EUROPEAN COMMISSION
JOINT RESEARCH CENTRE

Environment Institute
Air Quality Unit
I-21020 Ispra (VA) Italy

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P. Dilara, R. Hummel
A. Krasenbrink (DLR-IVF)

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Summary

Particulate emissions from vehicles, specially from diesel-driven vehicles, are studied in order to evaluate the effects of technological engine improvements or new fuel formulations. These effects can be changes in total mass emissions, in mass/size or number/size distributions, in chemical composition and in health effects. Results of measurements performed to study the following items are shown in this report:

- The interaction between fuels and fuel injection systems. Two similar diesel-driven vehicles, one with a standard fuel injection pump, and one with common rail system were tested together with a standard fuel and a "clean" low sulphur and low aromatics fuel.

- The importance of the measurement method and sampling position. Particulate matter was measured as total mass concentration collected on a filter, as mass/size distribution sampled with low pressure impactors in the undiluted exhaust gas at the exhaust pipe's exit and after dilution in the CVS tunnel, and as number/size distribution with an SMPS after dilution in the CVS tunnel.

As main results it was found that:

- The common rail vehicle emitted less total mass of particles than the standard direct injection vehicle.
- The "clean" fuel reduced significantly (up to 50%) the total mass of particles emitted from both vehicles.
- In most cases the emitted particle number concentrations (#/s) and mass/size distributions were not significantly affected by the fuel choice.
- More particles of smaller diameter where observed when using the "clean" fuel at medium speed (32-50 km/h) with the direct injection vehicle and at low speed (0-32 km/h) with the common rail vehicle.
- Most effects on the particles emitted were observed at constant high speeds (120 km/h), but none of these effects were observed in the results of the ECE15+EUDC test cycle due to the short high speed sequence.
- Impactors could serve as a quick and easy size resolving measuring method for particulate emissions.

In conclusion it can be said that the low sulphur and low aromatics fuel reduced significantly the particle total mass emissions without significantly changing the particle mass and number size distributions. Observed changes in particle distributions depend in a complex way on the combination of fuel injection technology, mode of operation, fuel specification and measuring method.

1. Introduction

As evidence grows on the potentially significant health effects of micro-particles emitted from combustion engines [1], [2], [3], [4] the research efforts of the scientific community are more and more focused on the effect of new and advanced fuel formulations and engine technologies on the emissions with emphasis placed on the particulate matter (PM).

Recently several studies [5], [6], [7], [8], [9], [10], [11], [12] coming mainly from the industrial sector, have been published, where the effect of various technological option and fuel quality were more or less studied. For example, in the CONCAWE study on PM emitted from diesel and gasoline cars [8], the low sulphur fuel emitted substantially less particulate mass than the other two normal diesel fuels, though in terms of the emitted particulate number, no significant differences were seen. Similarly, the ACEA study on the sulphur effect [6] and the "World-wide Fuel Charter" published in April 2000 [13] by a coalition of trade organisations, including ACEA, JAMA and EMA stress the need for sulphur-free fuels in order to meet the future vehicle emission standards and in order to introduce the use of NO_x storage catalysts and Continuously Regenerative Traps (CRT), which can function properly only when operated with sulphur-free fuel. Finally, one of the main conclusions of the US Diesel Emission Control – Sulfur Effects (DECSE) programme [11] is that fuel sulphur has significant effects on PM emissions, with the conversion efficiency of fuel sulphur to sulphate particulate reaching 50%. Other studies, estimate this conversion to close 100% depending in the efficiency of the catalyst [13]. As a comparison the engine SO_2 conversion rates, before passing through the after-treatment system, are merely 1-3%.

Furthermore, the European Commission has recently adopted a proposal to introduce sulphur-free diesel and gasoline fuels in all Member States from January 1, 2005. The use of zero sulphur (i.e. less than 10ppm) gasoline fuel will be mandatory effective 2011. A later review will establish the date in which the diesel sulphur-free fuel will become mandatory. Evidence in the present study supports the introduction of sulphur-free fuel since it may reduce the emission of PM by as much as 50%.

Only one major publication [5] studies the effect of advanced diesel engine technology, where the advanced Diesel vehicles (including those with common-rail injection systems) were shown to substantially reduce regulated particle mass emission and the number of particles when compared to conventional Diesel vehicles. Earlier studies [8] did not demonstrate big differences between Diesel vehicles with similar (older) technology.

As part of the research programme in the vehicle emissions in CORSE, a co-operation agreement on common research efforts has been signed between Agip Petroli spa (Milano, Italy) and the European Commission's Joint Research Centre (JRC, Ispra, Italy) in 1998. Within the co-operation several tests were foreseen to study vehicle emissions with the focus on the particulate matter. During a first series of tests, a comparative study of particulate emissions from a gasoline-driven vehicle with a normal multi-point injection and a gasoline direct injection vehicle has been carried out. Test results have been included in the EU Report No. 18993 on *Particulate Emissions from Gasoline and Diesel Vehicles (ERLIVE Project).* "Fuel effects" was also identified as one of the important topics of common interest and consequently studied in the second measuring campaign, reported herein.

In close co-operation with Agip Petroli several tests have been performed in April 2000 on a chassis dynamometer to detect the relationship between particulate emissions of diesel-driven vehicles and:

- the diesel injection system,
- the diesel fuel specification,
- the mode of operation
- the measurement method
- the location of sample extraction.

The parameters and topics of main interest studied in this measuring campaign were:

- total particulate emissions
- particle number/size distributions
- particle mass/size distributions
- relation between number and mass
- relation between ECE15+EUDC test cycle and constant speed results.

It should be noted that it was not intended to set up a comprehensive and complete test programme, nor to come to final conclusions for the questions under examination. The study will contribute with two specific vehicles and two specific fuels, tested under a limited number of driving conditions to the world-wide ongoing research on the influence of engines, test procedures and sampling methods on the emission pattern.

2. Fuel properties, vehicles and test condition

2.1 Fuel properties

Two different test fuels were used for the test sequences, one was a "standard" fuel (SF), the other one a "clean" low sulphur and low aromatics fuel (CF). In **Table 2.1** the specifications of both fuels are given, major differences as sulphur and aromatics content are highlighted.

Table 2.1: Specification of both test fuels used for emission measurements under ECE15+EUDC test conditions and at constant velocities.

		Fuel	*CF*	*SF*
		Fuel Name	Diesel 2000	SWCL1
		LIMS Ref.	T48408	T57215
PROPERTIES	*UNIT*	*METHOD*		
Sulphur content	ppm wt	ASTM D5453	199	< 1
Density at 15 °C		ASTM D4052	0.8392	0.8097
Kinematic Viscosity at 40 °C	cSt	ASTM D445	0.832	1.96
C.F.P.P.	°C	EN 116	-3	
Cloud Point	°C	ASTM D2500	0	-35
Flash Point	°C	ASTM D93	93	76
Cetane Index (4 Var.)		ASTM D4737	52.1	51.1
Cetane Number		ASTM D613	56.5	58
ASTM Distillation I.B.P.	°C	ASTM D86	220.0	197.1
ASTM Distillation 5% vol.	°C		246.0	210.4
ASTM Distillation 10% vol.	°C		254.0	212.3
ASTM Distillation 20% vol.	°C		264.0	215.5
ASTM Distillation 30% vol.	°C		272.0	219.2
ASTM Distillation 40% vol.	°C		281.0	223.1
ASTM Distillation 50% vol.	°C		291.0	227.6
ASTM Distillation 60% vol.	°C		302.0	232.8
ASTM Distillation 70% vol.	°C		314.0	239.6
ASTM Distillation 80% vol.	°C		329.0	249.0
ASTM Distillation 90% vol.	°C		349.0	263.6
T95	°C		359.0	276.1
ASTM Distillation F.B.P.	°C		378.0	291.6
ASTM Distillation recov. at 250 °C	% vol.		7.3	80.9
ASTM Distillation recov. at 350 °C	% vol.		90.6	
ASTM Distillation recov. at 370 °C	% vol.			
Monoaromatics	% wt	IP391	24.2	3.7
Diaromatics	% wt		3.9	0
Triaromatics	% wt		0.7	0
Polyaromatics	% wt		4.6	0
Total aromatics	% wt		28.8	3.7

2.2 Vehicles

The vehicles used for the tests were both new diesel vehicles with similar displacement of about 1.9 litre. One of the vehicles used a standard diesel direct injection pump (SI) while the second was equipped with a common rail system (CR). Both vehicles have been driven less than 5000 km. In the following **Table 2.2** the main specifications of both vehicles are summarised.

Table 2.2: Summary of the main specification of vehicles used for the tests. Fuel consumption: as given by the manufacturers.

	Vehicle	SI	CR
PROPERTIES	*UNIT*		
No. of cylinders		4	4
No. of valves per cylinder		4	4
Displacement	cm^3	1995	1910
Compression ratio	-	18.5:1	18.5:1
Max. power	kW at min^{-1}	60 at 4300	77 at 4000
Injection type		Direct injection pump Bosch VP44	Direct injection Common Rail
Mass	kg	1280	1270
Fuel consumption			
Urban	litre per 100 km	7.9	7.8
Extra-urban	litre per 100 km	4.9	4.7
Combined	litre per 100 km	6.0	5.8
Others			
Turbocharger		yes	yes
Intercooler		no	yes
EGR		yes	yes
Oxidation Catalyst		yes	yes

2.3 Test conditions

The vehicles were pre-conditioned over night, already fixed on the chassis dynamometer. The test sequence was started in the morning with the ECE15+EUDC test cycle. During the test cycle regulated pollutants HC, CO, NO_x, CO_2 and PM were measured. Dilution factors and diesel consumption were calculated according to Directive 93/116/EC. These data are given separately for the ECE15 and EUDC test part and as average over the total test cycle.

In parallel to the standard PM measurement on filter media, size segregated samples of particulate matter were taken with an 11-stage Berner Low Pressure Impactor (LPI-11) from the diluted exhaust gas. Particles are separated in an impactor according to their aerodynamic diameter (d.ae.). The LPI-11 covers with its 11 stages an aerodynamic diameter size range from 0.008 μm to 16 μm, mass/size distributions are determined by weighing the particulate mass deposited on the impactor stages covered with Al-substrates. In order to collect enough mass on each impactor stage the measurements had to be integrated over the whole test cycle. The sampling port was located at the end of the dilution tunnel near the probe used for the filter samples. No impactor samples were taken from the undiluted exhaust gas, the high mass load and the length of the test sequence would have led to an overloading of the LPI.

A third sampling port next to the other two PM measuring probes was used for extraction of a small gas flow for the particle number or number/size distribution measurements with a TSI Scanning Mobility Particle Sizer (SMPS). Scanning time of an SMPS is too long to allow for a size resolved measurement during the dynamic test cycle. The SMPS was set to a fixed particle size of 100 nm, measuring continuously the change of concentration given as particle number per cm^3 at this particle mobility diameter.

Following the ECE15+EUDC test cycle, particle number, mass and size measurements at constant velocities of 0 km/h (idle), 32 km/h, 50 km/h and 120 km/h were performed. As before, the dilution ratio was determined but no regulated gaseous pollutants were measured. In addition to the LPI measurement in the diluted gas, a second 8 stages impactor (LPI-8) was installed next to the exhaust pipe exit to measure the mass/size distribution in the undiluted raw gas. The impactor covers in 8 size bins an aerodynamic diameter range from 0.082 μm to 16 μm, and was equipped with an additional back-up filter to collect particles with d.ae. < 0.082 μm and make results comparable with the LPI-11 measurements. The SMPS was used in the scanning mode during constant velocity tests, giving number/size distributions in the mobility diameter range from 15.68 nm to 685.4 nm. In chapter 4.2 further details are given on SMPS settings, number of measurements and measurement time.

Due to a malfunction of the SMPS, the number concentration measurements with the CR vehicle had to be discarded. Number/size distribution measurements for constant velocity tests with the CR vehicle have been repeated later without a repetition of the mass/size distribution measurements. All mass data given in the report are from the original test phase, while the number/size distributions from CR vehicle emissions are those from the second series. In cases where mass and number data from the CR vehicle emissions are compared, it is assumed that emissions measured under well defined boundary conditions did not change significantly.

3. ECE15+EUDC test cycle results

In the following paragraphs the results of the dynamic ECE15+EUDC test cycle are presented. These tests have been performed on a single roller chassis dynamometer. Beside the regulated pollutants HC, NO_x, CO, PM the mass/size distribution was measured with the LPI-11 in the diluted gas. Due to the length of the test cycle, an integrating LPI measurement of the mass/size distribution in the undiluted exhaust was not possible since the impactor would have been overloaded.

3.1 Regulated emissions under ECE15+EUDC test conditions

Regarding the regulated emissions it was found that independent of the fuel type the HC, CO, CO_2 and NO_x emissions were always significantly higher for the CR vehicle. Only PM emissions and fuel consumption - the latter one mainly during the EUCD test cycle sequence - were lower than those values found for the SI vehicle. A fuel effect on emissions, in terms of percent reduction compared to emission values with the SF was observed for both vehicles, but changes were higher for the (always higher emitting) CR vehicle.

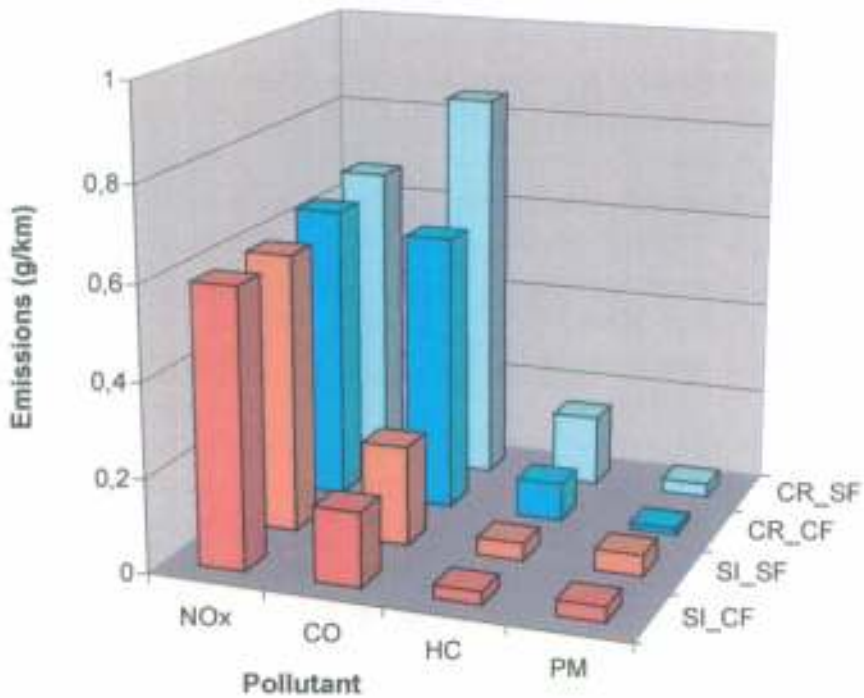

Fig. 3.1. Influence of fuels on regulated emissions averaged over the ECE15+EUDC test cycle. SI: vehicle with standard injection; CR: vehicle with common rail technology; SF: standard fuel; CF: clean fuel.

