple assumptions gave reasonable results. Very good correlation was obtained to the CPC (R19: $R^2 = 0.98$) and to coulometry (R11E: $R^2 = 0.91$). The correlation to the LQ1-DC (R15), which is based on the same principle of diffusion charging, showed correlation with $R^2 = 0.98$.

Calibration

The calibration of absolute length concentration by a traceable standard has not yet been solved.

Summary

The EAD 3070A is based on turbulent diffusion charging and provides time-resolved data on an integral particle length. The instrument performed very well in repeatability and showed very good correlation to other instruments for the high-emission configuration (about 60% of Euro 4). The sensitivity of the instrument was found to be very high, but problems were found at low concentrations due to zero-point drifting. The measurement is susceptible to nucleation particles, so the removal of volatile particles (e.g. by thermal treatment) is highly recommended in order to obtain more repeatable results. Calibration is found to be very difficult as the integral particle length has to be calculated using the number concentration of a monodisperse aerosol.

Scan. SMPS 3936-L10 (CPC3010) (R21)

These instruments were operated in three different configurations depending on the test cycle and the emission level: SMPS scanning mode for all steady-state operating modes, stand-alone CPC for transient low-emission tests (CPC3010 alone without using the DMA) and DMA-CPC combination with fixed voltage setting for transient high-emission tests (scanning SMPS was in the DMA-Bandpass mode with CPC detection). An integrated assessment is consequently difficult.

Robustness

The instrument was found to operate without any problems during the measurement programme.

Repeatability

Very good repeatability was observed for SMPS scanning mode setting and DMA-CPC combination at high-emission level with a COV of 4% and 5% respectively. For the post-trap configuration, the SMPS and the stand-alone CPC showed significantly higher COV values of 59% and up to 33%.

Response time

A measurement with the scanning SMPS 3936-L10 requires a stable aerosol for at least one minute. For this reason it is not able to carry out transient measurements. The combination DMA-CPC with fixed voltage on the DMA in order to select a defined particle diameter was slow ($t_{90-10} > 60$ s). The long response times are probably due to by the large aerosol volume inside the DMA and an error in the read-out software.
The DMA-CPC combination (selection of defined particle diameters) was able to follow a transient test cycle. The detection of individual peaks in particle concentration was limited due to short load peaks during the transient ETC.

Limit of detection (LOD)

The LOD was found to be in the same range as the measured ETC low-emission concentration. The concentration of the 80 nm bandpass mode was about 670 times higher for the ETC high-emission (about 60% of Euro 4) than the LOD.

Sensitivity

The SMPS 3936-L10 showed high differences in the ratio between high (60% Euro 4) and low-emission (post-trap) configurations. For the SMPS, ratios between 24 and 3000 were determined for the different single modes. Because of different settings of the SMPS 3936-L10 in ETC low-emission measurements, a ratio between the ETC high and low-emission levels could only be calculated from a few measurements. The ratio comparing the ETC cycles by measuring the 80 nm particles was calculated at about 1660.
The concentration for the background and post-trap were measured in the same range as for most instruments.

Linearity

The tests with the CAST revealed flawless performance in linearity of the SMPS for both investigated size settings.

Comparison with other instruments

The engine tests showed that the SMPS measured only about 60% of the particle concentration as determined for the stand-alone CPC (R19) and the ELPI (R22). A similar finding was also observed for the smaller size setting of the CAST measurements.
Two major reasons are assumed to explain the discrepancy: the difference in the lower cut size and the diffusion losses in the DMA. The lower size range was 12 to 14 nm for the SMPS 3936L-10 (R21) compared to 7 nm for the stand-alone CPC 3022A. Diffusion losses of the particles smaller than 20 nm caused by the low flow rate and the length of the DMA may play an important role. The direct comparison to the seq. SMPS+C (R13) revealed a significant discrepancy approximately a factor of 2 higher for the steady-state tests and about 35% higher concentration for the stand-alone CPC3010 compared to the UPC5400 (R13).

Calibration

The calibration of absolute number concentration by a traceable standard has not yet been solved.
The calibration of size can be carried out using standard reference particles (latex, gold).

Summary

The SMPS provides detailed number size distributions. The abundance of size information is offset by the inability to follow a transient test cycle, as a constant particle emission of at least a minute is needed for the measurement. The measurement of number concentrations within a single mobility channel as applied in some measurements of this study enables transient measurements and can exclude the interference of nucleation particles in most cases. But the method delivers very little information, and small shifts in the size distribution affect the result significantly. For this reason a stand-alone CPC would be the better option for future type approval applications.
A significant discrepancy in total particle number as measured by SMPS and stand-alone CPC was observed in the study. A correction for the diffusion losses and the specification of the lower cut size would probably improve the results. Removal of nucleation particles is strongly recommended for more repeatable results as the CPC is highly susceptible to such particles.

ELPI (R22)

Robustness

The instrument was found to operate without any problems during the measurement programme.

Repeatability

Good repeatability was observed for the test cycles at the high-emission level (60% Euro 4). For the transient ETC cycle, the COV of the measurement results were found to be within 10%. For the post-trap configuration the COV was in the range of 30% for the ETC and SM, but with one exception (A50: 140%).

Response time

The response time of the ELPI to well defined concentration changes was observed to be very short ($t_{50-10} < 3$ s). For t_{90-10} times were found to be between 4 s and 15 s. The ELPI was able

to follow a transient test cycle and to detect individual peaks in particle concentration due to short load pulses during the transient ETC.

Limit of detection (LOD)

The LOD was found to be about 90% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission (about 60% of Euro 4) was about 1800 times higher than the LOD.

Sensitivity

The ELPI showed high differences in concentration between the high (60% Euro 4) and low-emission (post-trap) configuration. Ratios between 25 and 4300 were determined for the different test cycles (ETC: 1500). The results demonstrate very high sensitivity of the instrument. Slightly higher number concentration was measured for the post-trap than for the background configuration.

Linearity

The tests with the CAST revealed flawless performance in linearity of the ELPI for both investigated size settings.

Comparison with other instruments

In general, an acceptable agreement to other number-based methods were found with few exceptions. For the ETC, good agreement in absolute values was found to the CPC (R21) and EAD (R20) within 20%. The ELPI showed very good correlation to the CPC (R19: $R^2 = 0.99$) and coulometry (R11E: $R^2 = 0.90$) and to many other instruments.

Calibration

The calibration of absolute number concentration by a traceable standard has not yet been solved.
The calibration of size can be carried out using standard reference particles (latex, gold).

Summary

The ELPI is a low-pressure impactor that provides time-resolved number size distributions. The instrument performed very well in repeatability and sensitivity and showed good correlation to other instruments. The measurement principle of the ELPI is quite complex as the measured number concentration and sizing is affected by the particle morphology and bulk density. The concentration of particle below 35 nm as determined by a filter stage revealed significant discrepancies in relation to other instruments. As the filter stage undergoes further development, performance is expected to improve. The ELPI is susceptible to nucleation particles. The removal of volatile particles (e.g. by a thermodesorber) is therefore highly recommended for more repeatable results. The calibration for number concentration is found to be very difficult, as charging and sizing are based on different physical principles.

DQL (R23)

Robustness

The instrument was found to operate without any problems during the measurement programme.

Repeatability

The DQL showed good repeatability at the high-emission level (60% Euro 4). The COVs of the measurement results were found to be within 10% for the ETC and 12% for the SM. The COVs showed comparable low variation for the low-emission tests (ETC: 16%, SM: < 35%), but it is questionable whether the signal is related to the particle concentration only and not influenced by NO_2.

Response time

The response of the DQL was found to be rather slow (t_{90-10} > 40 s). The DQL was not really able to follow a transient test cycle in a satisfactory manner due to a long relaxation time after high peaks of the signal.

Limit of detection (LOD)

The LOD was found to be about 50% of the measured ETC low-emission concentration.
The concentration for the ETC high-emission (about 60% of Euro 4) was about 21 times higher than the LOD.
Due to the low concentrations the DQL was not able to measure the engine background and to participate in the CAST measurements. Therefore, a limit of detection (LOD) of the instrument in relation to the background could not be determined.

Sensitivity

Whereas the concentrations of the CAST aerosol were too low, the DQL was able to measure during the low-emission configuration of the engine tests. The DQL showed low differences in concentration between the high (60% Euro 4) and low-emission (post-trap) configurations. Ratios between 2 and 10 were determined for the different test cycles (ETC: 10). The results revealed very low sensitivity for the instrument.

Linearity

The particle concentration provided by the CAST was too low for the DQL for the linearity check.

Comparison with other instruments

The absolute values measured by the DQL could not be compared with other instruments as the DQL is the only instrument calibrated on integral particle volume. However, a cross-check by transferring the volume to number applying very simple assumptions gave reasonable results. Very good correlation was obtained to the CPC (R19: $R^2 = 0.94$) and to coulometry (R11E: $R^2 = 0.96$).

Calibration

Calibration of absolute number concentration by a traceable standard has not yet been solved.
The calibration of size can be carried out using standard reference particles (latex, gold).

Summary

The measurement principle of the DQL is based on laser light extinction at three wavelengths and applies a very extensive optical absorption path. The DQL provides time-resolved data on integral particle volume and a calculated mean size of the primary particles. The instrument tested in this program was a prototype and was not yet optimised regarding sensitivity and time response behaviour. In general, the instrument performed very well in repeatability and showed good correlation to other instruments. The sensitivity was observed to be low compared to many other instruments. Due to the lack of sensitivity, the DQL was not able to measure the low concentrations of the CAST aerosol. The DQL represents an advanced development of the light-extinction method to overcome the low sensitivity and the NO_2 cross-sensitivity of common opacimeters. Nevertheless, the results show the limited suitability of the instrument for future low-emission levels.

AVL 439 (R24)

The AVL439 is not considered as an option for a future measurement technique for type approval, but has been included in the programme for the sake of completeness.
The measurements revealed a strong NO_2 sensitivity of the instruments that did not allow a straightforward data evaluation and comparison to the other measurement systems. For example, the instrument had the tendency to measure higher concentrations for the post-trap (low-emission) than for the bypass (high-emission) configuration.

CAST

The CAST produced a very stable aerosol during the continuous operation phases of 10 minutes duration. The COV for the majority of the instruments were within 5%. The adjustment of the relative concentration levels by means of a rotating disk dilution could be carried out in a very repeatable way. For the tests for linearity in this investigation the CAST fulfilled the requirements completely and in a good manner. The absolute values for concentration and size distribution could be repeated after a break of two weeks within the specified measurement uncertainties of 30% by the majority of the instruments. With a few exceptions, all the instruments measured lower concentrations for the repetition, indicating a drift of the CAST. The drift could be caused by the clearly different ambient conditions for the two measurement phases. A final assessment of the CAST for calibration use was outside the scope of this study and cannot be made on the basis of these data.

11 Conclusions

In this comparison study, twenty-one measurement systems were investigated and compared to each other. The aim was to generate a uniform data set of the performance of a wide range of instruments with regard to their suitability for future type approval application.
On the basis of the data and the experience gained during this investigation, we suggest four major criteria that have to be taken into consideration for the definition of future particle measurement systems.

Sensitivity

The future legislative measurement system will have to face emission levels well below the Euro 4 emission level and a wider variation in particle composition than at present. This will also be the consequence of the application of particle traps and SCR systems. In the future, more economically and technically optimised particle traps may penetrate the market, which will result in lower pressure drop and reduced regeneration efforts, but perhaps also in lower precipitation efficiency. Methods with high sensitivity would be able to identify clear differences in emissions on a very low level.
Our study revealed a significantly higher sensitivity of number-based, length-based or surface-based particle measurement methods than for the mass-based methods. Advanced mass measurement methods that are based on solid matter, mainly EC, did not improve the situation significantly.

Reproducibility

An important aspect is the stability of the measured particle concentration in respect of the sampling conditions. As volatile components are an important source that causes variation in the particle concentration, measurement methods based on solid particles (material) will achieve better repeatability and reproducibility. Most systems in this study were only sensitive to solid matter or followed the strategy of removing volatile material before the detection.
Our measurements gave some indication that the elimination of volatile particles by a hot dilution procedure was not always sufficient. Another option is the application of a thermodesorber, but its performance was not investigated in this study.

Relation to impact on health

Diesel engines generate particles mainly in the size range below 100 nm. Although there are many unanswered questions about the mechanisms of impact on health, recent studies indicate the possible adverse effect of small particles (diameter smaller than 100 nm) on human health. Future measurement methods should therefore be able to detect particles in this low particle size range. In this study optical instruments based on extinction and light scattering (without CPC) were found to have limited sensitivity for such small particles. The mass-based instruments detect small particles, but in principle their measured result is dominated by the larger particles. Restricted to solid particles and mono-modal NSDs a decrease in mass also results in a decrease in number.

Calibration

A very important aspect for future measurement methods is the ability for them to be calibrated according to a traceable standard. A concept is mainly established for mass-based methods, whereas a standard for particle number does not yet exist. As well as the metrics of number, this open question also applies to length and surface area. In principle, the concentration of number, length and surface area is affected by the coagulation process in contrast to the mass concentration. For this reason sampling conditions need to be specified in absolute concentration range, dilution ratio and residence time.
The feasibility of calibration of the instruments was not investigated in this study. The measurements with the aerosol generator CAST showed promising performance with regard to stability and repeatability and could be a suitable approach for a particle number standard.

As a final conclusion, we wish to stress that there are several candidates for measurement systems that are of great value to be considered for closer investigation within Phase III of the GRPE-PMP. Their individual potential for the future type approval application depends mainly on the requirements defined in a detailed catalogue of criteria.

12 Acknowledgements

This investigation was funded in large part by the Swiss Federal Roads Authority (FEDRO) and the Swiss Agency for the Environment, Forest and Landscape (SAEFL) and supported by the Swiss Federal Office of Metrology and Accreditation (METAS). We are indebted to Jürg Schlatter from METAS for his overall control of the CAST measurements. We would like to thank the Volvo Truck Cooperation for putting the engine at our disposal. Rupprecht&Patashnick Co., Inc. deserves special mention for providing filter holders and pre-samplers that met the specification of the US2007 Federal Register. Finally, we wish to express our gratitude to the instrument manufacturers for their participation and their representatives during the measurements for very good co-operation and the friendly working atmosphere.
Thanks are due to the co-ordinator of the Swiss contributions to PMP, Mr Andreas Mayer, TTM, for launching this project.
The authors acknowledge the contribution of their colleagues at EMPA in carrying out the measurement programme: Roland Graf, Alfred Mack, Hans-Kristian Opstad, Josef Rütter, Uzi Saghi, Daniel Schreiber, Thomas Schweizer and Rolf Ziegler.