While NO_x and CO_2 remained nearly unchanged, the other regulated emissions were reduced by 50% (PM), 47% (HC) and 30% (CO) for the CR vehicle and by 29% (PM), 27% (HC) and 25% (CO) for the SI vehicle when both were using the low sulphur, low aromatic containing clean fuel (CF). In addition an increase in fuel consumption by about 4.5% was observed for the CR vehicle during the EUDC sequence when it was operated with the CF.

The main results for the regulated compounds are shown in **Fig. 3.1**, data are given as average values from two tests for the whole ECE15+EUDC test cycle. The complete data set, including the fuel consumption and the split between ECE15 and EUDC, is listed in the following **Table 3.1**.

Table 3.1: Full data set of the ECE15+EUDC test cycle results for regulated pollutants, impactor measurements and fuel consumption.
SI: diesel driven vehicle with standard direct injection system;
CR: diesel driven vehicle with common rail technology;
SF: standard fuel; CF: "clean" low sulphur and aromatics fuel;
LPI-11: mass concentration measured with the 11 stages low pressure impactor.

	Vehicle	SI				CR			
	Fuel	SF		CF		SF		CF	
HC (g/km)	total	0.037	0.037	0.026	0.028	0.126	0.177	0.090	0.073
	ECE15	0.087	0.085	0.059	0.065	0.242	0.295	0.144	0.118
	EUCD	0.009	0.009	0.008	0.007	0.060	0.110	0.059	0.047
CO (g/km)	total	0.216	0.208	0.153	0.164	0.852	0.841	0.613	0.576
	ECE15	0.582	0.560	0.416	0.444	2.012	1.934	1.482	1.417
	EUCD	0.005	0.006	0.003	0.003	0.188	0.218	0.114	0.095
CO_2 (g/km)	total	170	166	162	162	154	157	153	157
	ECE15	222	215	209	210	209	215	207	212
	EUCD	141	138	134	135	122	124	123	126
NO_x (g/km)	total	0.587	0.605	0.612	0.576	0.633	0.698	0.639	0.631
	ECE15	0.683	0.702	0.755	0.711	0.805	0.911	0.842	0.806
	EUCD	0.531	0.550	0.530	0.500	0.534	0.577	0.523	0.531
HC+NO_x (g/km)	total	0.624	0.642	0.638	0.604	0.759	0.875	0.729	0.704
	ECE15	0.770	0.787	0.814	0.776	1.047	1.206	0.986	0.924
	EUDC	0.540	0.559	0.538	0.507	0.594	0.687	0.582	0.578
PM (g/km)	Filter	0.046	0.044	0.032	0.032	0.022	0.034	0.014	0.014
	LPI-11	0.044	0.041	0.028	0.027	0.019	0.023	0.014	0.019
Fuel (litre/100 km)	total	6.4	6.3	6.3	6.3	5.8	6.0	6.0	6.2
	ECE15	8.4	8.1	8.2	8.2	8.0	8.2	8.2	8.3
	EUCD	5.3	5.2	5.2	5.3	4.6	4.7	4.8	4.9

Table 3.2 gives an overview of the vehicle emission levels reached in accordance with the EURO I-IV levels. It can be seen that the CR-CF combination fulfils already the PM emissions requirements of EURO IV, while the SI vehicle CO emissions are already below the future EURO IV levels coming in 2005. Although significant reductions in emission levels of most regulated pollutants were observed when using the low sulphur/aromatics fuel (CF), there is only one remarkable change, from EURO II to EURO III level, for the CO emissions of the CR vehicle.

Tab. 3.2: EURO I-IV levels reached with the different fuel and fuel injection systems.

	SI		CR	
Pollutant	SF	CF	SF	CF
CO	EURO IV	EURO IV	EURO II	EURO III
NO_x	(EURO II)	(EURO II)	(EURO II)	(EURO II)
HC+NO_x	EURO II	EURO II	EURO II	EURO II
PM	EURO III	EURO III	EURO IV	EURO IV

3.2 Particle emissions under ECE15+EUDC test conditions

Particle emissions were measured in the diluted exhaust gas with filters, giving the total particulate mass concentration (PM) and in parallel with the LPI-11, giving the mass/size distribution (or the mass concentration in discrete size ranges) over the entire test cycle. Results can be expressed as mass concentration in the exhaust gas (g/m³), as mass emitted per time (g/s) or - as usual - as mass emitted per driven distance (g/km). The latter one can not be applied to idling conditions, in that case one has to compare the exhaust gas concentrations or the emissions per time.

Total mass concentration measured in parallel with filters and impactors are in fairly good agreement (**Fig 3.2**). In most cases the impactor data are slightly lower than those of the filter measurements. This could be due to losses of volatile compounds on the lower stages of the impactor, where most of the mass is collected and where the stage pressure goes down to $p < 10$ kPa. The CR vehicle emitted always less PM than the SI vehicle and for both vehicles a significant reduction of the PM emission was observed when the low sulphur, low aromatics fuel (CF) was used.

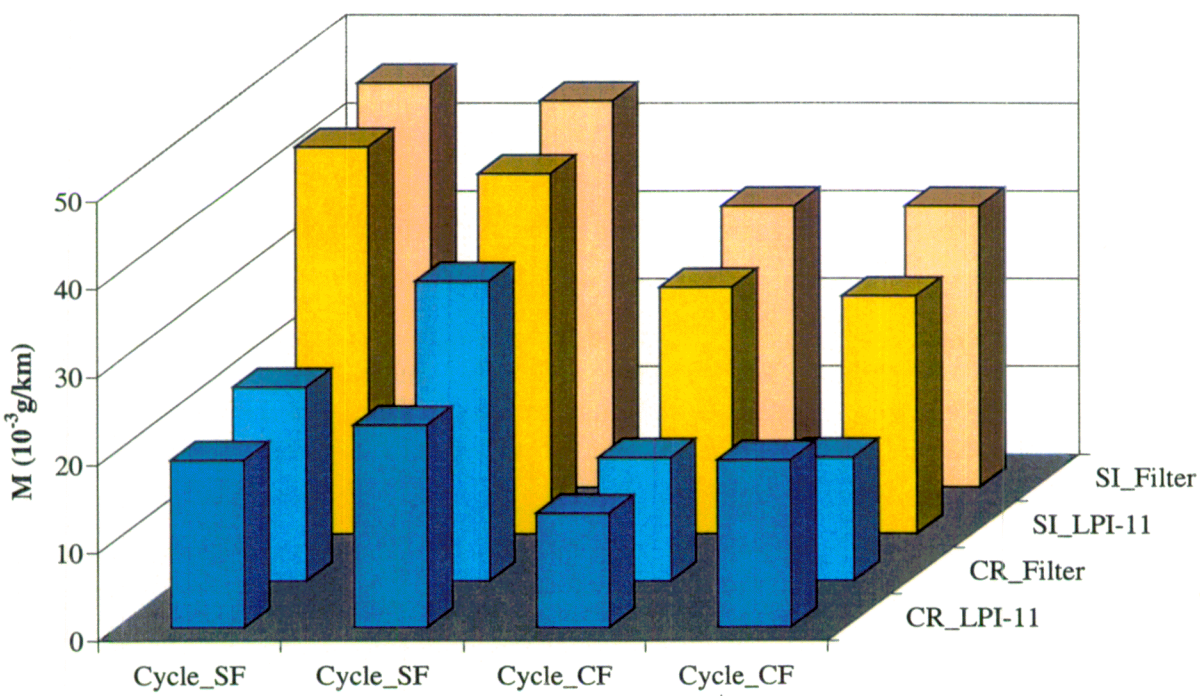

Fig. 3.2. Total mass concentration M measured over the whole ECE15+EUDC test cycle in parallel with filters and 11-stages low pressure impactor (LPI-11). The data show also – independent of the measuring system - some variability for the CR repetition measurements carried out the following day with the same fuel/injection system combination.

The mass/size distributions, integrated over the whole test cycle, are shown in **Fig. 3.3**. Data are plotted here as emissions per driven distance, given in mg/km, but are in addition normalised with the logarithmic width of the size bin dLn(d.ae.). This makes the area under the curves to a measure of the total emitted mass per kilometre and allows comparison of mass/size distributions obtained with different size bin widths. For a better view of details in the fine particle range, data of the last impactor stage (8-16 μm) are not shown.

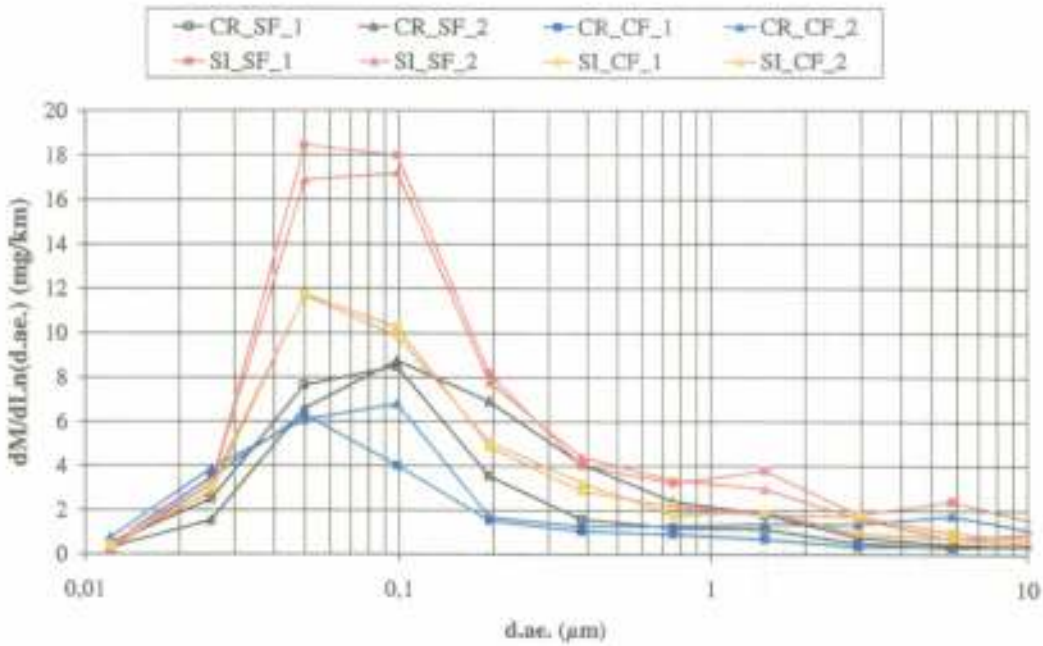

Fig. 3.3. Mass/size distributions measured under ECE15+EUDC test conditions.

The graph reveals clearly that in all cases the main mass is located in the sub-micron size range between 0.02 μm and 0.4 μm. There is no clear indication that the fuel or the fuel injection technology has a significant influence on the mass/size distributions. This is obvious for the SI vehicle but has to be proved for the CR vehicle (see Fig. 3.4) where data scatter too much to allow for a final conclusion.

In Chapter 4 it will be shown that there is a strong and significant shift in the mass/size distribution for the CR vehicle, specially when running at high speed. This disappears in test cycle measurements, probably because of the short duration of the high-speed test sequence.

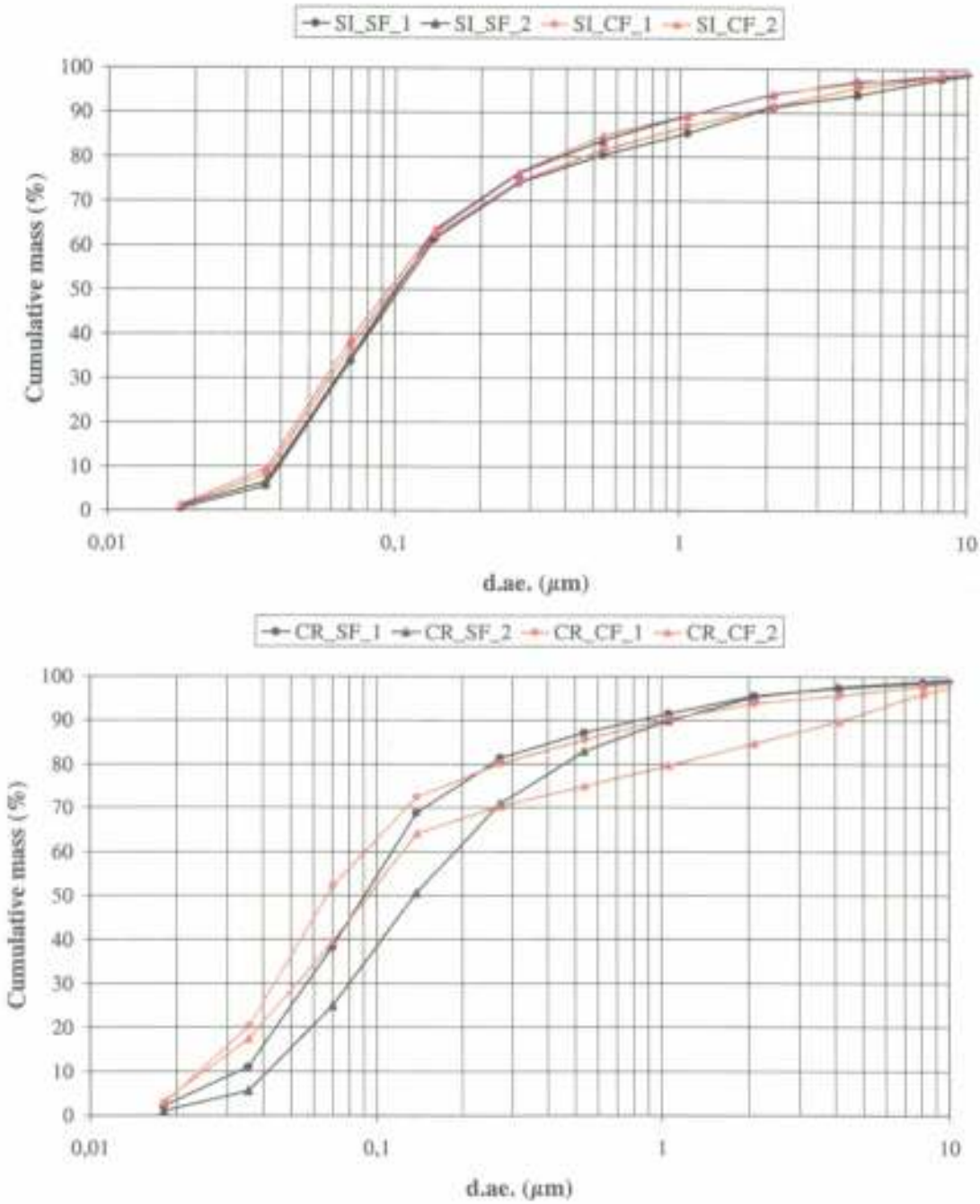

Fig. 3.4. Cumulative mass/size distributions of particulate emissions from both vehicles, obtained from the mass/size distributions shown in **Fig. 3.3**;
top: SI vehicle; bottom: CR vehicle.