13 References

[ACEA, 2002] «ACEA programme on emissions of fine particles from passenger cars [2]», ACEA Report July 2002.

[Dixon, 1953] «Processing data for outliers », Dixon W.J., Biometrics 9 (1953) 74-89, Appendix p. 89

[AEAT, 2002] «Final Report of Phase 1 of Module 3: Development of Candidate Systems – Light Duty Vehicles», Particle Measurement Programme (PMP), Dickens C.J., Payne E.L., Reading A.H., Feest E.A., AEA Technology /DDSE/R/ED 15003, A report produced for the DTLR, January 2002

[HTL Biel (1), 2001] «NanoMet an option for supplementing the legal exhaust gas measuring procedure for the diesel vehicles with particle filter (DPF)», Czerwinski J., Napoli S., Matter U., Mosimann T., Preliminary research phase 1, technical report, University of applied Sciences, Biel (Switzerland), Mai 2001

[HTL Biel (2), 2001] «NanoMet a Nanoparticle Analyser for supplementing the legal exhaust gas measuring procedure for diesel vehicles with particle filter (DPF) Part II», Czerwinski J., Napoli S., Wili Ph., Matter U., Mosimann T., Kasper M., Preliminary research phase 1, technical report, University of applied Sciences, Biel (Switzerland), October 2001

[Ricardo, 2002] «UK Particle measurement Programme – Heavy duty, Methodology development», Andersson J.D., Final Report DP 02/2493, Ricardo Consulting Engineers Ltd., July 2002

[MTC] «Investigation of Thermodenuder Effect», Cleas de Serves, Karlsson, presented at GRPE-Meeting 15.1.2003

14 Appendices

Appendix A : Fuel specifications

Analyse	unit	result	Limit low	Limit high	method
Density at 15°C	kg/m^3	834.4	800	845	ASTM D 4052
Viscosity at 40°C	mm^2/s	3.36	1.50	4.00	ISO 3104
Flash point	°C	99.0	55		ISO 2719
Cloud point	°C	-25		-10	ISO 3015
CFPP	°C	-22		-20	EN 116
Carbon residue (10% Dist.)	mass.%	< 0.01		0.3	ISO 10370
Water content (KF)	mg/kg	50		200	ASTM D 1744
Sulphur content	mg/kg	8		350	ASTM D 5453
Sulphur content	mg/kg	8		350	EN 24260
Ash content	mass.%	17.2			ISO 6245
Elemental analysis					ASTM D 5291
Carbon	mass.%	87.30			
Hydrogen	mass.%	13.32			
Caloric value					DIN 51900
Heat of combustion, gross	MJ/kg	45.94			
Heat of combustion, net	MJ/kg	43.03			
Cetane number		57.6	49.0		ISO 5165
Aromatics	Vol.%	17.2			ASTM D 1319
Benzene (Benzol)	Vol.%	< 0.1			EN 238
Olefins	Vol.%	10.9			ASTM D 1319

Table 13: *Diesel-fuel specifications (CEC-RF-06-99)*

Analyse	unit	result	method
Density at 15°C	kg/m3	861	DIN 51757
Viscosity at 40°C	mm^2/s	89.7	DIN 51562/1
Viscosity at 100°C	mm^2/s	14.41	ISO 2719
Additive			XRF/ICP
Barium	g/100g	n.n.	
Calcium	g/100g	0.504	
Magnesium	g/100g	0.002	
Phosphorus	g/100g	0.119	
Sulphur	g/100g	0.387	
Zinc	g/100g	0.134	
Chlorine	mg/kg	< 20	WD - XRF

Table 14: *Lubricant oil specifications (Shell Myrina TX Oil 10W-40)*

Appendix B : HD-engine test bench at EMPA
Fixed asynchronous motor with 6-pulse static converter (AEG) for 4 quadrant operation

Dynamic engine test bench Schenck DYNAS 680 for engines up to 680 kW

Technical data	Rated power of brake (as generator and motor)	680 kW
	Maximum speed	4000 rpm
	Maximum torque (up to 2600 rpm)	2500 Nm
	Maximum angular acceleration (no load)	3300 rpm/s
	CVS system (Pierburg)	120 WT (PDP)
	Exhaust-gas analyser system (Horiba)	MEXA-9200 DF
	Online [g/s] : CO, CO_2, T.HC, NOx	undiluted
	Bag [g/kWh] : CO, CO_2, T.HC, NOx, CH_4	diluted
	Particle measuring system (Pierburg)	PS-2000
Fuels	Diesel/Gasoline (Petrol)	
	Natural gas/Liquefied petroleum gas	
All the various test cycles used throughout the world can be run on an EMPA dynamic test bench (ECE R49, BSO, ISO 8178, ESC, ETC, ...)		
The use of modern, extremely flexible control and evaluation software allows real-world driving conditions to be simulated, including vehicle loads, road gradient, aerodynamic drag, vehicle starting, engine braking and shifting operations.		

Appendix C : Total measuring Programme

Day		Configuration	Action
1	Th	CAST	set-up, linearity tests
2	Fr	CAST	set-up, linearity tests
3	Mo	Engine & Filter bypass	set-up, pre-tests
4	Tu	Engine & Filter bypass	BG, 3 ETC, 1 SM, 1 SCT
5	We	Engine & Filter bypass	BG, 3 ETC, 1 SM, 1 SCT
6	Th	Engine & Filter bypass	BG, 1 ETC, 1 ESC, 1 SCT
7	Fr	Engine & Filter bypass	BG, 2 ESC
8	Mo	Engine & 100% trap	BG, 3 ETC, 1 SM, 1 SCT
9	Tu	Engine & 100% trap	BG, 3 ETC, 1 SM, 1 SCT
10	We	Engine & 100% trap	BG, 3 ETC, 1 SM, 1 SCT, 2 ESC
11	Th	CAST	set-up, linearity tests
12	Fr	CAST	Sampling for coulometric analysis
13	Mo	CAST	Sampling for coulometric analysis

Table 15: *Time schedule of measurements*

Appendix D : Detailed sequence of CAST measuring programme

Action	Size setting	Concentration setting	Duration
warm-up	200 / 150 nm	10 %	45 min
measurement	150 nm	10 %	10 min
change conc.			5 min
measurement	150 nm	30 %	10 min
change conc.			5 min
measurement	150 nm	60 %	10 min
change conc.			5 min
measurement	150 nm	90 %	10 min
change conc. & size			20 min
measurement	50 nm	10 %	10 min
change conc.			5 min
measurement	50 nm	30 %	10 min
change conc.			5 min
measurement	50 nm	60 %	10 min
change conc.			5 min
measurement	50 nm	90 %	10 min

Table 16: *Detailed sequence of CAST measuring programme*

Appendix E : Time-resolved data for SCT

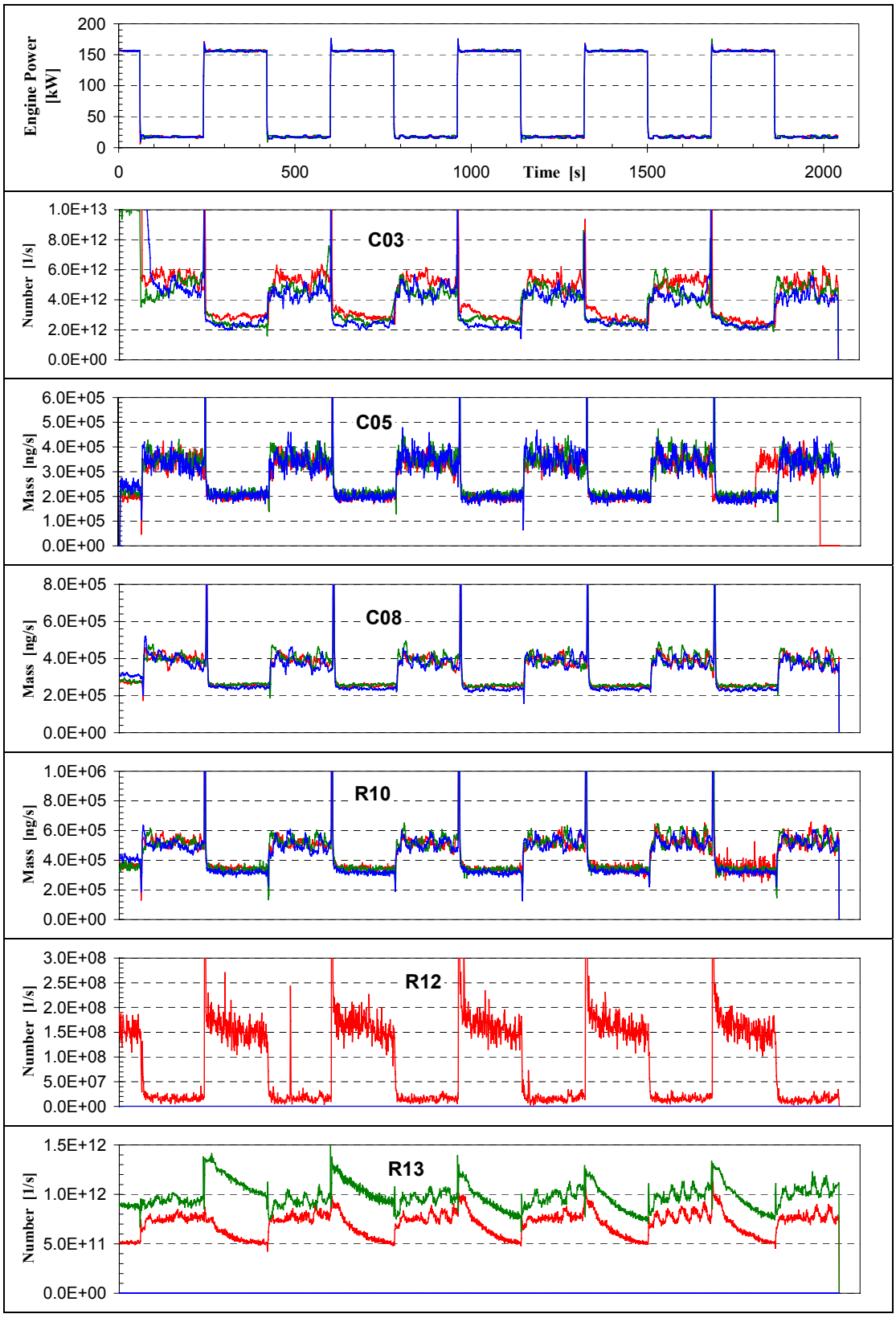


Figure 89: *Time-resolved data of engine power and instruments C03, C05, C08, R10, R12, R12, R13 for SCT at high-emission configuration*

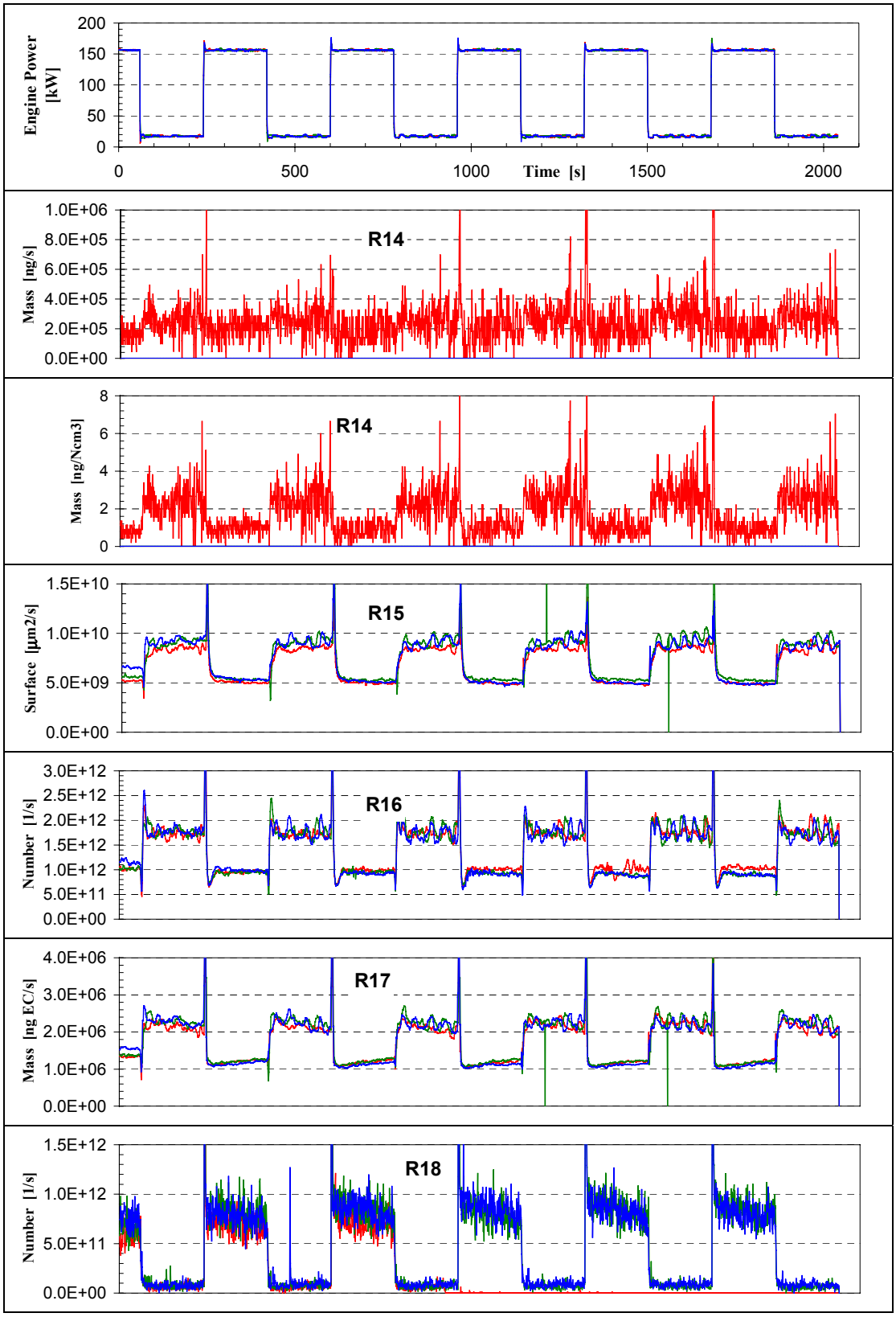


Figure 90: *Time-resolved data of engine power and instruments R14 ([ng/s],[ng/Ncm3]), R15, R16, R17, R18 for SCT at high-emission configuration*

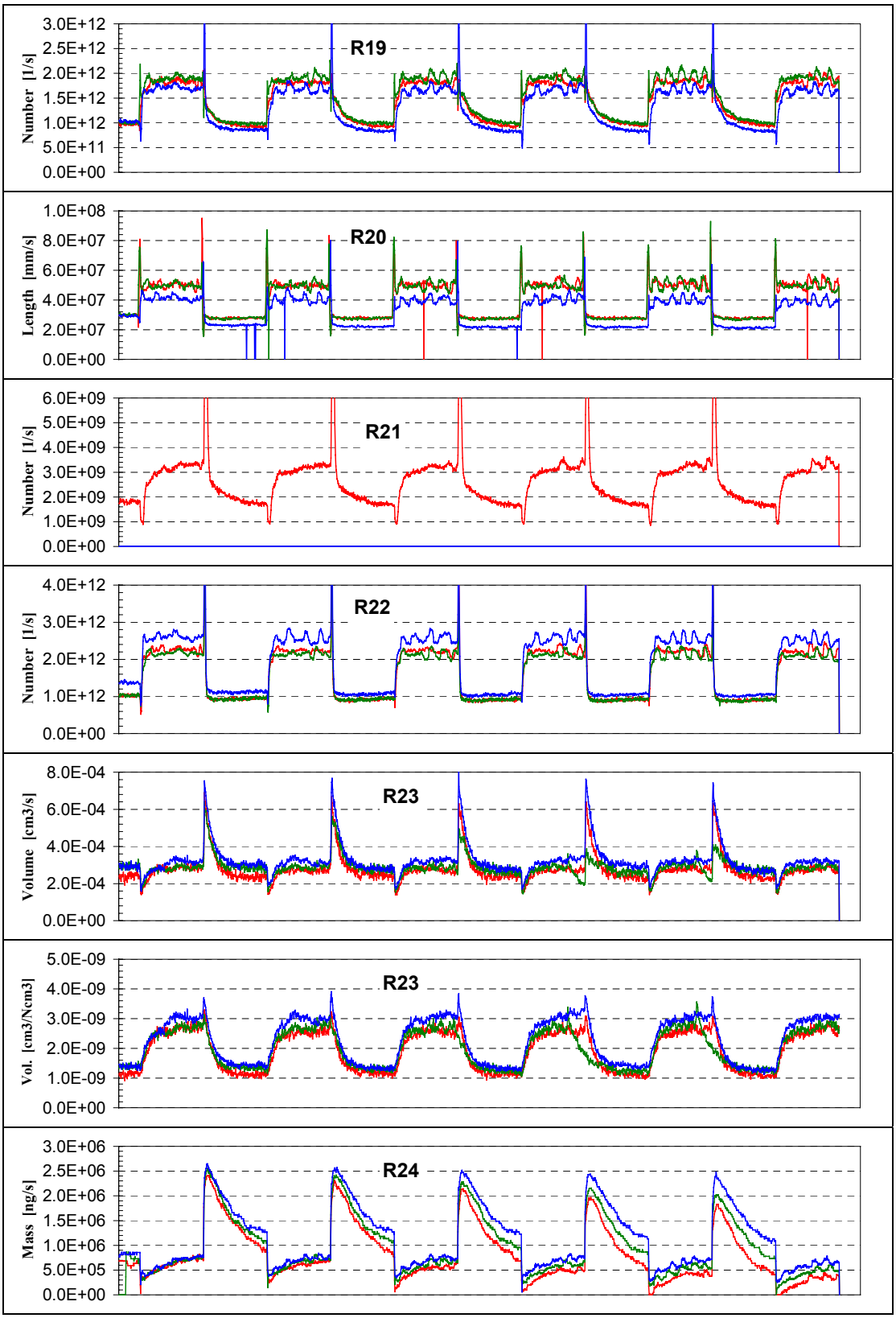


Figure 91: *Time-resolved data of instruments R19 R20, R21, R22, R23 ([cm3/s], [cm3/Ncm3]), R24 for SCT in high-emission configuration*