4. Results from constant velocity tests

In this paragraph the results of the tests carried out at constant speed levels are presented. The main goals of the constant velocity tests were:

- detection of the influence of advanced diesel fuels on particle emissions for different injection technologies
- comparison of mass/size distributions measured at constant velocities in the raw gas and after dilution in the CVS system
- comparison of inertia based results giving particle mass over aerodynamic diameter with diffusion related results giving particle number over mobility diameter
- comparison of static results with test cycle results, influence of high speed test section on the overall result

4.1 Test description

Immediately after the ECE15+EUDC measurements the testing program was continued with constant velocity tests. This was a series of dynamometer tests where the vehicle's speed was kept constant at 0 km/h (idle), 32 km/h, 50 km/h and finally 120 km/h. After all measurements performed at a certain speed the vehicle was stopped and switched off. Measurements of the following test sequence at a higher speed were started after reaching stable engine conditions.

The three parameters that were changed during the test phase were:

vehicle	vehicle 1: „standard" pressure injection system (SI) vehicle 2: common rail „high" pressure injection (CR)
speed	idle, 32 km/h *, 50 km/h, 120 km/h**,
fuel	fuel 1: „standard" fuel (SF) fuel 2: low sulphur and low aromatic "clean" fuel (CF)

The measured quantities were:

particulate mass	particle emissions per time or driven distance, given in mg/s or g/km, as measured at the exhaust pipe exit and at the end of the dilution tunnel
particle number	particle emissions per time or driven distance, given in #/s or #/km, as measured at the end of the dilution tunnel
size distribution	mass/size dM/dLog(d.ae.) and number/size dN/dLog(d) distributions, giving the mass concentration M versus the aerodynamic diameter d.ae. and the number concentration N versus the mobility diameter d

It should be noted that due to a malfunction of the instrument, the SMPS measurements with the common rail vehicle have been repeated a week after the campaign. Mass concentration data reported herein are those of the first measurements, number concentrations those of the second series.

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* low speed means high emission rate for volatile compounds and high dilution
** high speed means low emission rate for volatile compounds and low dilution

4.2 Instrumentation and sampling

Size resolved particle samples were taken during the tests in parallel with:

- a TSI Scanning Mobility Particle Sizer (SMPS) for number/size distribution measurements in the diluted exhaust gas. The probe was located at the end of the dynamometer's dilution tunnel, measurements were performed without further dilution between probe and SMPS. The instrument was set to a sheath and aerosol flow of 3 and 0.3 l/min, giving a particle diameter range of 15.68 nm to 685.39 nm. SMPS scan times were set to 90 s up-scanning and 40 s down-scanning, samples were taken without time delay between scans. During tests at 0, 32 and 50 km/h seven scans (with 910 s for total measurement) were taken, and 3 scans (with 390 s for total measurement) at 120 km/h. The total measurement time had to be reduced for the high speed tests to avoid heat-up problems in the dilution tunnel.

- an 11-stages Berner Low Pressure Impactor (LPI-11) for mass/size distribution measurements in the diluted exhaust gas. LPI-11 impactor stage cut-offs range from 0.008 μm to 16 μm aerodynamic diameter, the probe was located next to the SMPS probe at the end of the dynamometer's dilution tunnel. The impactor was not heated, only for some of the measurements at 120 km/h humidity deposition was observed. Diluted size segregated samples were taken over sampling times of 990 s at 0 km/h, 870 s at 32 and 50 km/h, and 390 s at 120 km/h.

- an 8-stages Berner Low Pressure Impactor (LPI-8) for mass/size distribution measurements in the undiluted exhaust gas. LPI-8 impactor stage cut-offs range from 0.082 μm to 16 μm aerodynamic diameter, particles smaller than the indicated lowest cut-point were collected on a quartz fibre back-up filter. The probe was located directly at the exhaust pipe exit and is usually used as extraction port for gas phase analysis. In this position no strict isokinetic sampling was possible. To avoid condensation on the impactor stages, the LPI-8 was heated up to 80 °C prior to sampling. No humidity deposition on the impactor stages was observed. Raw gas samples were taken over a sampling period of 240 s at 0, 32 and 50 km/h, and 180 s at 120 km/h. Although impactor stages were not overloaded, some (not quantified) particle loss below the impactor's jet-plates was observed. From earlier investigations it is known that these losses from the main loaded impactor stage can account for up to 20% of the total mass collected on this stage.

In order to make the different data comparable, the measured mass and particle number concentrations were corrected for dilution. These values were then converted to emission quantities per time and per driven distance. For a better visibility of changes in mass/size and number/size distributions some data are shown as (normalised) cumulative distributions.

Impactor samples were taken on pre-conditioned and weighed Al-substrates. After the tests the substrates were again conditioned for more than 24 hours before weighing on a micro-balance (1 μg resolution). The repeatability and the measuring error of the balance is better than ±5 μg for the Al-substrates.

In the next paragraphs the main results of the constant speed measurements are given. In general it can be said that the data showed strong fluctuations, especially those from SMPS measurements at high speed (120 km/h), but trends could still be elaborated.

4.3 Results of mass and number concentration measurements

Mass and number concentrations given in this section have been calculated from the size distribution measurements carried out with the low pressure impactors and the SMPS. In **Table 4.1** the main test parameters fuel, speed, raw gas flow rate and dilution factor are listed. Exhaust gas flow rates differ between the two vehicles at maximum by less than 20% for tests at 50 km/h, dilution ratios are highest for idling engines where lowest emissions are expected and lowest for high speed tests at 120 km/h where the highest emissions are expected.

Table 4.1: Average dilution factors and raw gas flows for constant velocity tests.

speed	av. dilution ratio		av. raw gas flow (l/s)	
(km/h)	SI-vehicle	CR-vehicle	SI-vehicle	CR-vehicle
0	8.4	7.2	10.2	11.9
32	4.5	4.1	19.0	21.3
50	4.5	5.7	18.8	15.6
120	2.3	2.0	36.7	41.7

An overview of all measured mass and number concentrations is given in **Table 4.2**. It can be seen that both vehicles emitted a higher total mass per second with increasing speed, while the number of particles emitted per second (#/s) and the particle mass per kilometre (g/km) showed a minimum at 50 km/h. The values from LPI-11 measurements at 120 km/h, shown as example in **Fig. 4.1**, were highest in all cases and much higher for the SI-vehicle than for the CR-vehicle. Graphs of the other total mass and total number concentration data, as listed in **Table 4.2** are included in the annex.

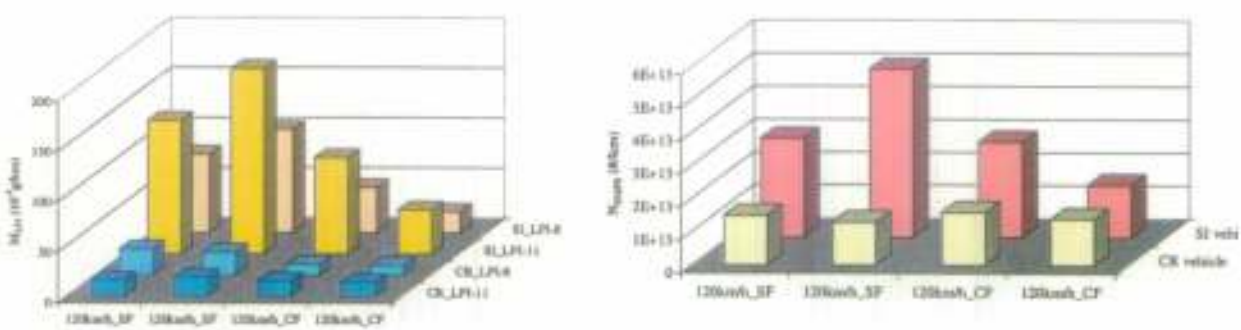

Fig. 4.1. Comparison of particulate mass emissions M_{LPI} and number emissions N_{SMPS} per driven kilometre from a vehicle with standard direct injection (SI) and an advanced common rail system (CR) running with a standard fuel (SF) and a „clean" low sulphur/aromatics fuel (CF) at a constant speed of 120 km/h. Mass measurements were taken undiluted at the exhaust pipe (LPI-8) and at the dilution tunnel (LPI-11), the latter one in parallel to the number concentration measurements (SMPS).

The investigated idling vehicles emitted less mass but a higher number of particles per second than under driving conditions at 32 km/h and 50 km/h. Getting a higher mass concentration

with a lower particle number concentration is possible when the average particle size increases. It will be shown later, that the determined mass and count median diameter of these measurements show a behaviour opposite to the expectations. These observations were independent of vehicle and fuel type, and should be proved with further repetition of these measurements in order to reduce the strong variability of the SMPS data.

Table 4.2: Mass and number concentrations measured in the exhaust gas with the LPI-8 and in the diluted gas with the LPI-11. For comparison, data of the ECE15+EUDC („cycle") measurements are also shown. Note: SMPS data of the CR-vehicle have been measured in separate tests. (*): no reliable data.

SI-vehicle test													
speed (km/h)	fuel	LPI-11 mg/s		LPI-8 mg/s		SMPS 10^{11} #/s		LPI-11 10^{-3} g/km		LPI-8 10^{-3} g/km		SMPS 10^{13} #/km	
0	SF	0.09	0.08	0.06	0.06	3.4	5.0						
0	CF	0.07	(*)	0.04	0.06	4.0	2.5						
32	SF	0.15	0.15	0.15	0.13	2.2	3.1	17	17	17	15	2.4	3.5
32	CF	0.09	0.10	0.08	0.08	2.0	1.7	10	11	9	9	2.3	1.9
50	SF	0.17	0.17	0.16	0.14	2.2	3.1	12	12	11	10	1.6	2.3
50	CF	0.12	0.11	0.10	0.10	2.5	1.9	9	8	7	7	1.8	1.3
120	SF	4.43	6.15	2.62	3.45	9.9	17.0	133	185	78	103	3.0	5.1
120	CF	3.19	1.46	1.51	0.70	9.5	5.2	96	44	45	21	2.9	1.6
cycle	SF	0.41	0.38					44	41				
cycle	CF	0.26	0.25					28	27				
CR-vehicle test													
speed (km/h)	fuel	LPI-11 mg/s		LPI-8 mg/s		SMPS 10^{11} #/s		LPI-11 10^{-3} g/km		LPI-8 10^{-3} g/km		SMPS 10^{13} #/km	
0	SF	0.08	0.07	0.08	0.08	4.7	4.9						
0	CF	0.04	0.04	0.04	0.04	3.9	3.5						
32	SF	0.17	0.17	0.20	0.18	3.5	2.7	20	20	23	20	3.9	3.0
32	CF	0.16	0.16	0.16	0.15	3.8	3.3	18	18	18	17	4.3	3.7
50	SF	0.22	0.22	0.16	0.14	3.2	2.4	16	16	11	10	2.3	1.8
50	CF	0.20	0.19	0.11	0.13	3.6	3.2	14	14	8	10	2.6	2.3
120	SF	0.57	0.66	0.86	0.76	4.9	4.2	17	20	26	23	1.5	1.3
120	CF	0.54	0.49	0.37	0.35	5.3	4.7	16	15	11	10	1.6	1.4
cycle	SF	0.18	0.22					19	23				
cycle	CF	0.13	0.17					13	19				

Particle mass emissions per driven kilometre were in the range of 0.012 to 0.185 g/km and 0.008 to 0.096 g/km for the SI-vehicle running with the standard fuel (SF) and with the low sulphur/aromatics fuel (CF) respectively. The range for the CR-vehicle was much narrower, with 0.016 to 0.020 g/km for the SF and 0.014 to 0.018 g/km for the CF. Emissions varied not more than about 25% for the CR-vehicle at different speed levels. In contrary, the emissions of the SI-vehicle at 120 km/h were up to 10 times higher compared to those measured at lower speed levels. The test cycle results show that the SI-vehicle emissions are in the range of the measurements at constant speed, while the CR-vehicle test cycle results are slightly lower than those gained from constant speed measurements. This could indicate the importance of transient phases on the emissions of such a vehicle, and should be elaborated in further detail.

Regarding the total mass, the emissions of both vehicles were always lower when the CF was used. The differences between the two fuels were more pronounced for the SI-vehicle, which at all speed levels showed a significant reduction of emitted mass. Calculated from averaged data a maximum reduction of 57% was reached with the SI-vehicle using the CF at 120 km/h and measured at the dilution tunnel. For both vehicles the total mass emission reduction effect is highest for the 120 km/h measurements carried out directly at the exhaust pipe.

For these mass measurements an effect of the sampling position is obvious: for both vehicles the ratio of total mass collected with the LPI-8 to the mass collected with the LPI-11 is increasing when the low sulphur/aromatics fuel (CF) is used. In case of the SI-vehicle the ratio increases from 1.7 to 2.1 and from 0.8 to 1.4 for the CR-vehicle. At all other velocities no significant change of the mass ratio (LPI-8 : LPI-11) with the fuel in use was observed.

The other mass ratios were almost 1 (or: mass{LPI-11} = mass{LPI-8}), except for the CR-vehicle at 50 km/h where values around 1.5 were found (see **Fig. 4.2**). These differences can not be explained with collection efficiency at the non-isokinetic probe for the raw gas sampling, because raw gas flow, thus flow velocity at the extraction point, and mass concentration in the raw gas were similar for the CR-vehicle tests at 32 km/h and 50 km/h and comparable to those of the SI-vehicle. In addition, one would expect that the collection efficiency at relative constant flow rates changes only when the particle size distribution changes. This is the case for the measurements in the diluted exhaust gas of the CR-vehicle at 120 km/h, where a reduction of the MMD was observed, but not for the similar SI-vehicle measurements.