Appendix F : Absolute values SM / high-emission

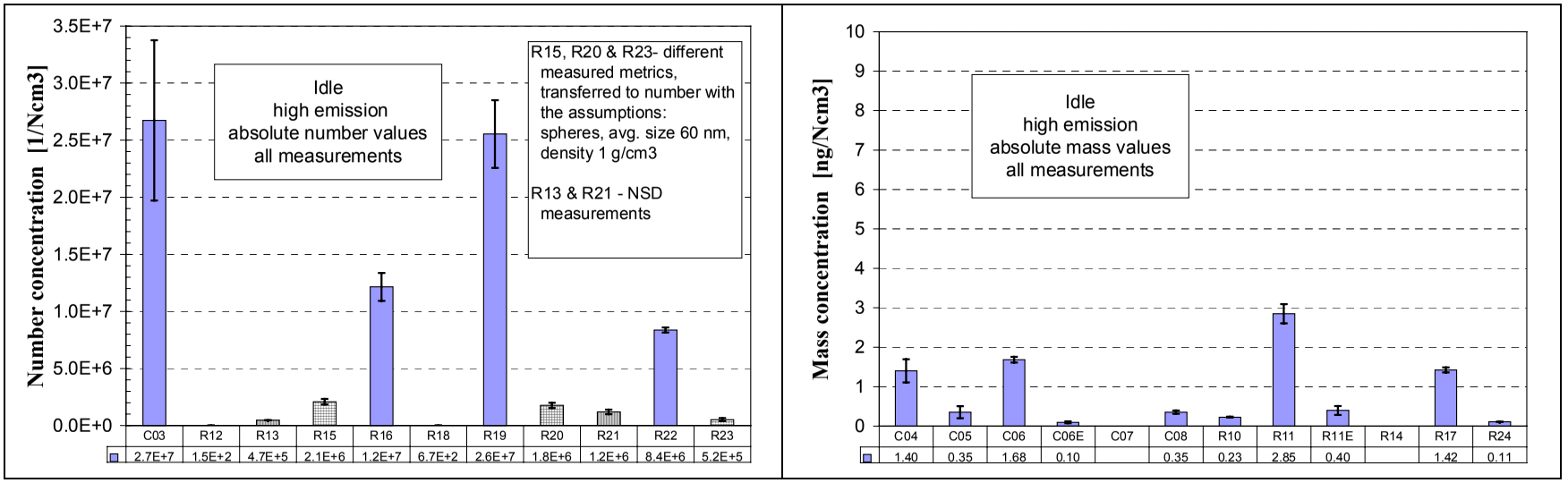


Figure 92: *Total number / SM high/low-emissions*

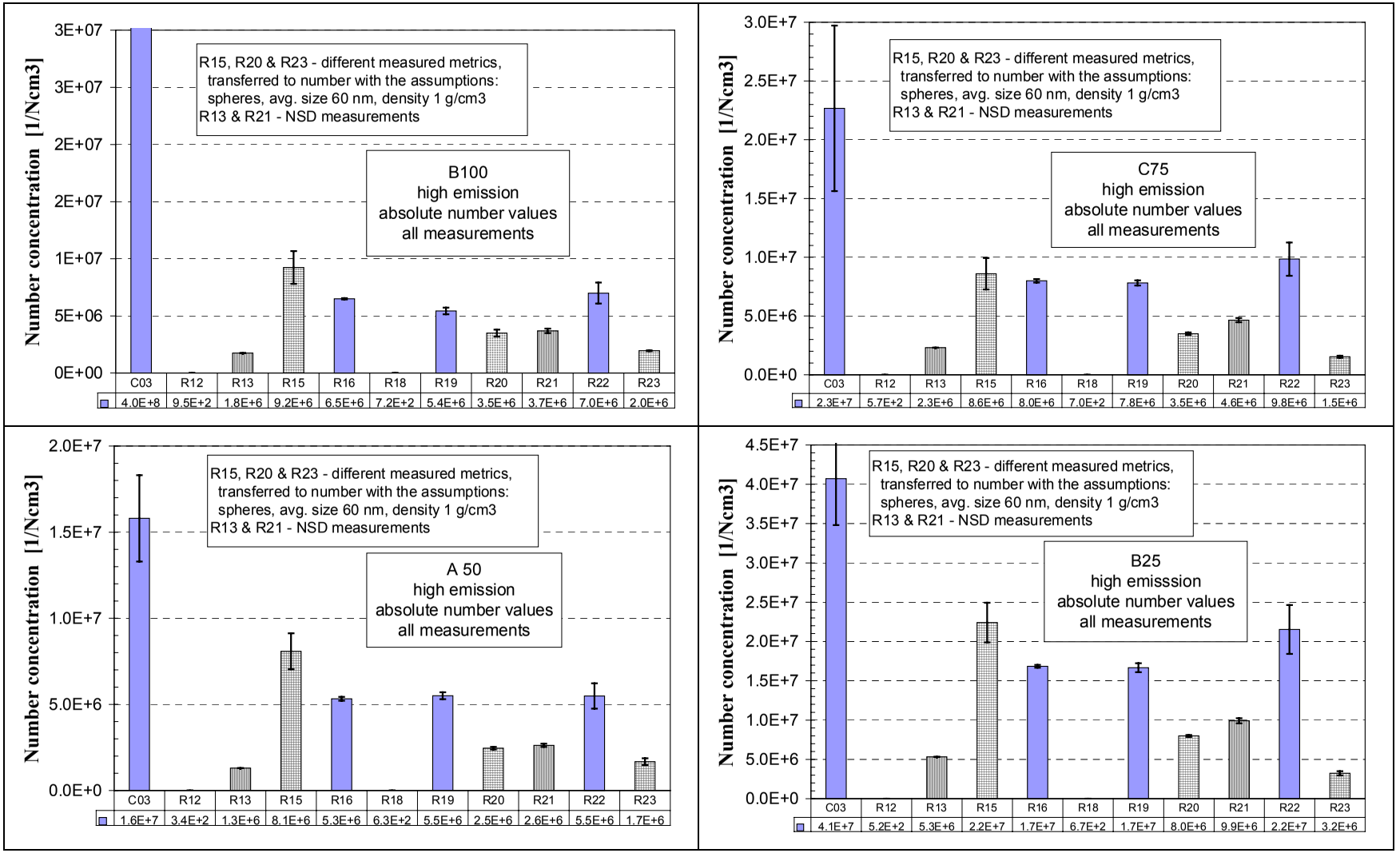


Figure 93: *Total number / SM high-emissions*

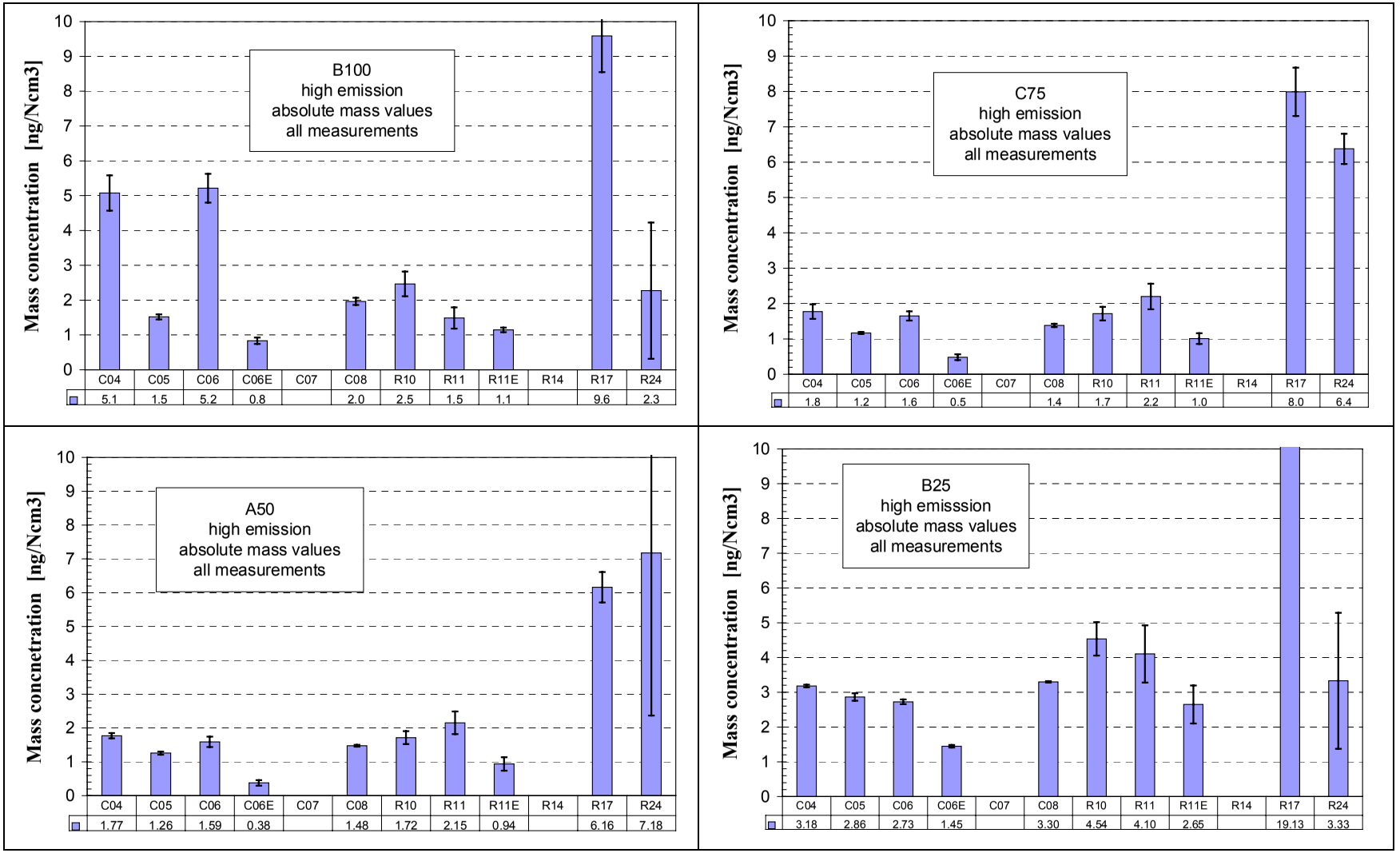


Figure 94: *Total mass / SM high-emissions*

Appendix G : Absolute values SM / low-emission

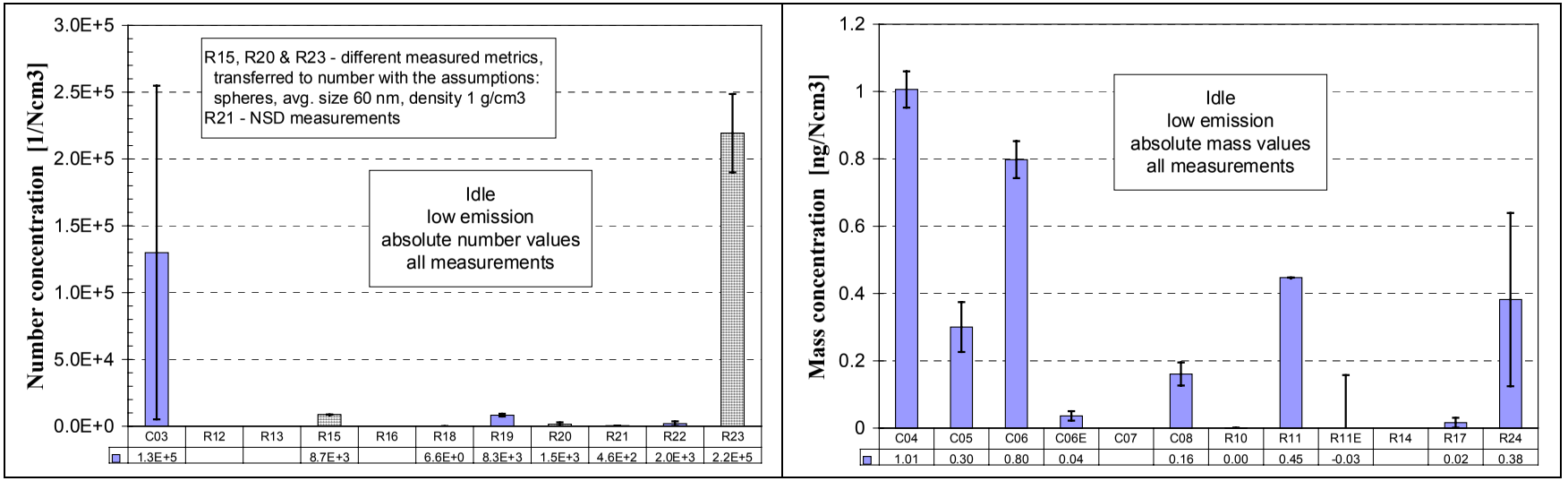


Figure 95: *Total number / SM low-emissions*

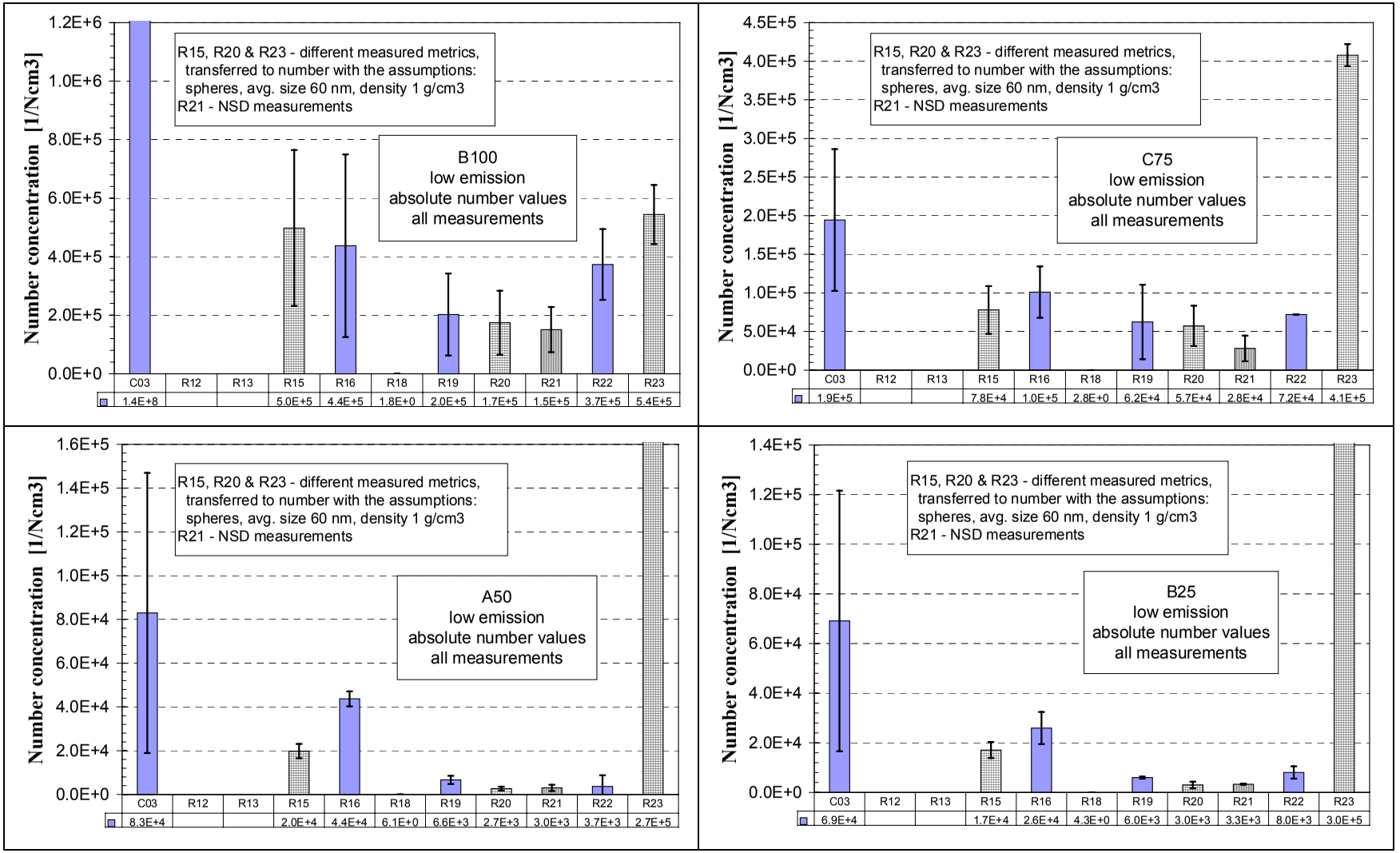


Figure 96: *Total number / SM low-emissions*

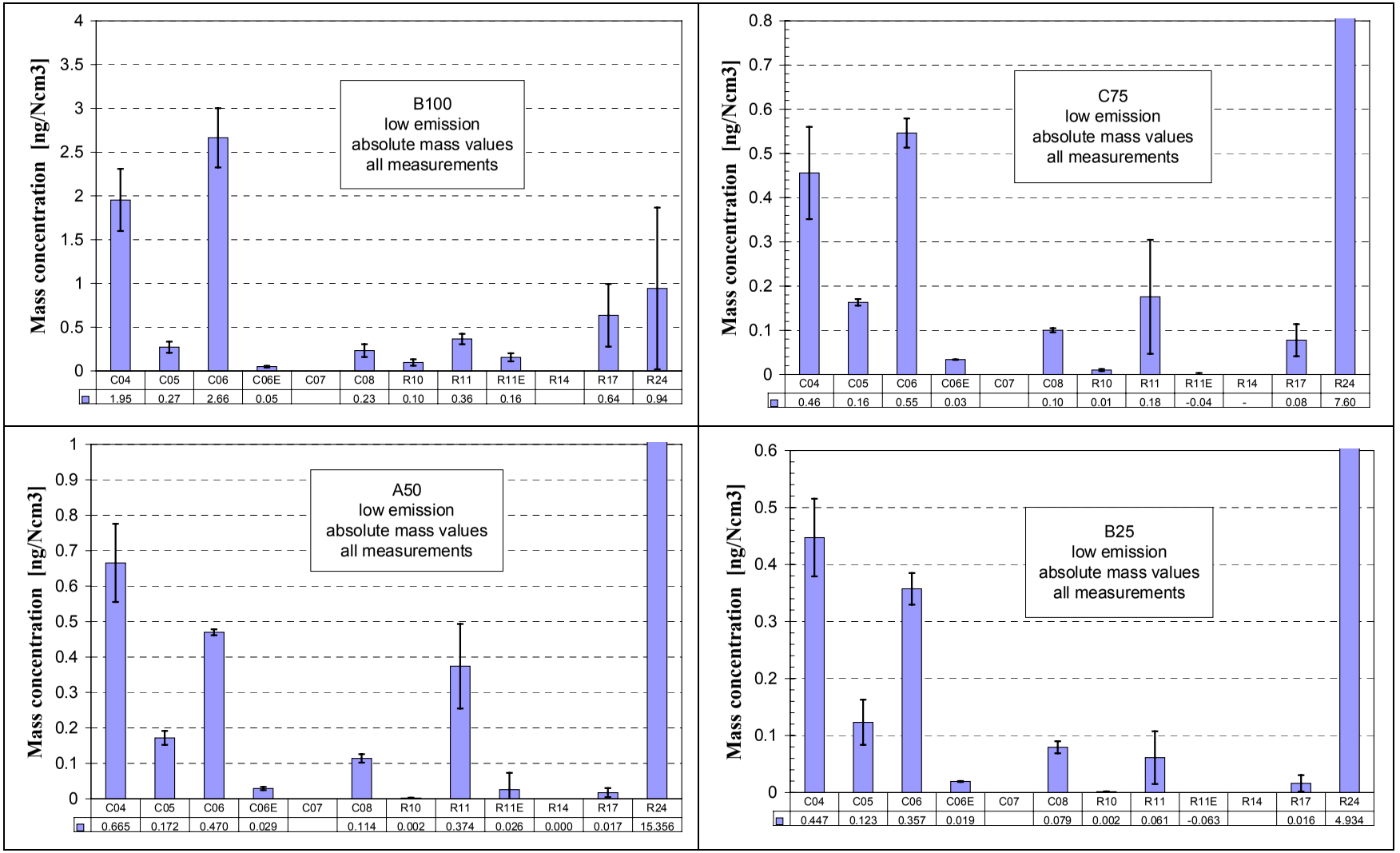


Figure 97: *Total mass / SM low-emissions*

Appendix H : Number size distribution / SM

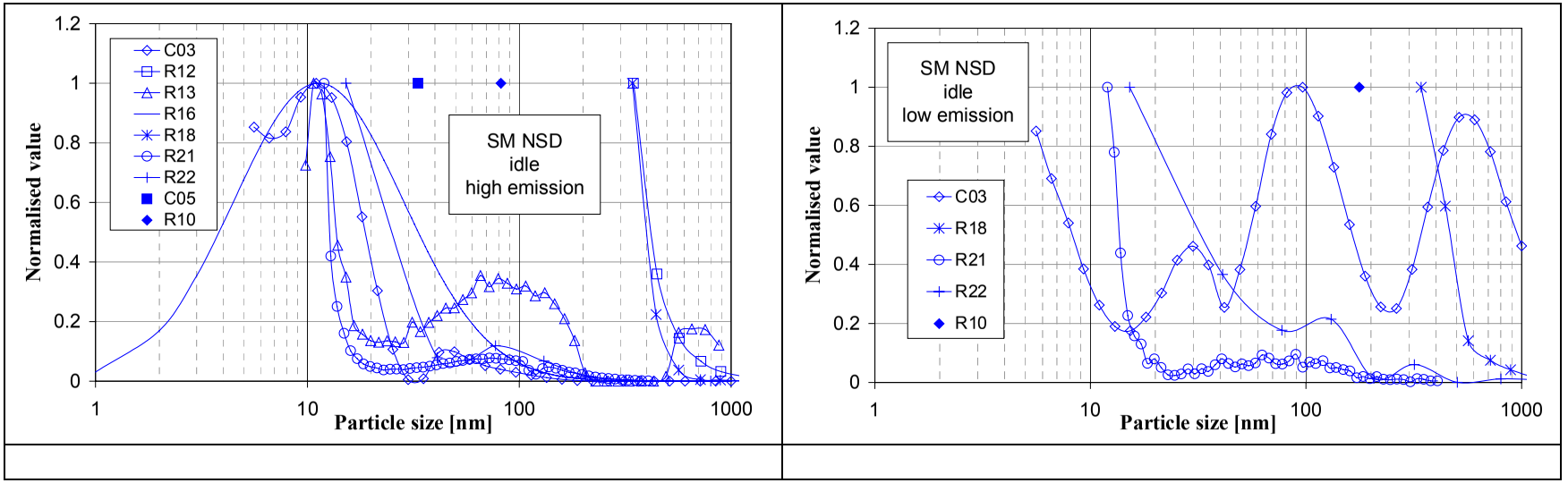


Figure 98: *Total number / SM low-emissions*

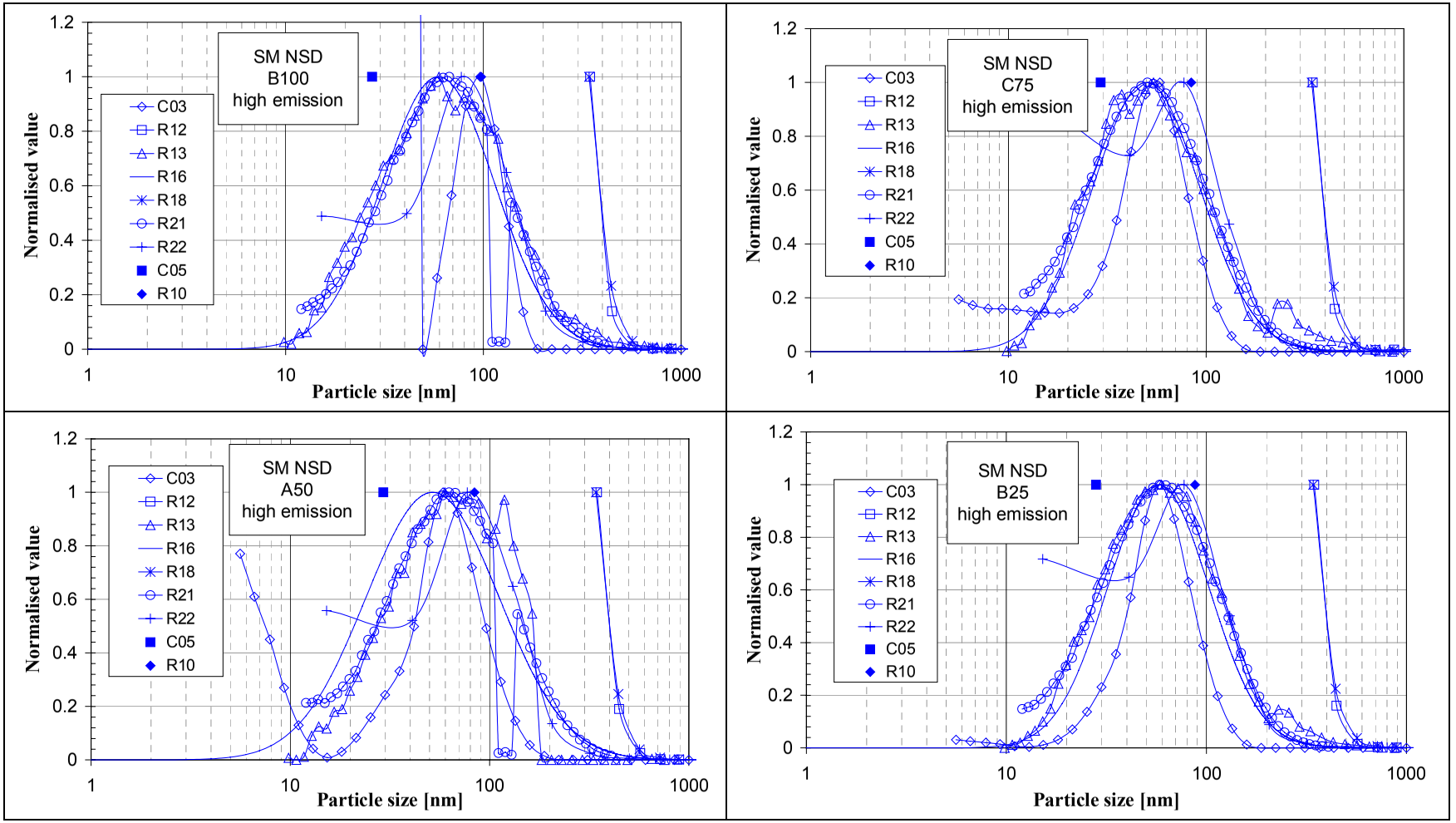


Figure 99: *Number Size Distribution (NSD) / SM high-emission*

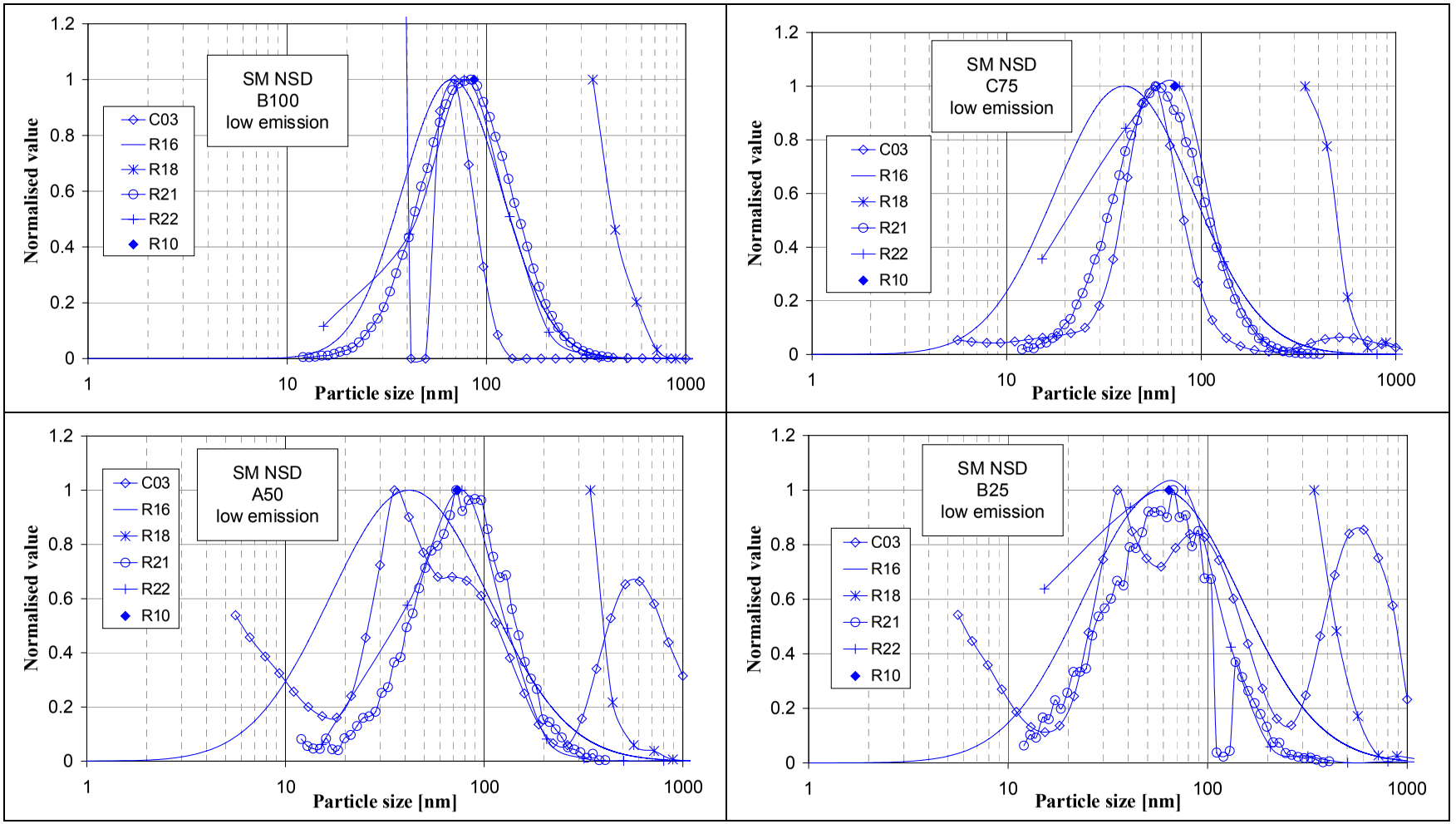


Figure 100: *Number Size Distribution (NSD) / SM low-emission*

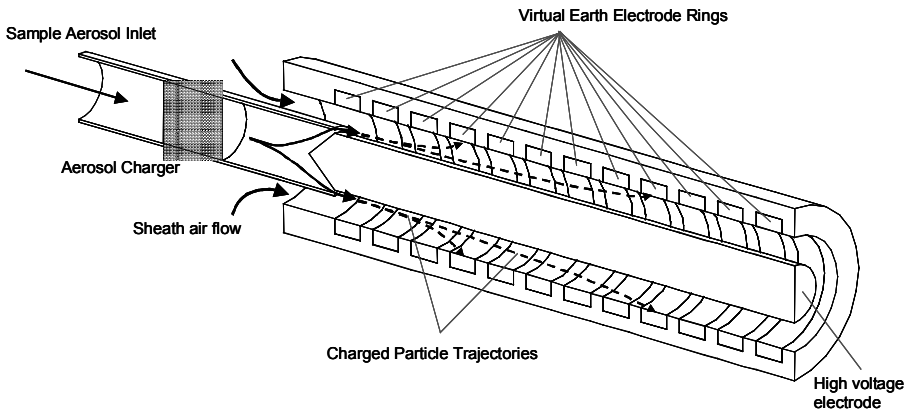
Appendix I : Test cycles

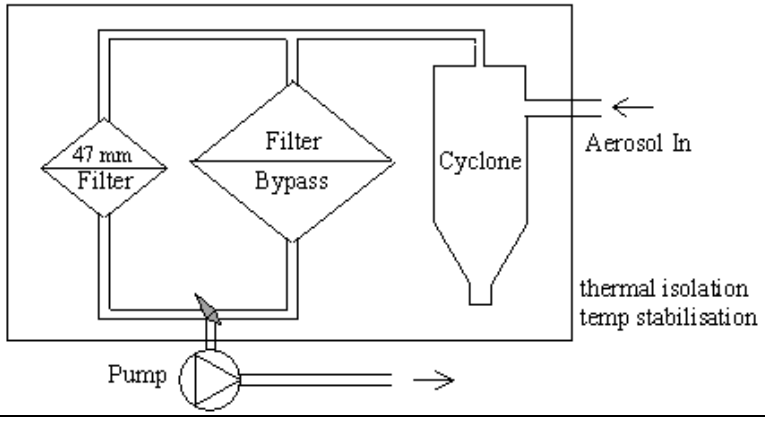
Step / Sequence	**ESC**			**SM**			**ETC**			**SCT**		
No	t_{start} [s]	t_{end} [s]	t_{sample} [s]	t_{start} [s]	t_{end} [s]	t_{sample} [s]	t_{start} [s]	t_{end} [s]	t_{sample} [s]	t_{start} [s]	t_{end} [s]	t_{sample} [s]
1	91	240	150	181	900	720	1	600	600	181	540	360
2	281	360	80	1081	1800	720	601	1200	600	541	900	360
3	381	480	100	1981	2700	720	1201	1800	600	901	1260	360
4	501	600	100	2881	3600	720	-	-	-	1261	1620	360
5	671	720	50	3781	4500	720	-	-	-	1621	1980	360
6	791	840	50	-	-	-	-	-	-	-	-	-
7	911	960	50	-	-	-	-	-	-	-	-	-
8	991	1080	90	-	-	-	-	-	-	-	-	-
9	1101	1200	100	-	-	-	-	-	-	-	-	-
10	1241	1320	80	-	-	-	-	-	-	-	-	-
11	1391	1440	50	-	-	-	-	-	-	-	-	-
12	1511	1560	50	-	-	-	-	-	-	-	-	-
13	1631	1680	50	-	-	-	-	-	-	-	-	-
total	-	-	-	-	-	-	1	1800	1800	1	2040	2040

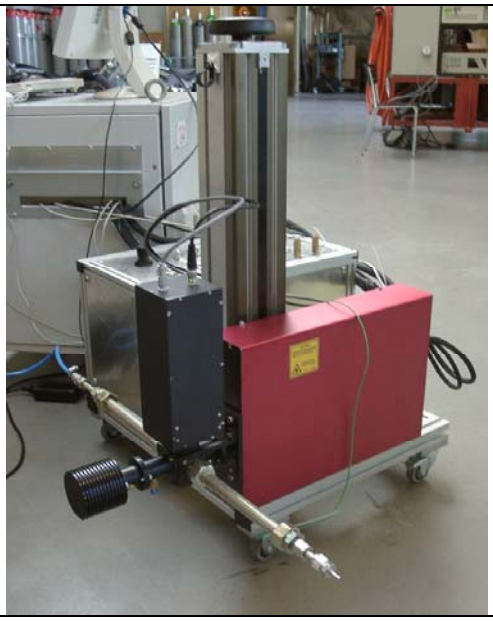
SM	(i = 1..5)	Last 12 min of steps are evaluated (red light phase)
ESC	(i = 1..13):	Evaluated period of step depends on step (red light phase)
ETC	(i = 1(urban), 2(rural), 3(highway))	Red light phase 1800 s w/o interruption
SCT	(i = 1..5)	Red light phase 2040 s w/o interruption
BG	(i = 1)	Background, red light phase 1800 s w/o interruption

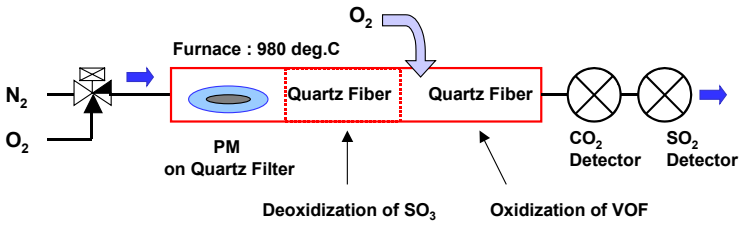
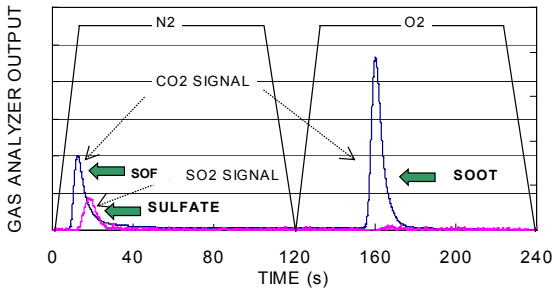
Stage	1	2	3	4	5
ESC stage	8	12	5	9	1
Mode	B100	C75	A50	B25	idle