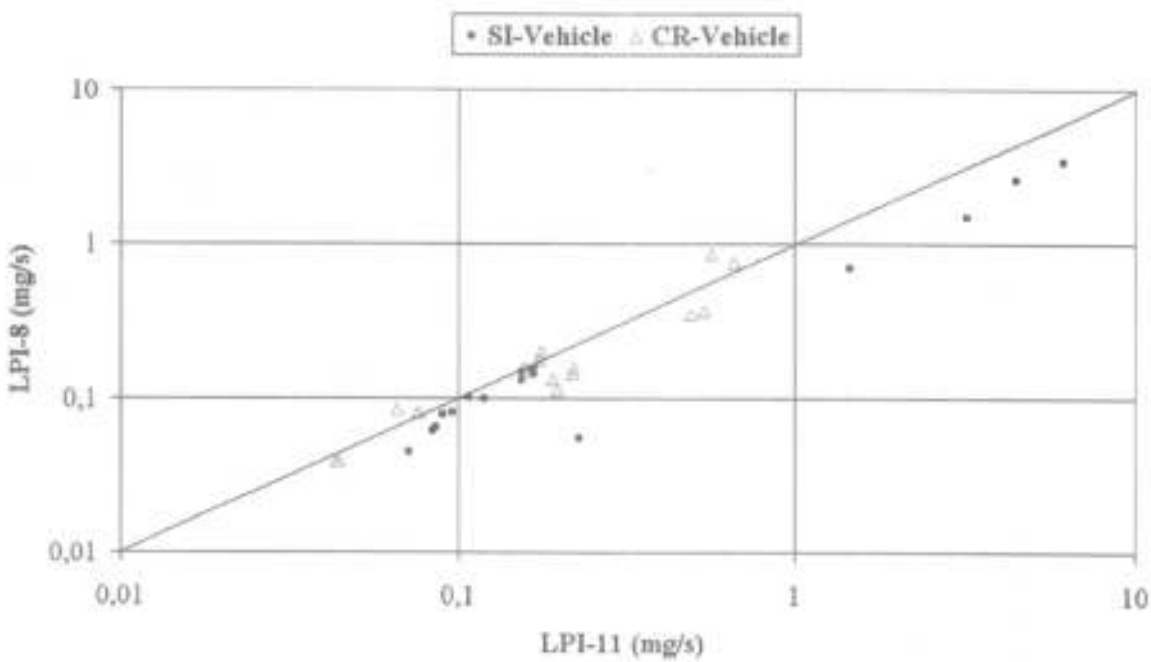

Fig. 4.2. Comparison of results from LPI-11 measurements at the CVS dilution tunnel with undiluted LPI-8 measurements at the exhaust pipe exit, showing the difference in total mass concentration at high concentrations.

Particle number concentrations showed strong fluctuations at 120 km/h and strong changes when repeating a test sequence the day after. For this reason the conclusions drawn here are preliminary and have to be proved with additional tests.

Measurements from other groups [5] revealed that advanced diesel vehicles, like the CR-vehicle used in these tests, emit less particles in terms of mass and number when operated with the clean fuel similar to the CF. From the averaged data it can be seen that the CF increased the number of particles emitted per kilometre by the CR-vehicle, while the average number concentration emitted per kilometre by the SI-vehicle was lower with the CF. In consequence the comparison of total particle number to total mass yields no obvious general correlation between these two quantities (**Fig. 4.3**) as shown by other authors.

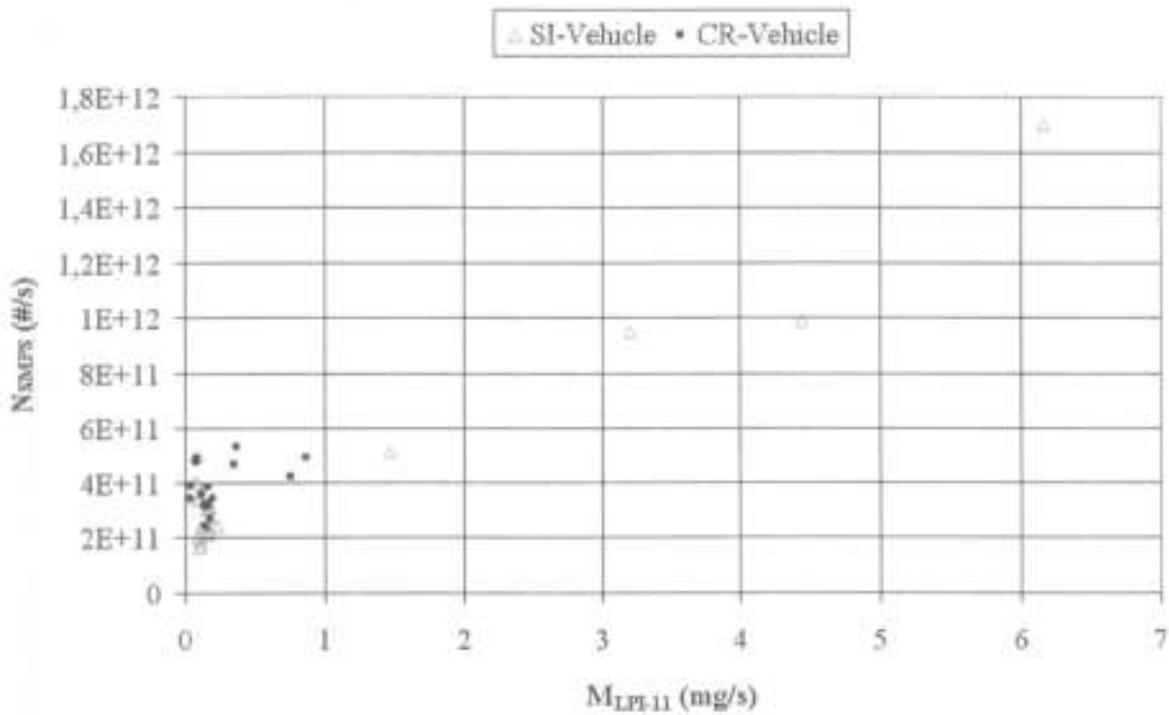

Fig. 4.3. Particle number emissions N_{SMPS} from SMPS measurements vs. total mass emissions M_{LPI-11} from LPI-11 measurements at constant speed tests.

4.4 Mass/size and number/size distributions

Size distributions indicate whether changes in the particle size occur (or not) after changing test parameters. Mass/size data from the impactors are distributed over a limited number of size bins. Here the aerodynamic mass median diameter (MMD) was determined graphically from the cumulative size distributions for all measurements with the LPI-11 and also for the 120 km/h measurement with the LPI-8 (see **Table 4.3**). In most other cases the lowest LPI-8 cut-off was bigger than the no longer detectable MMD, in other words: more than 50% of the total mass collected with the LPI-8 was found on the back-up filter.

Table 4.3: Aerodynamic mass median diameter (MMD) of the mass/size distributions obtained with the LPI-11. Data for LPI-8 measurements of undiluted exhaust gas at 120 km/h are included in brackets.

speed	**SI-vehicle tests, MMD (nm)**				**CR-vehicle tests, MMD (nm)**			
(km/h)	fuel: SF		fuel: CF		fuel: SF		fuel: CF	
0	85	80	95	80	75	65	80	65
32	40	40	35	35	55	55	45	45
50	40	40	35	35	57	60	50	50
120	430 (145)	390 (165)	400 (150)	400 (115)	225 (80)	200 (85)	125 (90)	100 (80)
cycle	105	100	100	95	90	110	65	95

Nevertheless, a simple method was chosen to make LPI-8 and LPI-11 data comparable. Instead of calculating a diameter related to a certain percentage of mass, the mass percentage below a certain diameter was determined. The first 8 impactor stages of the LPI-11 and LPI-8 cover about the same size range, so the mass collected on the lowest 3 stages of the LPI-11 and on the LPI-8 back-up filter give comparable results, shown in **Table 4.4**.

Table 4.4: Percentage of mass collected on the lowest 3 impactor stages of the LPI-11 (d.ae. < 70 nm) and on the back-up filter of the LPI-8 (d.ae. < 82 nm). A high percentage indicates a high amount of mass in the nucleation mode. (*): no reliable data.

speed	**SI-vehicle tests, fine mass fraction (%)**							
	fuel: SF				fuel: CF			
(km/h)	LPI-11		LPI-8		LPI-11		LPI-8	
0	41	43	32	33	45	(*)	23	45
32	74	73	74	70	70	69	65	65
50	76	77	73	75	73	73	67	70
120	9	4	12	6	6	8	12	18
cycle	34	35			37	39		

speed	**CR-vehicle tests, fine mass fraction (%)**							
	fuel: SF				fuel: CF			
(km/h)	LPI-11		LPI-8		LPI-11		LPI-8	
0	47	52	38	51	47	55	53	49
32	63	63	49	58	70	70	68	70
50	61	59	50	60	65	69	64	63
120	16	14	50	47	29	34	42	49
cycle	39	25			52	40		

Other authors [15], [16] reported that emissions of volatiles, material condensed on the particles, decrease when engine load is increasing, while PAH coverage of particles increase with load. They found that at high engine load the emitted particles consist mainly of „black carbon" with only low quantities of volatile compounds. This should in theory lead to a lower fuel effect at high load when comparing fuels with high and low sulphur/aromatics content. Although the authors worked with small power diesel engine (some kW), it can be expected that the reduction or full elimination of sulphur and aromatics in fuels would lead to a general reduction in mass emission at low load levels and also to a reduction of the average particle size due to the lack/reduction of condensing volatile compounds (i.e. PAH) on the carbonaceous particle core.

As general outcome of the impactor measurements it can be said that for both vehicles with both fuels the main mass (usually more than 90%) is emitted in the aerodynamic diameter range below d.ae. = 1 µm. Mass/size distributions were typically uni-modal with the main mass peak in the nucleation mode at d.ae. < 0.1 µm, shifting towards the accumulation mode with 0.1 µm < d.ae. < 1 µm when the vehicles were operated at 120 km/h. Examples for 32 and 120 km/h are shown in the following **Fig. 4.4**, the full data set is given in the annex.

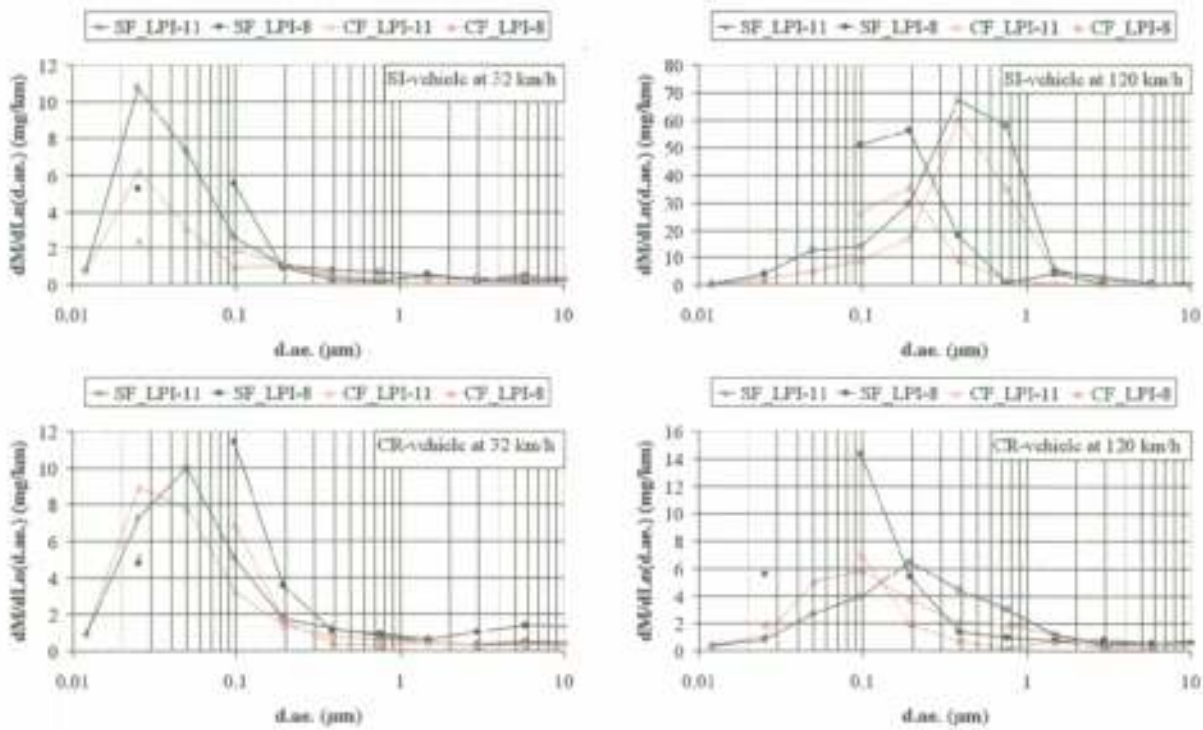

Fig. 4.4. Typical examples of mass/size distributions from SI- and CR-vehicle running at 32 and 120 km/h with the „standard" (SF) and „clean" (CR) fuels. Measurements of particulate matter from the diluted exhaust gas (LPI-11) and from the undiluted exhaust gas (LPI-8) are shown. Note that data for the back-up filter of LPI-8, located at 0.025 µm, have to be compared with the arithmetic average of the three last stages from LPI-11.

Other than expected the MMD is highest for particle emissions at 120 km/h and lowest for 32 and 50 km/h, where no significant difference between results from the two speed levels was observed (**Fig. 4.5**). The MMD for the more advanced CR-vehicle were significantly smaller at 120 km/h and also as average over the test cycle, compared to the SI-vehicle. For the CR-vehicle the MMD decreased when the „clean" (CF) was used. For the SI-vehicle the average MMD is lower for the CF, but there was always an overlap in the data from SF and CF measurements.