Appendix J : Instruments

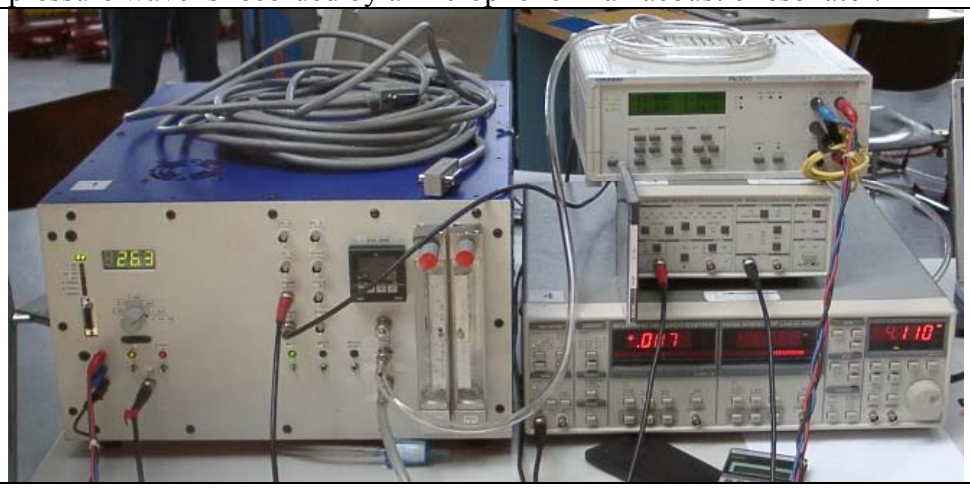
Instrument	DMS 500	Code	C03
Manufacturer	Cambustion Ltd.		
Metric	Number & Size		
Principle	The sample gas is first passed through an impactor to remove any particles greater than 1µm. It is then passed through a diffusion charger to positively charge any particulates present in the sample. The charged sample is then introduced into the centre of the classification column near the high voltage electrode along with a clean sheath flow of matched velocity. The charged particulates drift through the sheath flow under the influence of the strong electrical field in the classification column and land on one of several electrometer rings arranged along the column. The aerodynamic mobility of a particle dictates upon which of the rings it lands. The measured currents are then converted into size and number information using a non-negative least squares fit algorithm with Lagrangian regularisation.		
Schematic			
Sampling requirements	The sample is usually taken direct from a CVS tunnel, although a heated sampling system is available allowing direct measurement from the tailpipe.		
Size information	A spectrum of the particle distribution is produced from 5nm to 1µm.		
Interference	No cross sensitivity to other species has been detected. Main interference is caused by vibration. No distinction between volatile and solid material		
Adjustment Calibration	Each of the ring electrometers is calibrated prior to dispatch using a precision current source. The size classification of the instrument is then checked by using various aerosols of PSL spheres of a known size and the number calibration is checked against a CPC using the above aerosols. As a check calibration for the analyser an aerosol of D.O.P. in alcohol is suggested to confirm weekly repeatability.		
Commercially available	Yes, Delivery approx. 6 months	Price (approx.) in €	100,000
Contact address	Cambustion Ltd. The Paddocks, Cherry Hinton Road, Cambridge, England, CB1 8DH.		

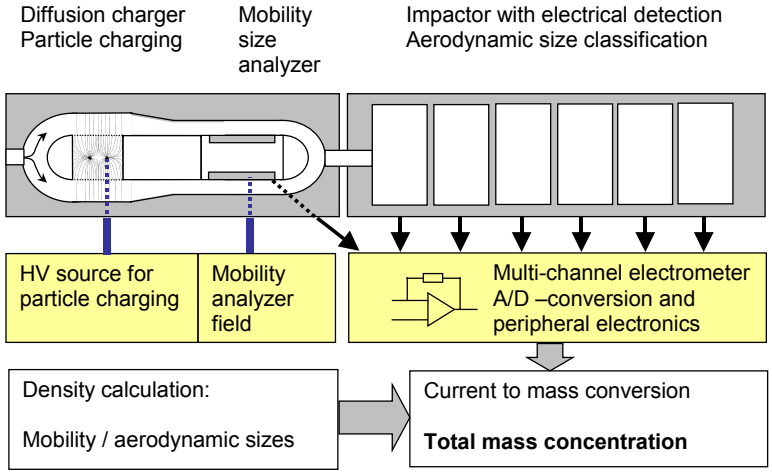
Instrument	Gravimetric filter methods (Gravimetry)	Code	C04
Manufacturer			
Metric	Mass		
Principle	filter method/balance the filter filter weighing before and after filter loading and conditioning provision for the measurement of particulate matter from diesel engines EU Directive 1999/96/EC, modified by some specifications of the US2007 Federal Register		
Schematic			
Sampling requirements	According to the provisions of EU Directive 1999/96/EC. In addition, some specifications of the US 2007 Federal Register were adopted (pre-cyclone, filter holders for filters of 47 mm diameter, filters of different quality, thermal isolation of the sampling system and conditioning of the dilution air).		
Size information	-		
Interference	No distinction between volatile and solid material		
Adjustment Calibration			
Commercially available	yes	Price (approx.) in €	--------
Contact address	EMPA Duebendorf		

Instrument	LI2SA – system	Code	C05
Manufacturer	ESYTEC Energie- und Systemtechnik GmbH,		
Metric	Soot Concentration c [mg/m^3] c = 0.05 ... 5 mg/m^3 (sample CVS) c = 0.01 ... 200 mg/m^3 (Raw gas) Spec. surface a [m²/mg] a = 0.03 ... 0,3 m²/mg Total surface A [m²/m³] A= 0.0017 …67 m²/m³ Conc. of primary particles [1/m³] n= 10^{10} … 10^{17} 1/m³		
Principle	Laser-Induced Incandescence Soot Analyser (LI2SA)		
Schematic			
Sampling requirements	Operating temperature: 15-35°C Humidity: 10-90% Pressurised air: 200 l/min, 5 bar Cooling water: 10 l/min, 3 bar		
Size information	Diameter of primary particle d_p [nm] / d_p = 10 ...100 nm		
Interference	Not known		
Adjustment Calibration	Comparison with coulometry and gravimetry		
Commercially available	yes	Price (approx.) in €	??
Contact address	ESYTEC Energie- und Systemtechnik GmbH Am Weichselgarten 6 D-91058 Erlangen, Germany Phone: ++49-9131/9959700 Email: info@esytec.de		

Instrument	Super-Low –Mass PM Analyser (MEXA-1370PM)	Code	C06
Manufacturer	HORIBA, Ltd.		
Metric	soot mass, SOF mass, sulphate mass and total PM mass (It is available to detect down to 0.2 micrograms)		
Principle	A process of vaporisation, oxidisation and deoxidisation is used to measure the mass of the PM components. First, the particulate laden particulate filter is installed in the furnace (980 deg.C), in a nitrogen gas flow. The SOF component, which vaporises, is oxidised and detected as CO_2. The sulphate component, which undergoes deoxidisation at high temperatures, is measured as SO_2. Next, oxygen flows through the furnace, oxidising the soot trapped at the filter, so that it, too, can be detected as CO_2.		
Schematic	System Flow   CO_2 and SO_2 Signal		
Sampling requirements	Particulate must be collected on the filter		
Size information	-		
Interference	Not known		
Adjustment Calibration	CO_2 and SO_2 gas are utilised for the calibration Known concentration span gas is introduced into the system and that span gas is filled in the constant volume tube that temperature is controlled constantly. Thus, the mass of span gas can be calculated and it is introduced into the gas detector. By measuring the area of detector's signal, it becomes possible to obtain the coefficient gas mass and signal area.		
Commercially available	Available	Price (approx.) in €	127k€
Contact Address	HORIBA EUROPE GmbH, Hauptstrasse 108, D-65843 Sulzbach / Ts, Germany		

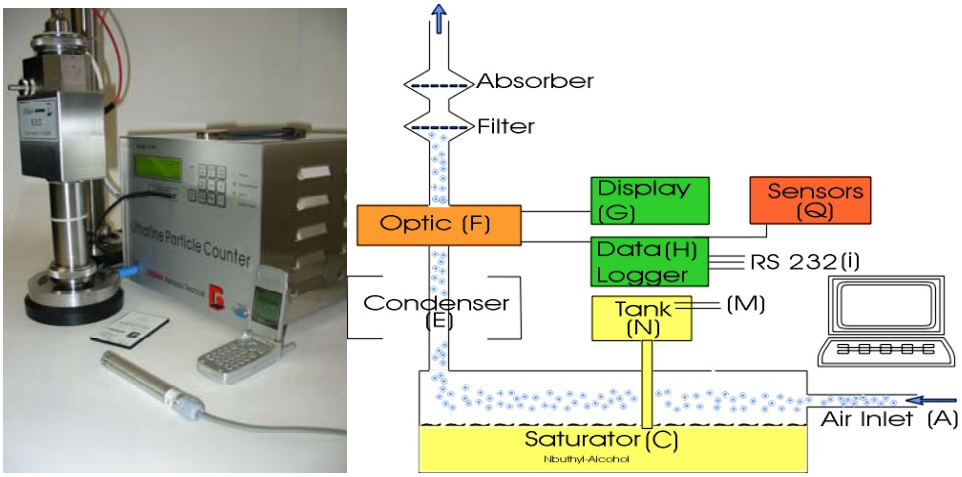
Instrument	TEOM / Series 1105 diesel Particulate Monitor	Code	C07
Manufacturer	Rupprecht & Patashnick Co., Inc., Albany, USA		
Metric	Oscillating inertial microbalance for direct (filter-based) mass measurement Mass concentration: +/- 0.2 mg/m3 Mass rate: +/- 10^{-8} g/sec		
Principle	The TEOM Series 1105 diesel Particulate Monitor incorporates a patented intertial balance that directly measures the mass collected on an exchangeable filter cartridge. It monitors the change in the natural oscillating frequency of a tapered element (see photo) as additional mass collects on the filter. The sample flow passes through the filter, where particulate matter collects, and then continues through the hollow tapered element on its way to a dynamic flow control system and vacuum pump.		
Schematic			
Sampling requirements	Sample temperature has to be less than 47°C Actual sample flow rate: 3-4.5 l/min		
Size information	--		
Interference	Not known		
Adjustment Calibration	The mass calibration may be verified, however using an optional Mass Calibration Verification Kit that contains a filter of known mass. A flow controller maintains the sample flow rate input by the user.		
Commercially available	yes	Price (approx.) in €	??
Contact address	Rupprecht & Patashnick Co., Inc. Robert C. Anderson 25 Corporate Circle, Albany, NY 12203, USA Phone: (518)452-0065 • Fax: (518)452-0067 Email: info@rpco.com • www.rpco.com		

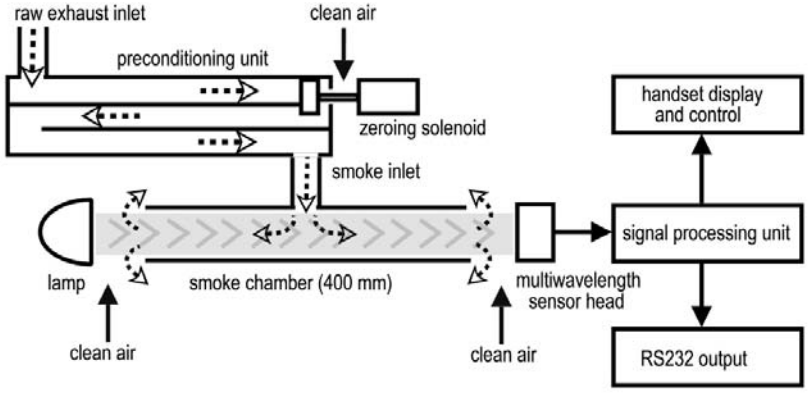
Instrument	Photoacoustic Soot Sensor PASS	Code	C08
Manufacturer	Technical University Munich Haisch, Beck, Niessner		
Metric	EC mass		
Principle	Photoacoustic absorption measurement: Absorption of a modulated IR laser beam by the soot particles leads to modulated heating and, consequently, to modulated expansion. The resulting pressure wave is recorded by a microphone in an acoustic resonator.		
Schematic			
Sampling requirements	Required only if the exhaust temperature is more than 52°C.		
Size information	Size-independent, mass proportional signal.		
Interference	Not known.		
Adjustment Calibration	Initial calibration by gravimetry and coulometry. No calibration drift found over about 1 year. Calibration and blank value checks by internal performance check, can be performed within seconds and repeated as many times as wanted.		
Commercially available	Not yet	Price (approx.) in €	--------
Contact address	C. Haisch or R. Nießner, Inst of Hydrochemistry, TU Munich Marchioninistrasse 17, D-81377 Munich, Germany		

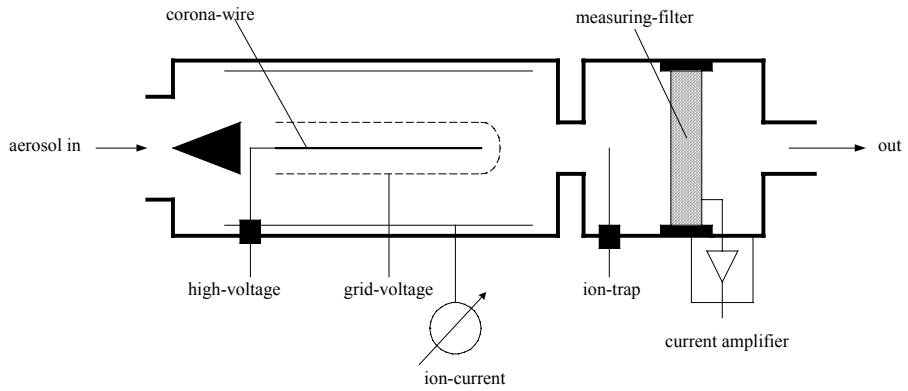
Instrument	Dekati Mass Monitor DMM	Code	R10
Manufacturer	Dekati Ltd. FIN-33700 Tampere, FINLAND		
Metric	Accumulation mode mass concentration and median diameter		
Principle	Particle charging in a diffusion charger, size classification in a low-pressure cascade impactor, electrical detection of charged particles. Particles in sample receive a known charge in an unipolar triode-type diffusion charger, and after that they are size-classified (aerodynamic size) in a cascade low-pressure impactor. The current measured from each collection electrode is proportional to the amount of particles in each size range. In addition, mobility size measurement is combined with aerodynamic size, and that information is used for effective density calculation. Density information is used for conversion from measured electrical currents to total mass concentration.		
Schematic			
Sampling requirements	Removal of volatile materials, no nucleation.		
Size information	Mass median diameter in real time.		
Interference	Nucleation mode particles prevent the density measurement		
Adjustment Calibration	Annual factory calibration recommended.		
Commercially available	Yes	Price (approx.) in €	43’000
Contact address	Dekati Ltd. Osuusmyllynkatu 13 FIN-33700 Tampere, FINLAND	Tel. +358-3-3578100 Fax. +358-3-3578140 www.dekati.com	