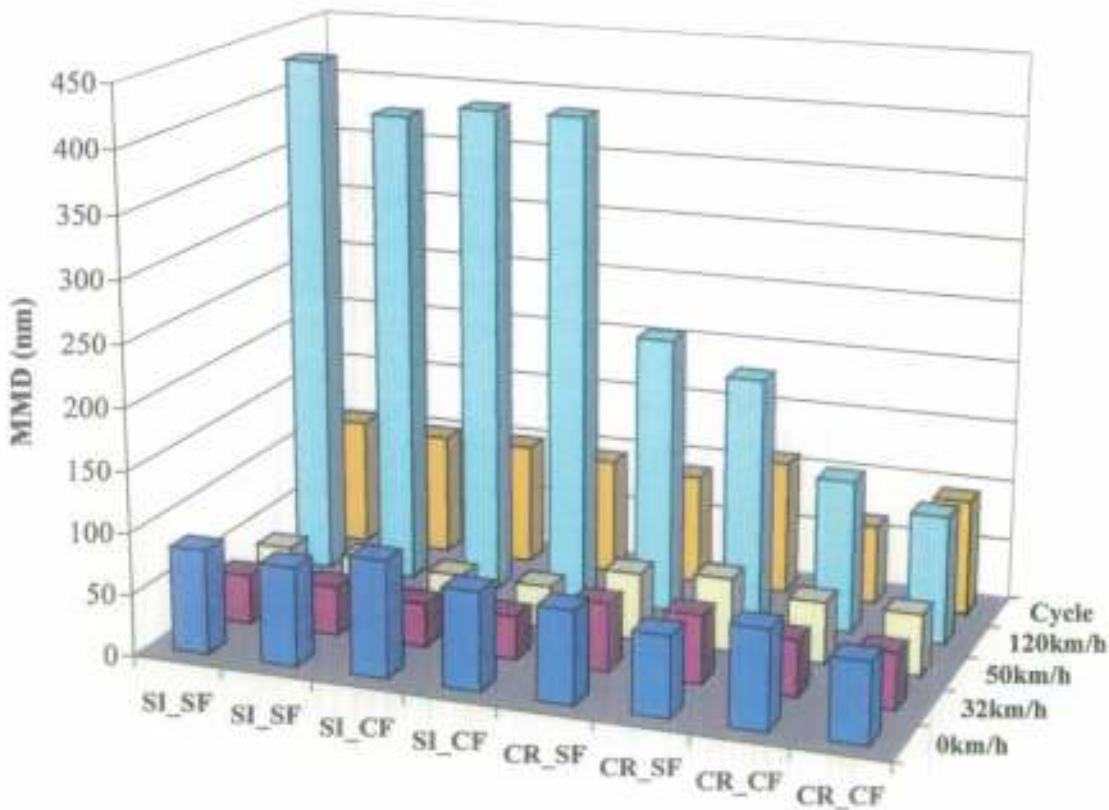

Fig. 4.5. Mass median diameters (MMD) obtained from the LPI mass/size distributions. For data see **Table 4.3**.

The MMD results are underlined by the analysis of the percentage of the mass at the lowest 3 impactor stages of the LPI-11, but also from the mass collected on the back-up filter of the LPI-8 (**Table 4.4**). All three data set show similar trends, with the main difference at speed 120 km/h, where independent of vehicle and fuel a larger fine mass fraction is collected at the sampling position for the undiluted gas at the end of the exhaust pipe.

From high resolution SMPS data the cumulative number/size distributions averaged over all scans were calculated for each speed and fuel combination. From this, the count median diameter (CMD) and the geometric standard deviation σ_g as measure for the width of the distribution were determined. Finally, assuming that particles are logarithmic normal distributed, the related mass median diameter (MMD) is calculated with the Hatch-Choate-Equation

$$MMD = CMD * \exp\{3*(Ln\ \sigma_g)^2\}.$$

The results from the number/size distribution analysis are summarised in **Table 4.5**.

Table 4.5: Count median diameter (CMD) and geometric standard deviation (σ_g) as determined from the averaged SMPS data, and mass median diameter MMD as calculated with the Hatch-Choate-Equation.

	SI-vehicle tests						**CR-vehicle tests**					
	fuel: SF			fuel: CF			fuel: SF			fuel: CF		
speed (km/h)	CMD (nm)	σ_g	MMD (nm)	CMD (nm)	σ_g	MMD (nm)	CMD (nm)	σ_g	MMD (nm)	CMD (nm)	σ_g	MMD (nm)
0	106	2.04	491	106	1.90	364	94	1.96	363	84	1.81	240
32	93	1.75	240	77	1.76	200	97	1.81	280	88	1.75	225
50	99	1.76	258	86	1.71	203	100	1.77	268	95	1.71	226
120	108	1.64	226	104	1.60	200	88	1.73	215	86	1.71	203

4.5 Effect of observed size distribution changes on airway deposition

Since a couple of years the chronic and acute health effects of diesel vehicle particles emissions is under discussion, including also the costs for the health system. In a recent economic study carried out for Switzerland, France and Austria [4] the authors found that health costs related to road traffic emissions in these three countries were at a level of 30 billion €. And there is still a lot of ongoing research in the field of particulate diesel vehicle emissions and their effects on human health. Several aspects are not clearly understood, as for example the effects of particle size and place of deposition, the contributions of the elemental carbon core and the particle surface coating with PAH and other volatile compounds.

One of the problems to face is the fact that particulate emissions from diesel-driven vehicles can be characterised quite easily at their point of exit (tail-pipe emissions), but this is not the realistic description of what humans inhale at home, at their working place or in the streets. Immediately after leaving the tail-pipe the particles undergo strong changes due to the mixing with ambient air resulting in dilution by factors of several hundreds to thousands within a few seconds after their emission, the adhesion to particles from other sources and the condensation of not traffic related gaseous compounds. Only in a few cases, where people work in near traffic areas or places with high traffic frequency (road tunnel, car park, bus depot) the conditions reached with dynamometer measurements can be regarded as „representative" or better as „typical". In the following paragraphs, considering the before mentioned restrictions, the dynamometer measurements will be taken to elaborate the effect of some of the observed changes in size distribution on the airway deposition.

The study of size distribution effects on airway deposition is carried out using known and accepted models and equations, described for example by Hinds [17]. There also exist the American Conference of Governmental Industrial Hygienists (ACGIH) criteria for the inhalable, thoracic and respirable aerosol mass fraction (**Fig. 4.6**), and simplified equations describing the International Commission on Radiological Protection model (ICPR, 1994) for head airway, tracheobronchial and alveolar deposition (**Fig. 4.7**).

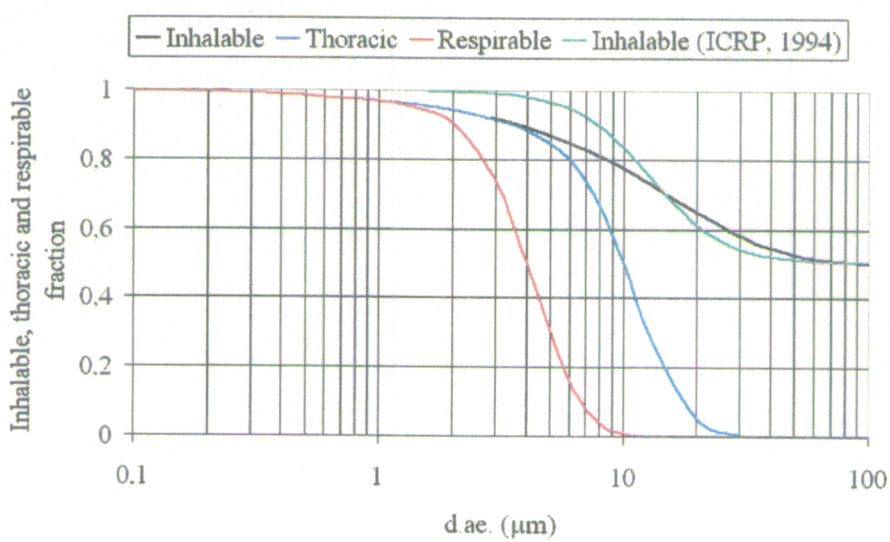

Fig. 4.6. ACGIH criteria for the inhalable, thoracic and respirable aerosol mass fraction.

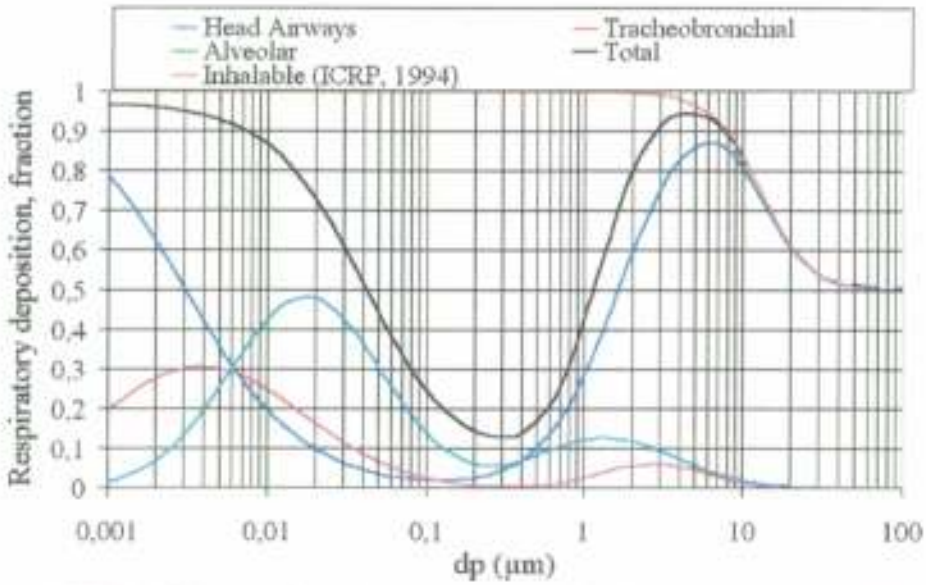

Fig. 4.7. ICRP Model aerosol respiratory deposition fraction, calculated with simplified equations taken from C. W. Hinds, "Aerosol Technology", 1999.

Inhalable, thoracic and respirable mass fraction is calculated from the particle mass as a function of the aerodynamic diameter. The ICPR models were developed for spherical particles with unit density and diameter dp. But the deposition model can also be used for other particles by replacing d with the aerodynamic diameter for particles larger than 0.5 µm and by replacing d by the physical diameter or equivalent volume diameter for particles smaller than 0.5 µm [17] (Hinds, 1999). For simplification and because it is only a qualitative comparison, the mass/ size distributions and the MMD calculated from these, will be used by setting d.ae. = dp to analyse the respiratory deposition fraction of particulate diesel vehicle emissions.

Taking the data from the measurements shown before, it can be easily seen that the aerosol mass/size distributions fall by nearly 100% within the respirable fraction given in **Fig. 4.6**, and that the observed shifts do not change the total amount of the inhalable, thoracic or respirable mass fraction from particulate emissions.

The mass/size distributions usually had a single maximum in the range of 50 nm to 100 nm. With the MMD determined from the mass/size distributions a decrease in the average particle size was observed at 50 km/h from 60 nm (CR/SF) to 50 nm (CR/CF) which accounts for an increase in the total respiratory deposition fraction from 48% to 52%. This change happens mainly in the alveolar fraction (**Fig. 4.7**). The biggest change in size distribution was observed for the same vehicle/fuel combination at 120 km/h, where the MMD decreased from about 210 nm (CR/SF) to 110 nm (CR/CF). In terms of respiratory deposition this large reduction by about 50% accounts for a reduction from 20% down to about 15%. Regarding the constant velocity tests, it can be seen that the minimum in the deposition fraction is reached for vehicles running at 120 km/h and the maximum for the vehicle emissions when running at 32 km/h and 50 km/h.

5. Discussion and remarks

Tests have been performed on a chassis dynamometer with diesel-driven vehicles, combining two different fuel injection systems with two different diesel fuels. As basic choice a vehicle with a standard fuel injection pump (SI) and a standard fuel (SF) were used and compared with a more advanced vehicle using the common rail technology (CR) and a clean fuel (CF) with a low sulphur and low aromatics content. This fuel is commercially available in Sweden. The main research topics were the comparison of particulate emissions from the different fuel and fuel injection system combinations under different driving conditions. Furthermore the consistency of the results from instrumentation using different physical particle properties for detection or collection were studied.

5.1 ECE15+EUDC test cycle

The combination of the standard vehicle with standard fuel had significantly lower HC, CO and NO_x emissions than the CR vehicle over the ECE15+EUDC test cycle. Emissions of HC and CO were further reduced when using the clean fuel CF. This reduction was also observed for the CR vehicle emissions. In contrary, CO_2 and particulate matter (PM) emissions were highest for the standard combination SI plus SF, both values were reduced when using the CF. A reduction of PM emission with the CF was also observed for the CR vehicle, but CO_2 values remained constant. The "advanced" combination of the CR vehicle running with CF showed its best performance with the lowest PM emissions of 0.014 g/km over the whole ECE15+EUDC test cycle.

Regarding the mass/size distributions no significant effect of the fuels was found, although emission spectra showed already a tendency towards smaller aerodynamic diameters (d.ae.) for the particles coming from the CR vehicle with CF. This trend, a reduction of the average MMD from 100 nm to 80 nm, results mainly of the shift towards smaller d.ae. when the CR vehicle is running with CF at 120 km/h. In the test cycle results this shift nearly disappears because of the short (10s at 120 km/h) high speed sequence.

PM measurements have been performed in parallel with a standard filter sampling system and with size resolved low pressure impactor measurements. Both data sets were in fairly good agreement, indication that an impactor – for practical reasons with much less than 11 stages – could serve as an alternative easy to handle sampling device for size resolved particulate mass measurements of diesel vehicle emissions.

Summary of the ECE15+EUDC test cycle results:

- The sulphur free and low aromatic content fuel reduces the regulated carbonaceous gaseous emissions and – in a more obvious way – the emissions of particulate matter, without significant changes in the particle mass/size distributions.

- Any shift towards smaller particles, expected from results gained from constant velocity tests at 120 km/h, disappears nearly completely in the "noise" of the measurements due to the short high speed sequence of the test cycle.

- Changes in the "classification" according to EURO I-IV levels occurred only for the CR vehicle where CO emissions improved from EURO II to EURO III level and PM emissions from EURO III to EURO IV level.

- Although most SI emissions were reduced, these were not sufficient to change the EURO classification.

- Impactors with two or three stages could serve as size resolving measuring method for particulate diesel vehicle emissions.

5.2 Constant velocity tests

At constant velocities some more effects were seen regarding the fuel effect on mass reduction and size distribution. The mass reduction of particulate emissions for the CR vehicle running with CF occurred mainly under idling and high speed conditions, while the emission reduction for the SI vehicle occurred at all speed levels except the idling.