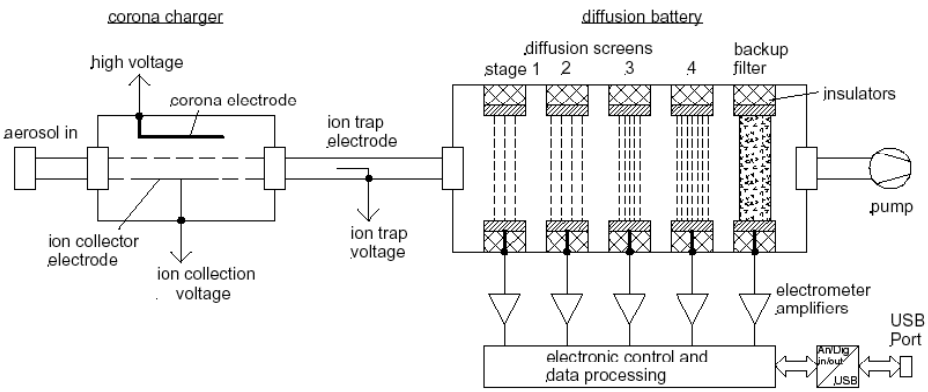
Instrument	Coulometry	Code	R11
Manufacturer	Ströhlein instruments		
Metric	Measurement of the organic bouned carbon (OC) and elemental carbon (EC) Measuring range: 10 ppm – 100%		
Principle	The coulometric characterisation of carbon is based on the principle of electro-chemical titration. Heating the filter sample to 650°C using oxygen for oxidation of the carbonaceous compounds to CO2. CO2 is measured by an absorption in a basic chemical solution (coulometric detection). The separation of organic bouned carbon (OC) and elemental carbon (EC) is done using Toluene/Isopropanol. Method is in accordance with standard ISO 8245 / DIN 38409 H3 / NPR 6522		
Schematic			
Sampling requirements	Filter sampling		
Size information	-		
Interference			
Adjustment Calibration	Calibration with a liquid carbon standard (oxalic acid)		
Commercially available	yes	Price (approx.) in €	--------
Contact address			

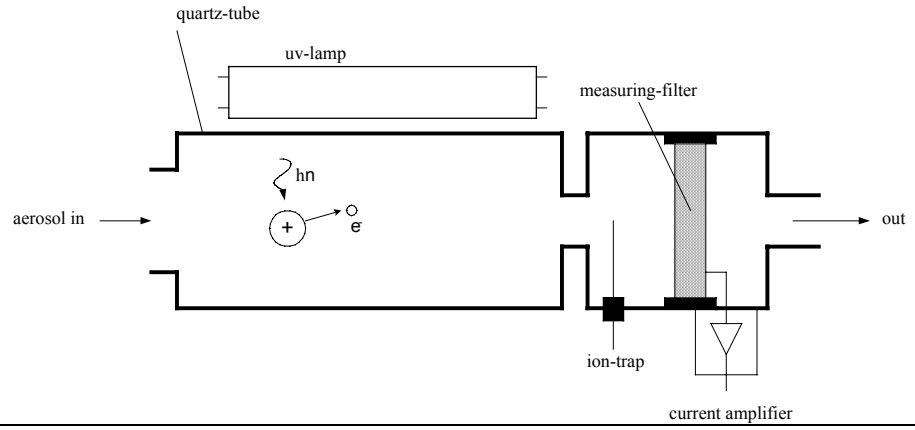
Instrument	”IAQcheck“, model no. 1108 - Portable Laser Dust Monitor (Aerosol Spectrometer) with 15 particle size channels	Code	R12
Manufacturer	Grimm Aerosol Technik GmbH & Co. KG		
Metric	Particle counting up to 2 million particles/litre Measures dust mass up to 100 mg/m³ Measuring range from 0.3 to 20 micron 15 different particle size channels		
Principle	Laser light scattering		
Schematic			
Sampling requirements	Active sample flow 72 litres per hour Operating temperature: +4 to +45°C		
Size information	only particles > 300 nm are detected		
Interference			
Adjustment Calibration	Automatic internal calibration check Routinely a yearly calibration check is recommended		
Commercially available	YES	Price (approx.) in €	~ 11.000,--
Contact address	Grimm Aerosol Technik GmbH & Co. KG Uwe Golz, Sales Dept. Dorfstraße 9, D – 83404 Ainring Phone: +49 (0) 8654 578-0, Fax: +49 (0) 8654 578-35 Email: sales@grimm-aerosol.com, Homepage: www.grimm-aerosol.com		

Instrument	SMPS + C – CPC (Condensation Particle Counter) "NANOcheck", UPC model 5400, with Classifier, model 5500	Code	R13
Manufacturer	Grimm Aerosol Technik GmbH & Co. KG		
Metric	Only CPC: Total number concentration, up to 10^{10} particles/litre CPC+DMA: Particle size, 5 – 875 nm		
Principle	Nucleous condensation + differential mobility analyser		
Schematic			
Sampling requirements	Low flow 0.3 l/min High flow 1.5 l/min Operating temperature: +5 to +30°C		
Size information	size range: 10 to 700 nm electrical mobility diameter		
Interference	No distinction between volatile and solid particles		
Adjustment/ Calibration	Automatic internal calibration check Routinely a yearly calibration check is recommended		
Commercially available	YES	Price (approx.) in €	CPC ~28.000,-- M-DMA ~15.000,--
Contact address	Grimm Aerosol Technik GmbH & Co. KG Dr. Ch. GERHART, Nanotechnology Division Dorfstraße 9, D – 83404 Ainring Phone: +49 (0) 8654 578-0, Fax: +49 (0) 8654 578-35 Email: sales@grimm-aerosol.com, Homepage: www.grimm-aerosol.com		

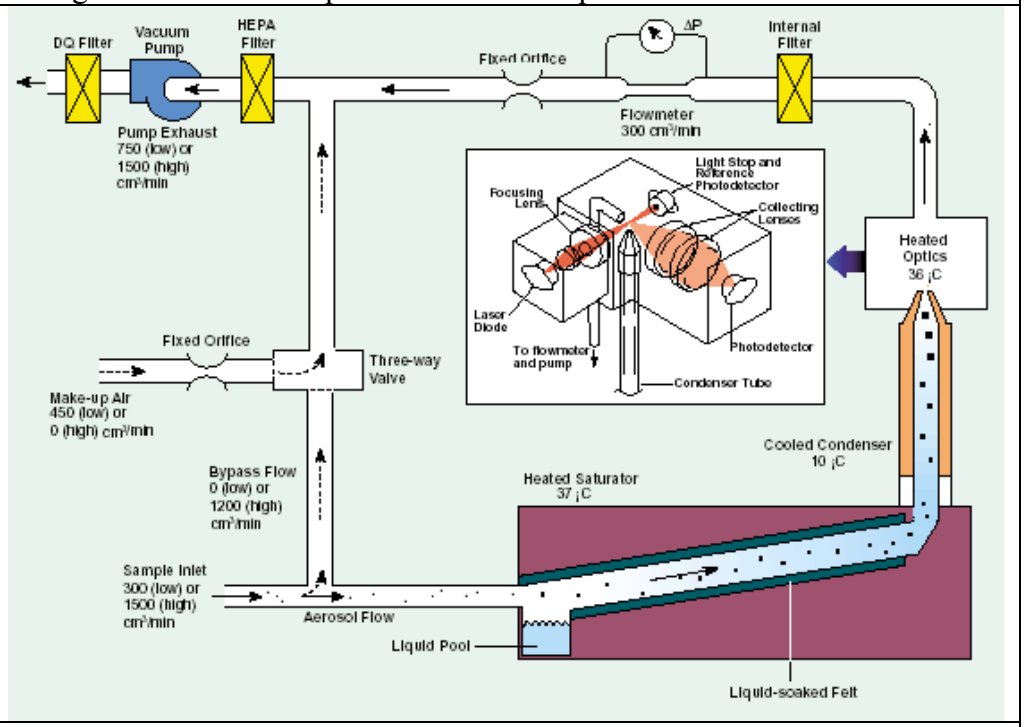
Instrument	DPSO-1 advanced opacimeter	Code	R14
Manufacturer	Hartridge Test Products DT Assembly & Test – Europe Ltd, UK		
Metric	Opacity (k value, units m-1) (can be converted to mg/m3)		
Principle	Exhaust enters centrally into a 400mm long by 25mm dia. smoke chamber. Broadband light shines through the chamber and sensors tuned to specific wavelengths measure the light intensity. No light and full light (no exhaust in the chamber) signals are recorded for calibration. Opacity for each wavelength is calculated, then used to extract particle size based on Mie theory for extinction. The basic analysis assumes a dominant particle size and spherical particles. It looks at a likely range of particle refractive indices for the signals measured to extract a particle size. An opacity of at least 0.01 m^{-1} is required for sizing. Resolution is 0.001 m^{-1} . A preconditioning unit has been added to reduce noise and drift resulting from temperature and pressure changes in the exhaust sample. The unit is portable and can be powered from 12V DC making it suitable for road test emissions measurement. Data is continuously transmitted at a rate up to 20 samples/sec to allow transients to be effectively observed.		
Schematic			
Sampling requirements	10mm ID minimum dia. tube directly into the raw exhaust flow. Approx 60 litres/min flow rate. Pressure: 0 to 1000 Pa static pressure at the probe inlet.		
Size information	Particle sizing in the range 50-200 nm diameter calculated using Mie theory for light extinction.		
Interference	Sensitivity to nitrogen dioxide can be reduced by choice of sensor		
Adjustment Calibration	Automatic zero & span adjustment. Manual linearity check by insertion of a neutral density filter.		
Commercially available	April 2003	Price (approx.) in €	15K
Contact address	Tingewick Rd, Buckingham, MK18 1EF, UK Phone: +44 (0)1280 828492 Email: mjones@dtindustries.com.		

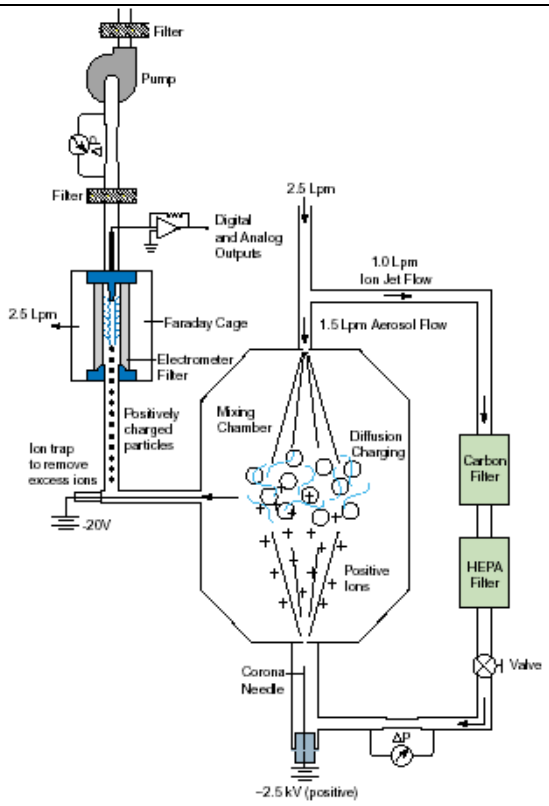
Instrument	LQ1-DC Diffusion Charger	Code	R15
Manufacturer	Matter Engineering AG, CH 5610 Wohlen		
Metric	Active Surface by diffusion charging; measurement using an electrometer amplifier		
Principle	A corona discharge is used to produce small ions which attach to the aerosol particles by diffusion. The average charge per particle is proportional to its active surface. All particles including the charged ones precipitate on an electrically insulated filter which is connected to a current amplifier. The current represents the total active surface of the measured aerosol.		
Schematic			
Sampling requirements	Dilution is recommended, especially if condensation of volatile particles is to be avoided. Dilution is required if particle concentrations in the sample exceed the sensor's range.		
Size information	The LQ1-DC does not provide any information about the size of the sampled particles.		
Interference	Diffusion charging is independent of particle material, no distinction between solid and volatile particles is possible in particular. Interferences with gases have not been encountered.		
Adjustment Calibration	The zero-point of LQ1-DC is adjusted using a small trimpot at the front panel. The amplification factor that converts current into active surface is calibrated using a DMA and a CPC. Monosdisperse aerosol from the DMA is fed into LQ1-DC and a CPC. The DMA settings provide the active surface per particle which is multiplied by the number measured in the CPC to calculate the total active surface in the monodisperse aerosol. The LQ1-DC amplification factor is tuned until the LQ1-DC display matches the calculated value. The procedure is repeated at various particle sizes and an average LQ1-DC amplification factor is used.		
Commercially available	yes	Price (approx.) in €	11 k
Contact address	Markus Kasper, Matter Engineering AG, CH 5610 Wohlen Phone: +41 56 618 66 30 Email: mkasper@matter-engineering		