Total mass emissions during the ECE15+EUDC test cycle were, as already said before, independent of the fuel type always higher for the SI vehicle. But the constant speed measurements show instead that particulate emissions from the SI vehicle are typically lower than those of the more advanced CR vehicle when the vehicles runs at low speed levels of 0 km/h, 32 km/h and 50 km/h. Only in case of the 120 km/h tests the particulate emission values of the SI vehicle were up to 9 times higher than those of the CR vehicle. This means that the extremely high emission levels during the short high speed phase (and probably also during acceleration phases) of the test cycle are responsible for the high total mass emission values of the SI vehicle.

Measured particulate mass concentrations at the exhaust pipe exit (undiluted) and at the CVS dilution tunnel exit (diluted) were in fairly good agreement for low concentration values, i.e. for measurements carried out at 0 km/h, 32 km/h and 50 km/h. In these cases also the mass/size distributions showed surprisingly no essential differences between the diluted and undiluted measurements.

Large mass concentration differences occurred in all measurements at 120 km/h, although the extraction nozzle at the exhaust pipe exit operated at 120 km/h tests for both vehicles nearly under isokinetic conditions. While the LPI-11 data for the SI/SF and SI/CF combinations were about two times higher than those measured with the LPI-8, the LPI-11 data were lower for the CR/SF combination and higher for the CR/CF combination than those measured in parallel with the LPI-8 in the undiluted raw gas. In that case, the LPI-8 mass/size distributions of the undiluted exhaust gas particulate matter had a similar average MMD (84 nm vs. 86 nm), while the LPI-11 MMD decreased from about 210 nm (CR/SF) to 110 nm (CR/CF).

CMD and MMD obtained from the number/size and mass/size distributions were lowest for the SI/CF combination. For the SI vehicle exhaust the CMD was high for idling conditions and at 120 km/h, and increasing with speed, while the MMD was equally low at 32 km/h and 50 km/h, and much higher at 120 km/h. For the CR vehicle exhaust the MMD showed a similar behaviour than the SI-MMD, but had lower values, specially at 120 km/h, while the CMD increased from 0 km/h to 50 km/h and was lower for 120 km/h, where values below or equal to those of idling conditions were obtained. Except for 120 km/h tests, all MMD were significantly lower (!) than the CMD, thus using the Hatch-Choate equation for the calculation of the MMD from number/size distributions gave no suitable results.

Summary of the constant velocity tests:

- The SI vehicle emitted always less and smaller particles (mass and number wise) at medium velocities of 32 km/h and 50 km/h.

- The SI vehicle emitted always much more and much bigger particles (mass and number wise) at high velocity of 120 km/h.

- Conclusions on the size distribution drawn from mass/size distributions did not in all cases correspond with conclusions drawn from the number/size distributions.

- No dilution effect on mass/size distributions was found for tests at velocities < 120 km/h.

- A fuel effect was seen in the mass/size distributions of the CR vehicle exhaust. The MMD was smaller for CF tests at 32 km/h and 50 km/h, and most obvious at 120 km/h. The parallel measured number/size distributions showed a significant shift towards smaller CMD only at 0 km/h and 32 km/h.

- A fuel effect was not clearly detectable from the mass/size distributions of the SI vehicle exhaust. But in this case the number/size distributions showed a shift towards smaller CMD at 32 km/h and 50 km/h.

- Although shifts towards smaller particle sizes reported herein have been significant, it must be noted that these changes in mass/size or number/size distributions might be not of relevance for health issues because of their small amplitudes. In cases where the changes were of a larger scale (i.e. when increasing speed to 120 km/h), the shift was towards bigger particle sizes thus reducing the deposition probability, or to smaller but (compared to other velocity test data) still big particle sizes.

5.3 Final remarks

The test with just two vehicles having different fuel injection technologies and operated with two different fuels indicated already the difficulty of coming to significant conclusions, when the particle emission performance should be evaluated. Depending on the measuring method and sampling location, the effects of fuel and injection technology were more or less pronounced or not even detected.

From the four combinations of injection technology and fuel, the Common Rail and Low Sulphur and Low Aromatics combination (CR/CF) showed the best performance, regarding the particulate mass emissions during the ECE15+EUCD test cycle, where the SI vehicle emitted less of the regulated gaseous compounds. The SI vehicle emitted also less particulate mass under urban driving conditions and showed the best improvement under all test conditions when using the clean fuel. The CR vehicle on the other hand improved only slightly under idling and high speed conditions. Data reveal that most of the emission differences between the two vehicles results from their behaviour at high speed levels.

List of abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
CF	"clean" diesel fuel with low sulphur and low aromatics content
CR	diesel driven vehicle with common rail system
CMD	count median diameter
ECE15+EUDC	European driving cycle for emission measurements
EGR	exhaust gas re-circulation
ICPR	International Commission on Radiological Protection
LPI	low pressure impactor
MMD	mass median diameter
PAH	polycyclic aromatic hydrocarbons
PM	particulate matter
SF	diesel fuel with standard specifications
SI	diesel driven vehicle with "standard" fuel injection system
SMPS	Scanning Mobility Particle Sizer
d.ae.	aerodynamic diameter
σ_g	geometric standard deviation of log-normal distribution

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Annex

A1: Number/size distributions of SI-vehicle particulate emissions from constant velocity tests.

A2: Number/size distributions of CR-vehicle particulate emissions from constant velocity tests.

A3: Average cumulative number/size distributions with standard deviation of the SI-vehicle particulate emissions, as measured during the constant velocity tests.

A4: Average cumulative number/size distributions with standard deviation of the CR-vehicle particulate emissions, as measured during the constant velocity tests.

A5: Mass/size distributions of SI-vehicle particulate emissions from constant velocity tests, measured in the diluted (LPI-11) and undiluted (LPI-8) exhaust.

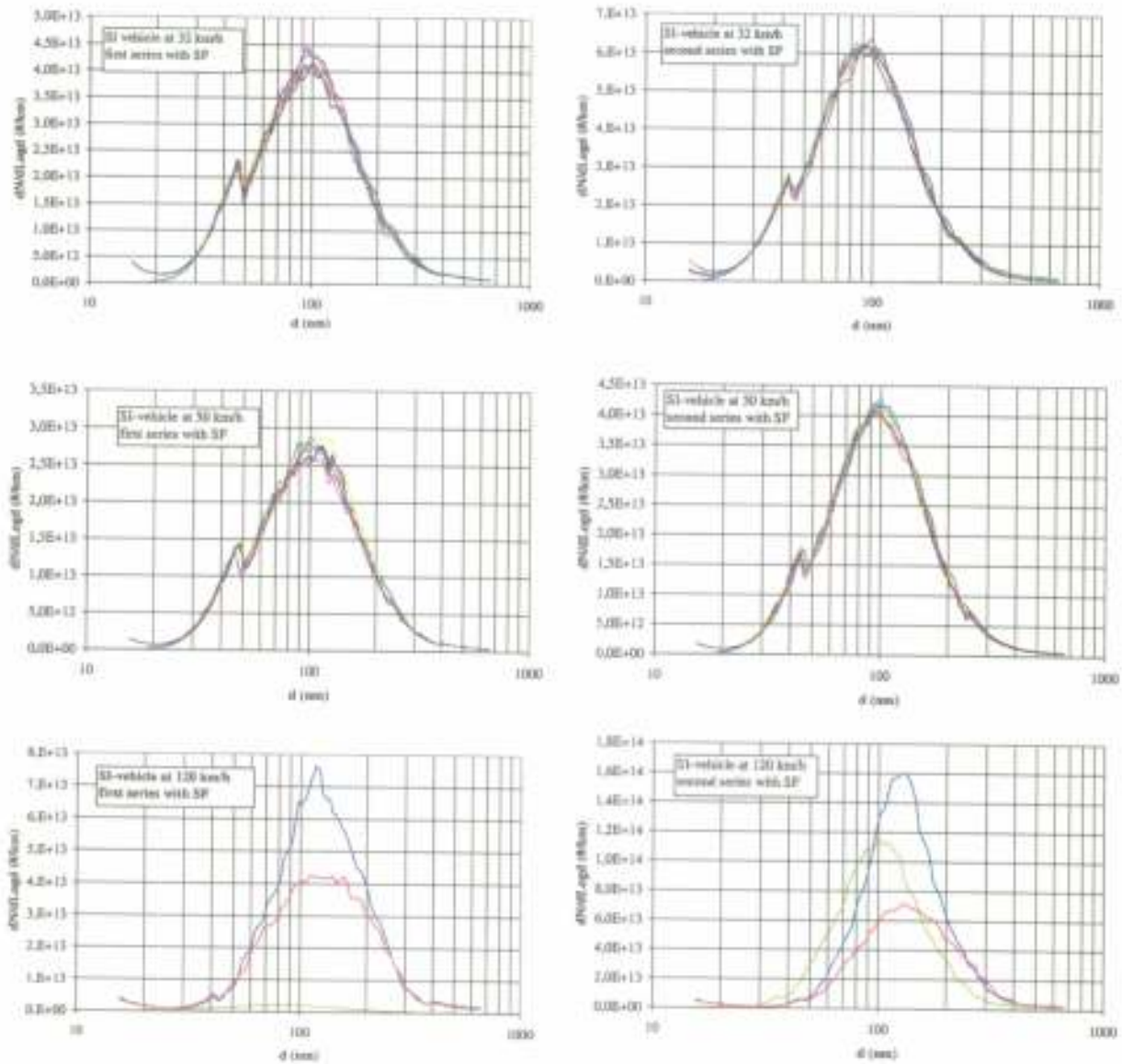
A6: Mass/size distributions of CR-vehicle particulate emissions from constant velocity tests, measured in the diluted (LPI-11) and undiluted (LPI-8) exhaust.

A7: Cumulative mass/size distributions of SI-vehicle particulate emissions derived from constant velocity tests and ECE15+EUDC test cycles.

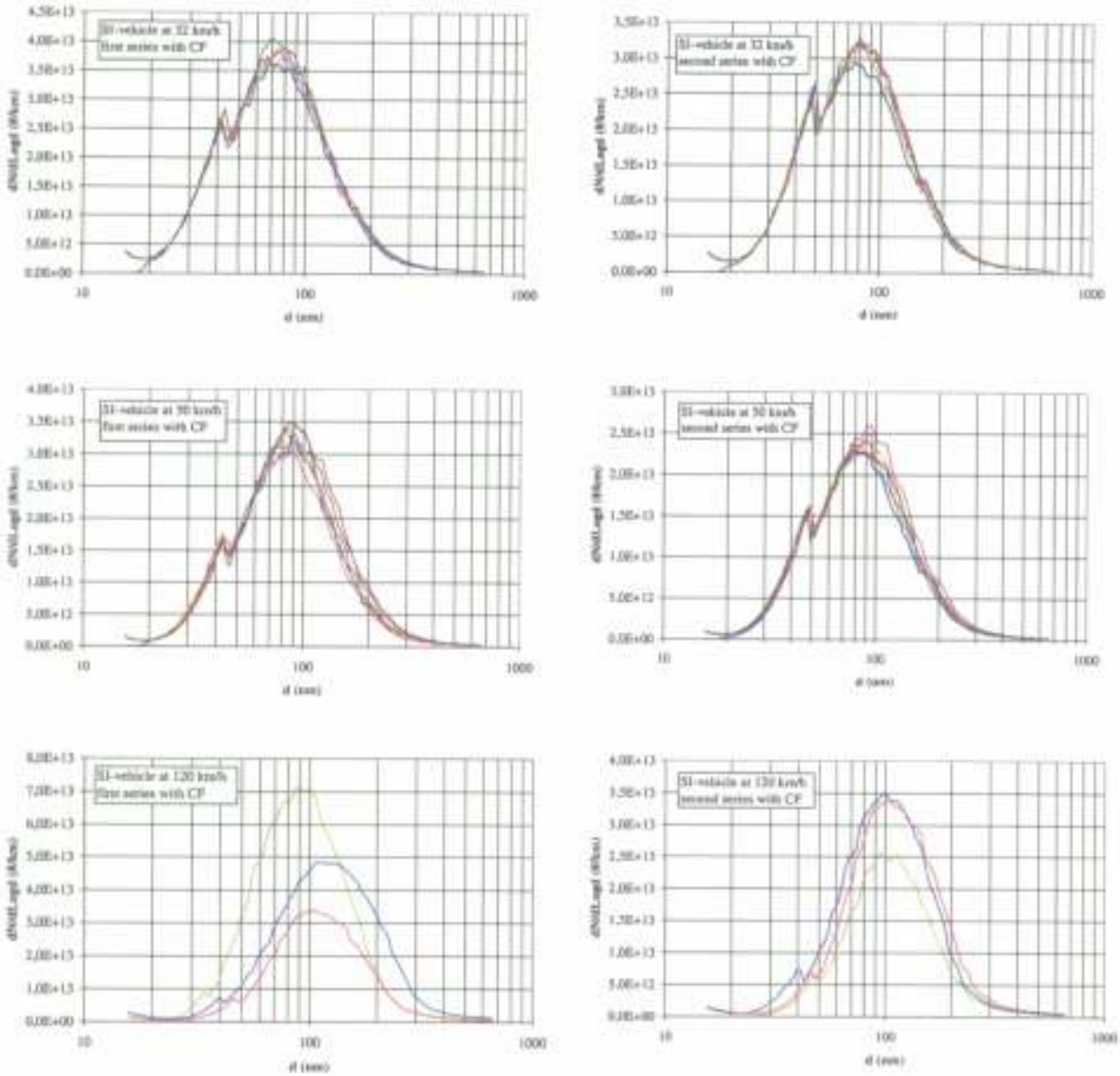
A8: Cumulative mass/size distributions of CR-vehicle particulate emissions derived from constant velocity tests and ECE15+EUDC test cycles.

A9: Count median diameters (CMD) derived from averaged SMPS cumulative number/size distributions for different vehicle/fuel combinations.