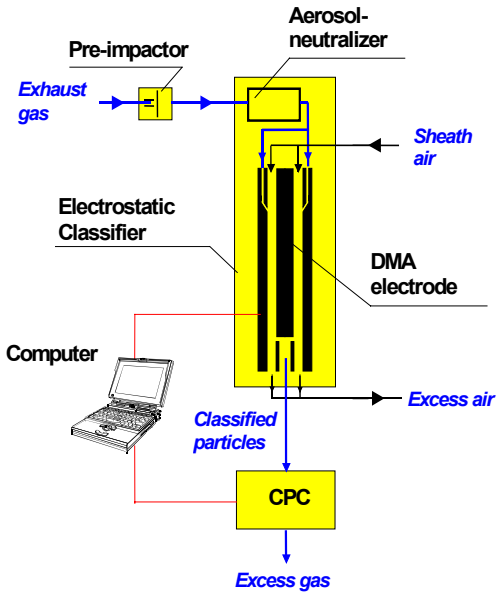
Instrument	EDB 200 Electrical Diffusion Battery	Code	R16
Manufacturer	Matter Engineering AG, CH 5610 Wohlen		
Metric	Number Size Distribution using diffusion charging and a diffusion battery; measurement using electrometer amplifiers		
Principle	A corona discharge is used to produce small ions which attach to the aerosol particles by diffusion. The particles pass several series of electrically insulated screens to which they eventually attach by diffusion. Smaller particles have a higher diffusivity and are therefore removed earlier than large particles. The particle charge is captured and amplified for each series of screens and a backup filter. From the electric currents the parameters of a monomodal or bimodal lognormal distribution function (LNDF) are calculated. The sum of all currents represents the active surface of the particles.		
Schematic			
Sampling requirements	Dilution is recommended, especially if condensation of volatile particles is to be avoided. Dilution is required if particle concentrations in the sample exceed the sensor's range.		
Size information	The EDB 200 is designed to measure number size distributions. The calculation is based on the assumption of a monomodal or bimodal lognormal distribution function.		
Interference	Diffusion charging is independent of particle material, no distinction between solid and volatile particles is possible in particular. Interferences with gases have not been encountered.		
Adjustment Calibration	The zero-point of EDB 200 can be determined before each measurement (implemented). The EDB 200 is calibrated using a DMA (particle size) and a CPC (number concentration).		
Commercially available	only prototype	Price (approx.) in €	60 k
Contact address	Markus Kasper, Matter Engineering AG, CH 5610 Wohlen Phone: +41 56 618 66 30 Email: mkasper@matter-engineering		

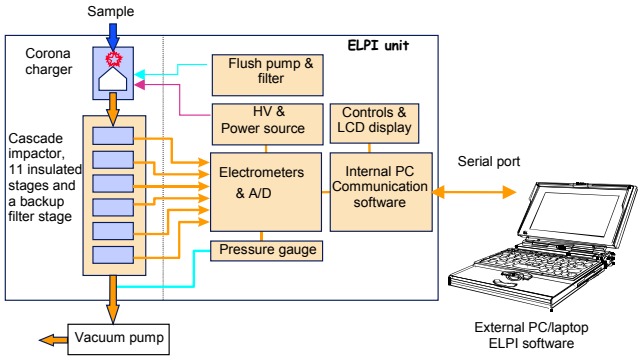
Instrument	PAS 2000 Photoelectric Aerosol Sensor	Code	R17
Manufacturer	EcoChem Analytics, c/o Matter Engineering AG, CH 5610 Wohlen		
Metric	Elemental Carbon Mass by photoelectric charging; measurement using electrometer amplifiers		
Principle	Aerosol particles are illuminated using a UV lamp. The particles are electrically charged by emitting photoelectrons upon light absorption. Aerosol photoemission depends on particle bulk and surface material, and on particle size. All particles including the charged ones precipitate on an electrically insulated filter which is connected to a current amplifier. The measured current correlates with elemental carbon (EC) mass concentration.		
Schematic			
Sampling requirements	Dilution is recommended, especially if condensation of volatile particles is to be avoided. Dilution is required if particle concentrations in the sample exceed the sensor's range.		
Size information	The PAS 2000 does not provide any information about the size of the sampled particles.		
Interference	Photoelectric charging of particles very strongly depend on the adsorbates on the surface. Interferences with gases have not been encountered.		
Adjustment Calibration	The zero-point of PAS 2000 is adjusted automatically during the measurement. The PAS 2000 is calibrated by comparing it to a reference instrument which is also a PAS 2000. The reference instrument is calibrated against an elemental carbon (EC) reference method. The correlation factor between EC mass and PAS current may vary with different sources.		
Commercially available	yes	Price (approx.) in €	14 k
Contact address	Markus Kasper, Matter Engineering AG, CH 5610 Wohlen Phone: +41 56 618 66 30 Email: mkasper@matter-engineering		

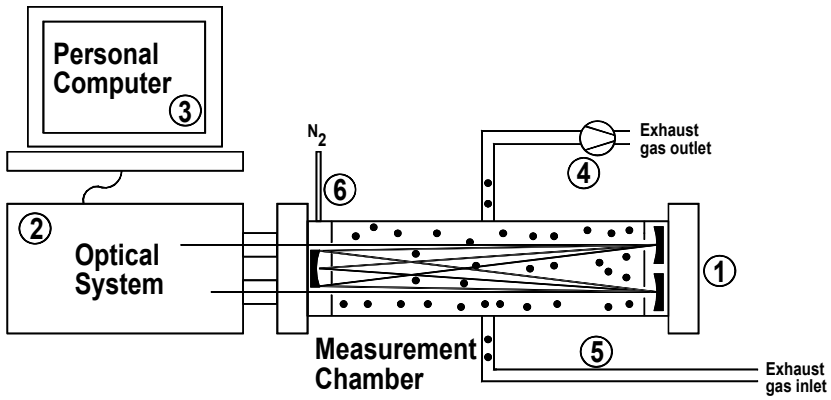
Instrument	PM 300	Code	R18
Manufacturer	Sensors Inc., Saline (Michigan, USA), 6812 S. State Rd.		
Metric	Counts of particles related to particle size between 300 nm to 2 µm diameter Presenting numbers(counts) and particle diameter		
Principle	Measurement of scattered Laser light pulses when particles crossing the laser beam		
Schematic	Raw exhaust is drawn through a heated sampling line in by a 5 l/min volume sampling pump. The raw hot gas gets diluted with clean ambient air in a micro diluter with adjustable dilution ratio (10-20-50-100). Hereafter, this is diluted additionally by a fixed dilution factor of 1:100 and provided into the laser beam area and vented to the drain output.		
Sampling requirements	External heated line (195 deg C), internal heated sample line to 65 deg C, adjustable mini diluter, Fine filter for ambient air filtering, dilutor w/ fixed dil. ratio of 1:100		
Size information	only particles larger than 300 nm are detected		
Interference	No distinction between volatile and solid particles		
Adjustment Calibration	PM 300 is initially calibrated at the factory in two steps verification of the optics against a "mother unit" for proper size classific. & distribution. Cross reference calibration using spherical glass beads. Under normal testing operations, with periodical internal cleaning and filter replacement the unit need not be re-calibrated		
Commercially available	Yes, upon order	Price (approx.) in €	36.000
Contact address	Sensors Europe GmbH, Papiermühlenweg 74, 40882 Ratingen (Germany) Phone 0049-2102-85680-0; att.: Thore Simon ext -30 / Peter Dierich ext -40		

Instrument	High-Concentration Condensation Particle Counter (CPC), Model 3022A	Code	R19
Manufacturer	TSI Incorporated, St. Paul, MN (USA)		
Metric	Particle number concentration = d^0 weighting unit: [P/cm^3]		
Principle	The operating principle of TSI Model 3022A is based on physical enlargement of ultrafine particles and their optical detection:		
Schematic			
Sampling requirements	None.		
Size information	Size range: 0.007 to >3 µm		
Interference	No distinction between volatile and solid particles		
Adjustment Calibration	Calibration check (either): Comparison with reference CPC; Comparison with Aerosol Electrometer 3068A measuring singly charged, monodisperse aerosol.		
Commercially available	Yes	Price (approx.) in €	39.500
Contact address	TSI GmbH Particle Instruments Neuköllner Str. 4 D-52068 Aachen, Germany Email: Particle-Europe@tsi.com		

Instrument	Electrical Aerosol Detector (EAD), Model 3070A	Code	R20
Manufacturer	TSI Incorporated, St. Paul, MN (USA)		
Metric	Equivalent aerosol length $= d^1$ weighting unit: [mm/cm^3]		
Principle	The operating principle of TSI Model 3070A is based on diffusional charging of the particles, followed by detection of the aerosol via electrometer:		
Schematic			
Sampling requirements	None.		
Size information	to >1 µm		
Interference	No distinction between volatile and solid particles		
Adjustment Calibration	Calibration check (either): Comparison with CPC measuring singly charged, monodisperse aerosol; Comparison with calculated 1st moment values from SMPS.		
Commercially available	Yes	Price (approx.) in €	21.500
Contact address	TSI GmbH Particle Instruments Neuköllner Str. 4 D-52068 Aachen, Germany Email: Particle-Europe@tsi.com		

Instrument	Scanning Mobility Particle Sizer (SMPS) system	Code	R21
Manufacturer	TSI Incorporated, St. Paul, MN (USA)		
Metric	Particle size distribution and number concentration = electrical mobility diameter & d^0 weighting unit: [P/ cm^3]		
Principle	TSI's SMPS Model 3936-L10 combines an Electrostatic Classifier for size classification (model 3080) with long DMA (DMA 3081) and a Condensation Particle Counter (CPC 3010-S) to measure the particle number:		
Schematic	 Measuring using the configuration "scanning SMPS 3936-L10 in the DMA-Bandpass mode (with CPC detection)" means that one selected particles size was pre-selected by the SMPS' electrostatic classifier 3080L (by setting the DMA to a well defined voltage) and subsequently measured by the CPC 3010-S. Also called "single-size measurement (over transient cycle)" Only for a few measurements (transient tests), the CPC 3010-S was running without the upstream DMA. Such results are marked		
Sampling requirements	Thermodenuder or two-stage dilution advisable to distinguish nucleation effects.		
Size information	Size range: 0.003 to 1 µm		
Interference	No distinction between volatile and solid particles		
Adjustment Calibration	Calibration check (either): Portable Atomiser Model 3079 with PSL size standards for sizing accuracy; Comparison with Aerosol Electrometer Model 3068A measuring singly charged, monodisperse aerosol for concentration accuracy.		
Commercially available	Yes, in variety of configurations.	Price (approx.) in €	From 92.000
Contact address	TSI GmbH Particle Instruments Neuköllner Str. 4 D-52068 Aachen, Germany Email: Particle-Europe@tsi.com		

Instrument	Electrical Low Pressure Impactor ELPI	Code	R22
Manufacturer	Dekati Ltd. FIN-33700 Tampere, FINLAND		
Metric	Particle number concentration and size distribution		
Principle	Particle charging in a diffusion charger, size classification in a low-pressure cascade impactor, electrical detection of charged particles. The sample passes through a unipolar positive polarity charger where the particles in the sample are charged electrically by small ions produced in a corona discharge. After the charger, the charged particles are size classified in a low-pressure impactor. The stages of the impactor are insulated electrically and each stage is connected individually to an electrometer current amplifier. The charged particles collected in a specific impactor stage produce an electrical current, which is recorded by the respective electrometer channel. A larger charge correlates to a higher particle population. The current value of each channel is proportional to the number of particles collected, and thus to the particle concentration in the particular size range. The current values are converted to a (aerodynamic) size distribution using particle size dependent relations describing the properties of the charger and the impactor stages.		
Schematic			
Sampling requirements			
Size information	Particle size distribution in real time 12 size channels in size range 7 nm – 10 µm		
Interference	-		
Adjustment Calibration	Annual factory calibration recommended.		
Commercially available	Yes	Price (approx.) in €	70 000
Contact address	Dekati Ltd. Osuusmyllynkatu 13 FIN-33700 Tampere, FINLAND	Tel. +358-3-3578100 Fax. +358-3-3578140 www.dekati.com	

Instrument	WIZARD-DQL	Code	R23
Manufacturer	WIZARD Zahoransky KG, 79674 Todtnau, Germany		
Metric	Volume (mass) concentration, mean diameter		
Principle	A sensor head ② containing three laser diodes of different wavelengths is adapted to an optical long-path-cell ① with a base path length of 62.5 cm. A mirror system (White principle) allows an adjustment of the optical path length from 2.5 to 15 m. For high-emissions, the spectral attenuation of the three wavelengths is captured at a single detector and the particle diameter and concentration is evaluated by the use of the Mie theory and shown on-line (mean diameter and volume and mass concentration). For low-emissions, the system works principally as a sensitive long path opacimeter with the advantage of an optical path length of 10 to 15 meters. This mode delivers the concentration information (volume and mass concentration).		
Schematic			
Sampling requirements	The system is capable to measure the hot, undiluted raw exhaust gas. The probe is sampled by a vacuum pump ④ through a heated and thermo-controlled hose ⑤ of 5 m length (standard). A nitrogen purging system keeps the optics clean ⑥.		
Size information	Average primary particle size is calculated		
Interference	The parallel determination of NO_2 concentration by one of the three wavelengths is under development.		
Adjustment Calibration	The system can be checked by reference material (e.g. SiO_2 mono spheres) for the size information. The concentration results can also be approved by checking the optical system on its own by reference materials (e.g. lattices in water solution)		
Commercially available	Yes	Price (approx.) in €	70.000
Contact address	WIZARD Zahoransky KG Schwarzwaldstr. 3 79674 Todtnau Germany	Tel. 0049-7671 9233 Fax 0049-7671 9234 Mail: info@wizard-zahoransky.de	

Instrument	Opacimeter AVL 439	Code	R24
Manufacturer	AVL List GmbH, Graz		
Metric	Opacity / time response: 0.1 sec		
Principle	Partial-flow system for online measurement of exhaust gas opacity (acc. to Beer-Lambert-law) in diesel engines		
Schematic	A constant flow of exhaust gas is drawn from the exhaust pipe through a welded sampling probe and conditioned sampling hose by means of a diaphragm-type pump. In the conditioned sampling line, the sampled gas is fed to the inlet of the measuring chamber with an optical path length of 430 mm at a temperature of 100°C. A new feature is the re-circulation of the sampled gas via a return line to the exhaust pipe of the test engine. The measurement results for opacity N (0 to 100%) and for the absorption coefficient k (0 to 10 m-1) are available both at a serial interface and at an analogue output.		
Sampling requirements	Exhaust temp < 600°C Sampling re-circulation		
Size information	-		
Interference	Interference to NO2		
Adjustment Calibration	Calibration with a well defined light absorption filter LIN-Check for linearity		
Commercially available	yes	Price (approx.) in €	??
Contact address	AVL LIST GmbH Hans-List-Platz 1 A-8020 Graz / Austria Phone: +43 316 787-0 Homepage: http://www.avl.com		