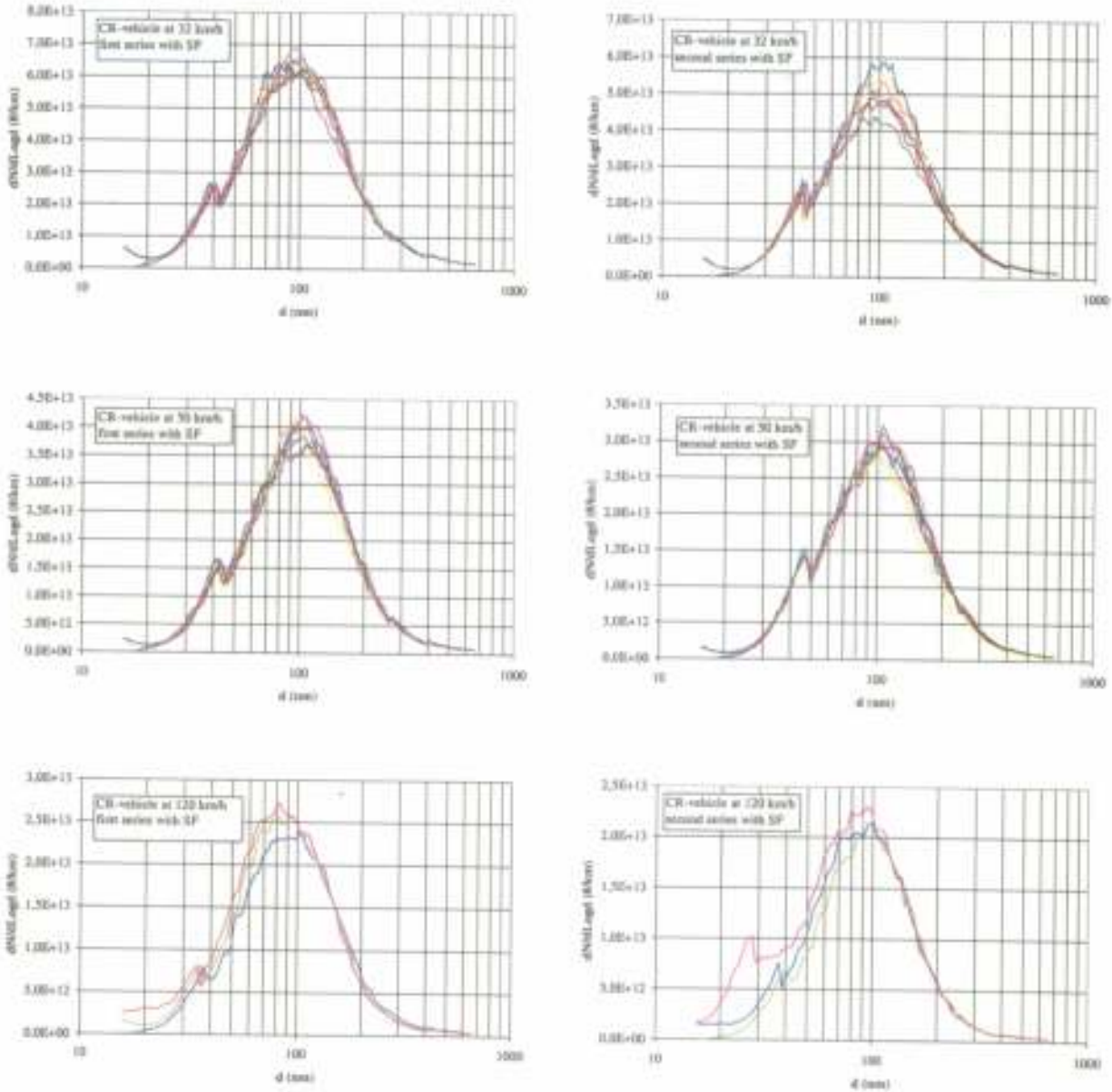
A10: Mass median diameters (MMD) derived from LPI-11 mass/size distributions.



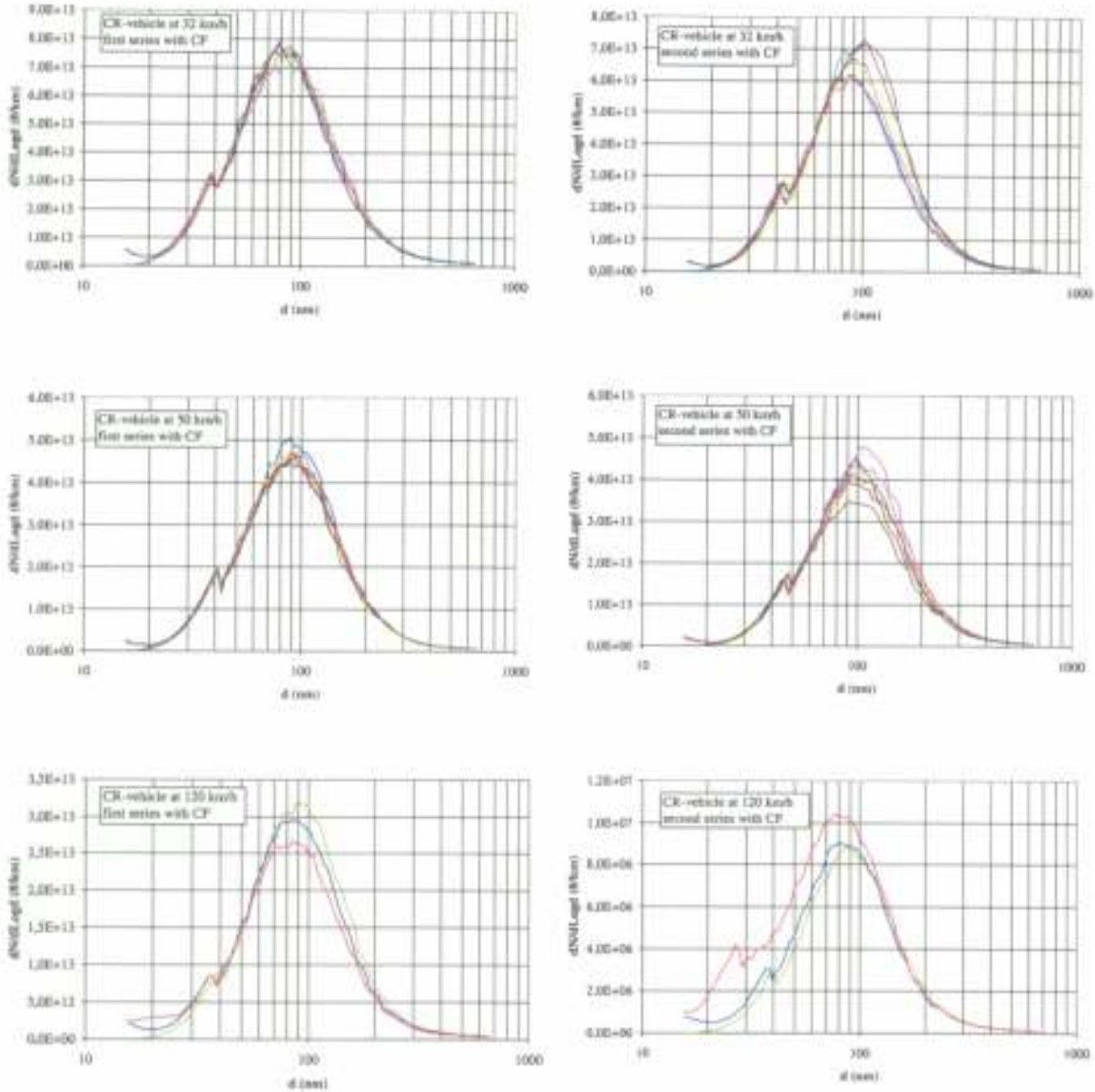
A1: Number/size distributions of SI-vehicle particulate emissions from constant velocity tests.



A1: Number/size distributions of SI-vehicle particulate emissions from constant velocity tests. (Continued for CF)



A2: Number/size distributions of CR-vehicle particulate emissions from constant velocity tests.



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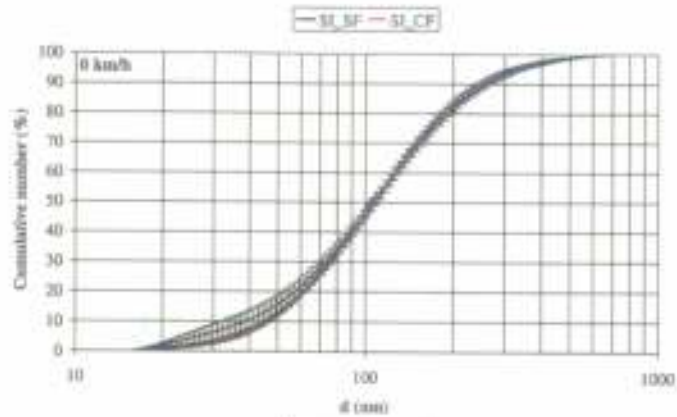
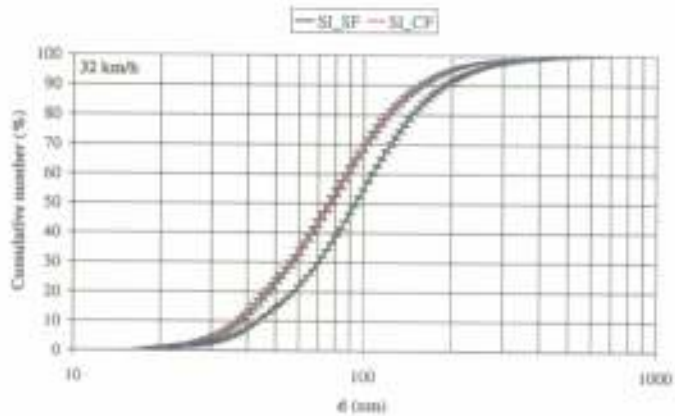
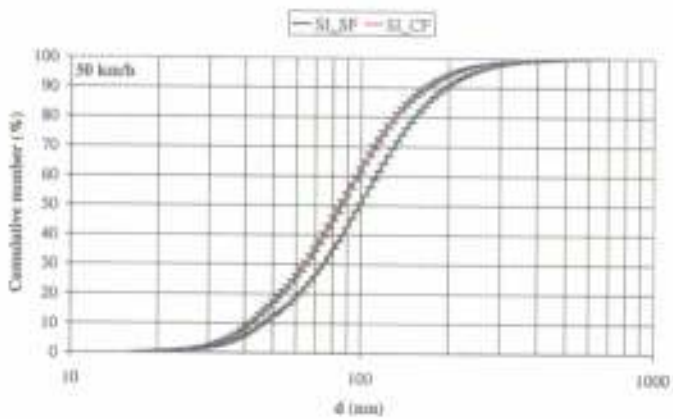
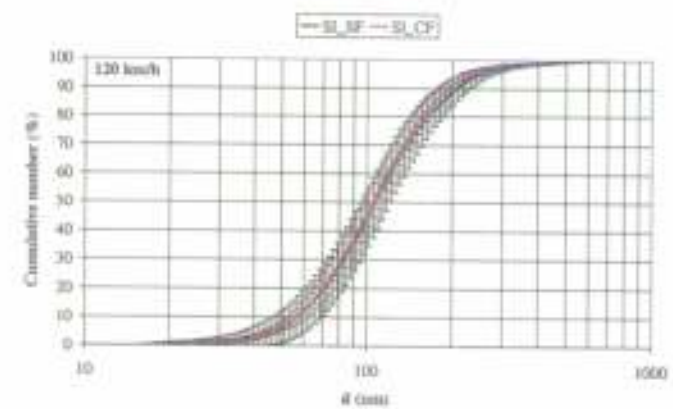
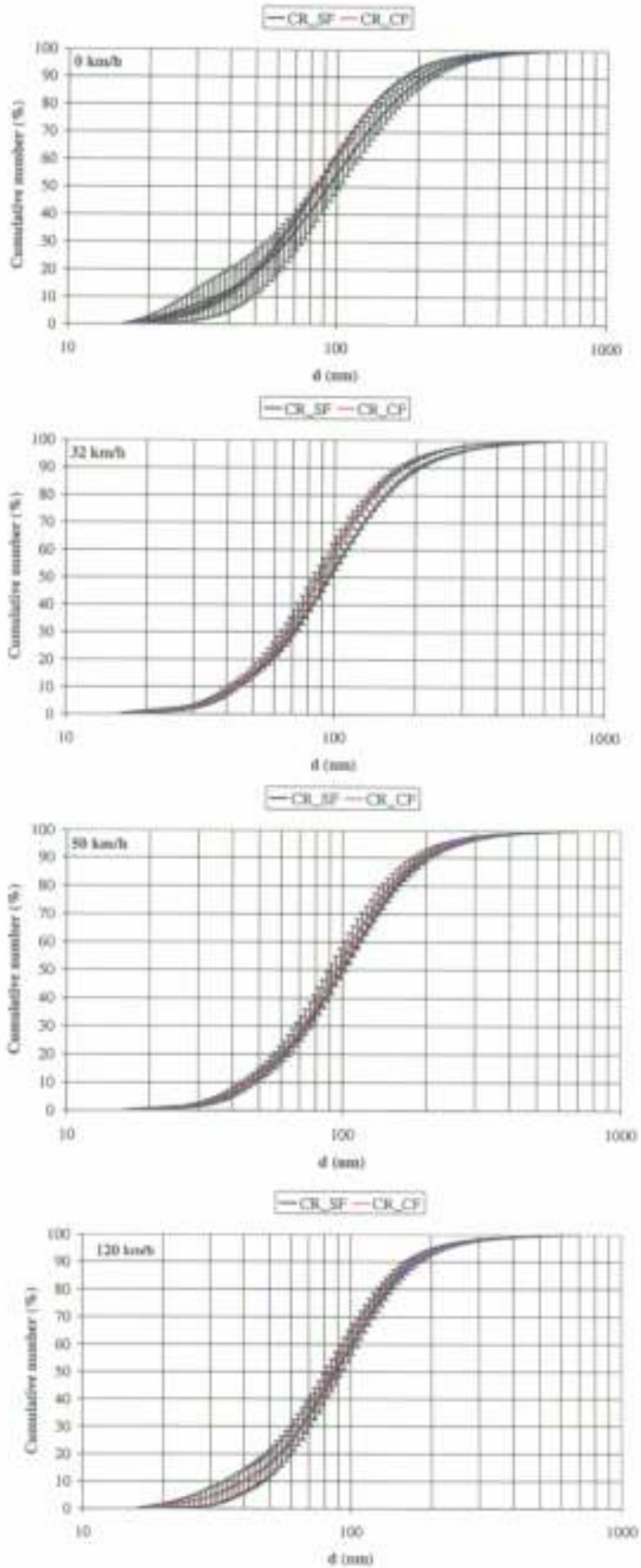




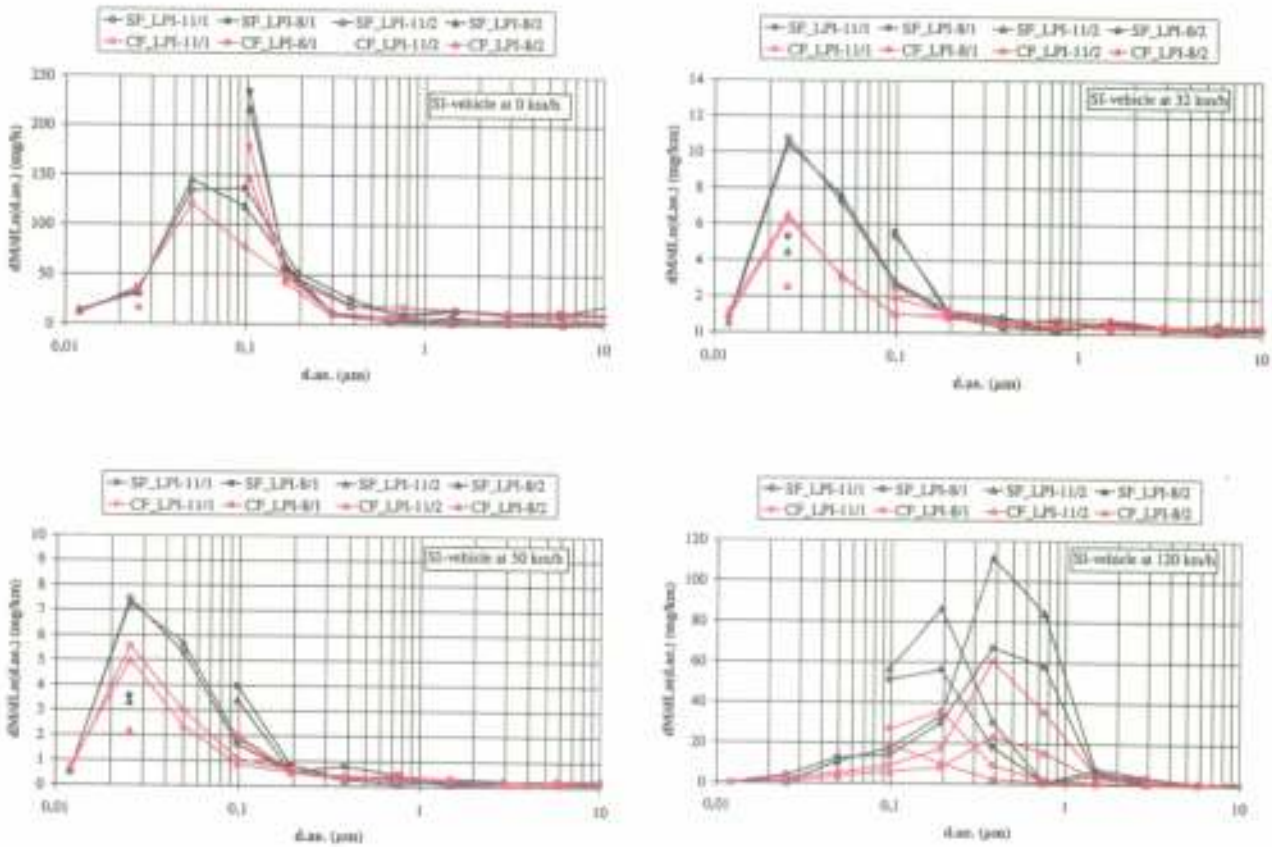




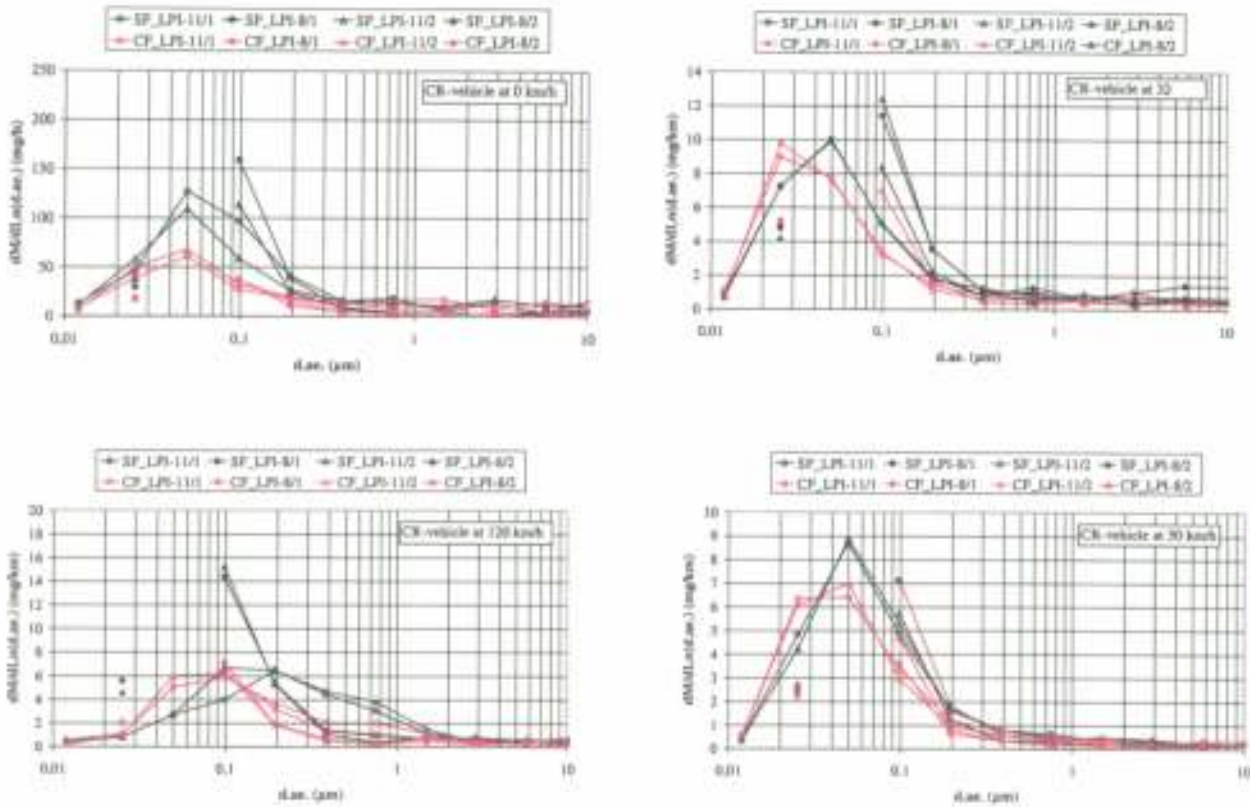
A3: Average cumulative number/size distributions with standard deviation of the SI-vehicle particulate emissions, as measured during the constant velocity tests.



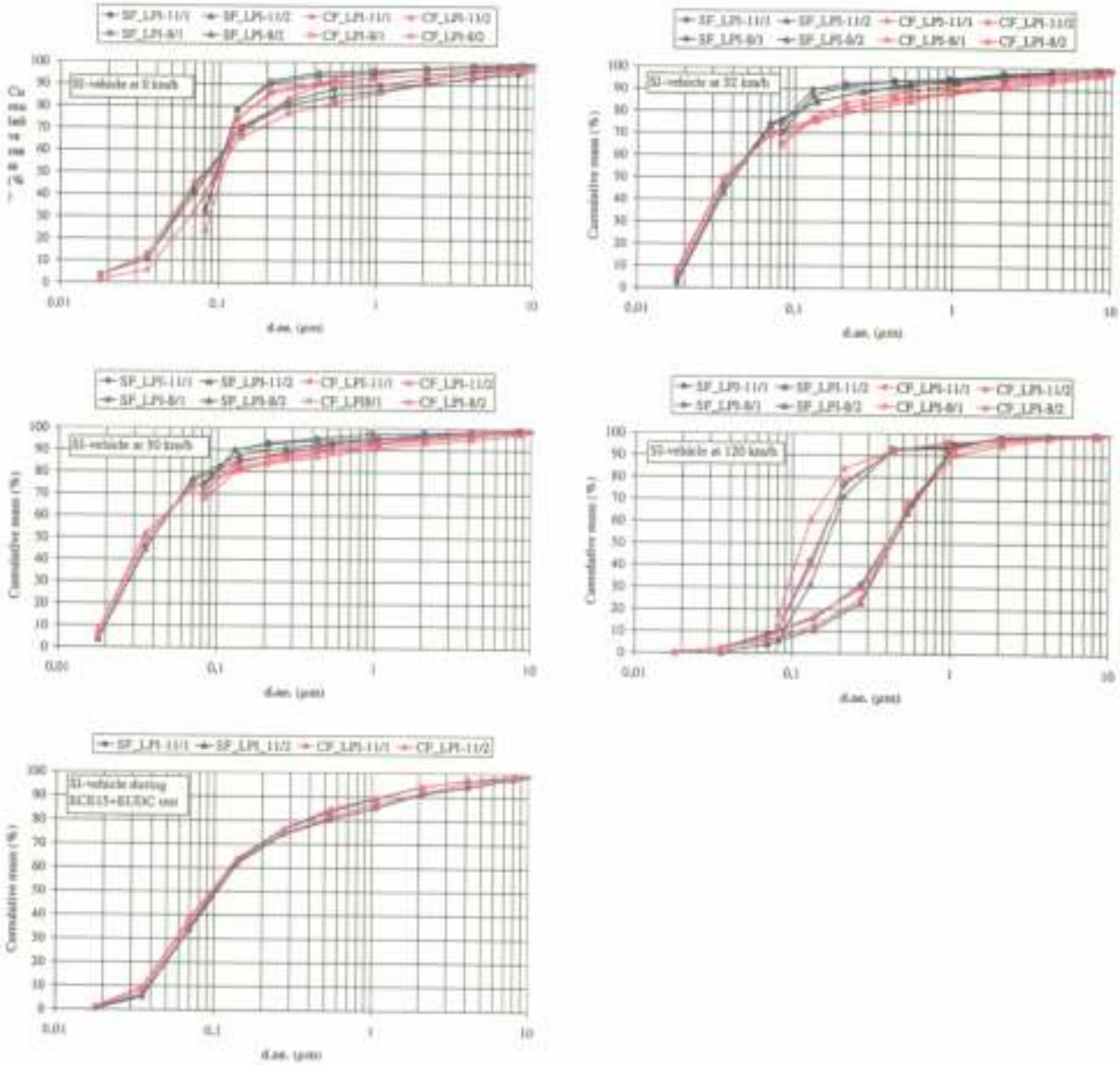
A4: Average cumulative number size distributions with standard deviation of the CR-vehicle particulate emissions, as measured during the constant velocity tests.



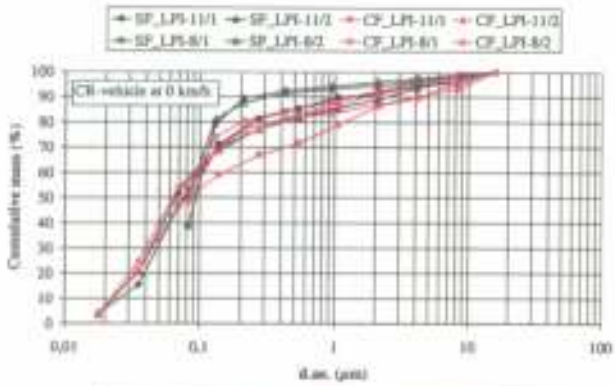
A5: Mass/size distributions of SI-vehicle particulate emissions from constant velocity tests, measured in the diluted (LPI-11) and undiluted (LPI-8) exhaust.

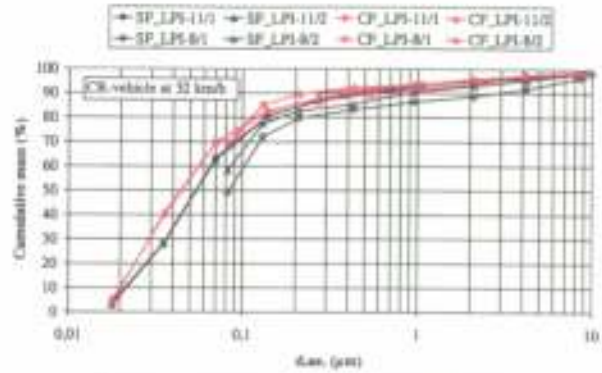


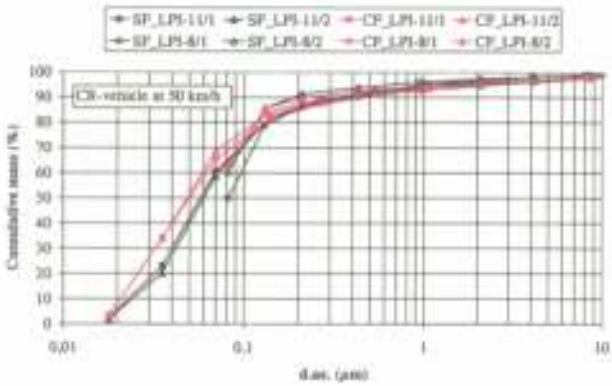
A6: Mass/size distributions of CR-vehicle particulate emissions from constant velocity tests, measured in the diluted (LPI-11) and undiluted (LPI-8) exhaust.

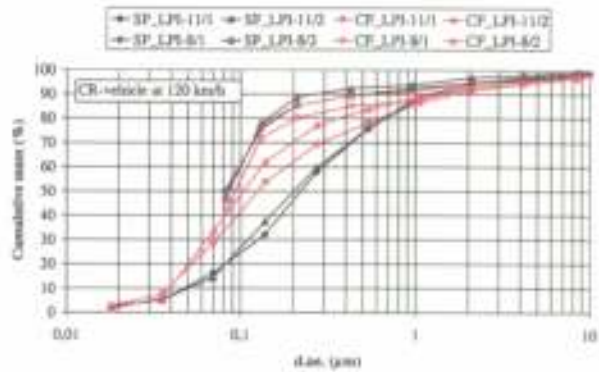


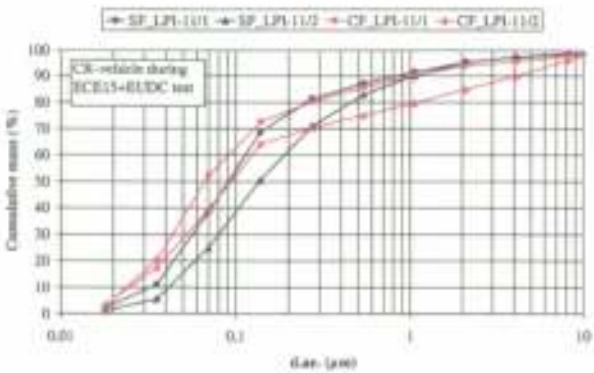
A7: Cumulative mass/size distributions of SI-vehicle particulate emissions derived from constant velocity tests and ECE15+EUDC test cycles.



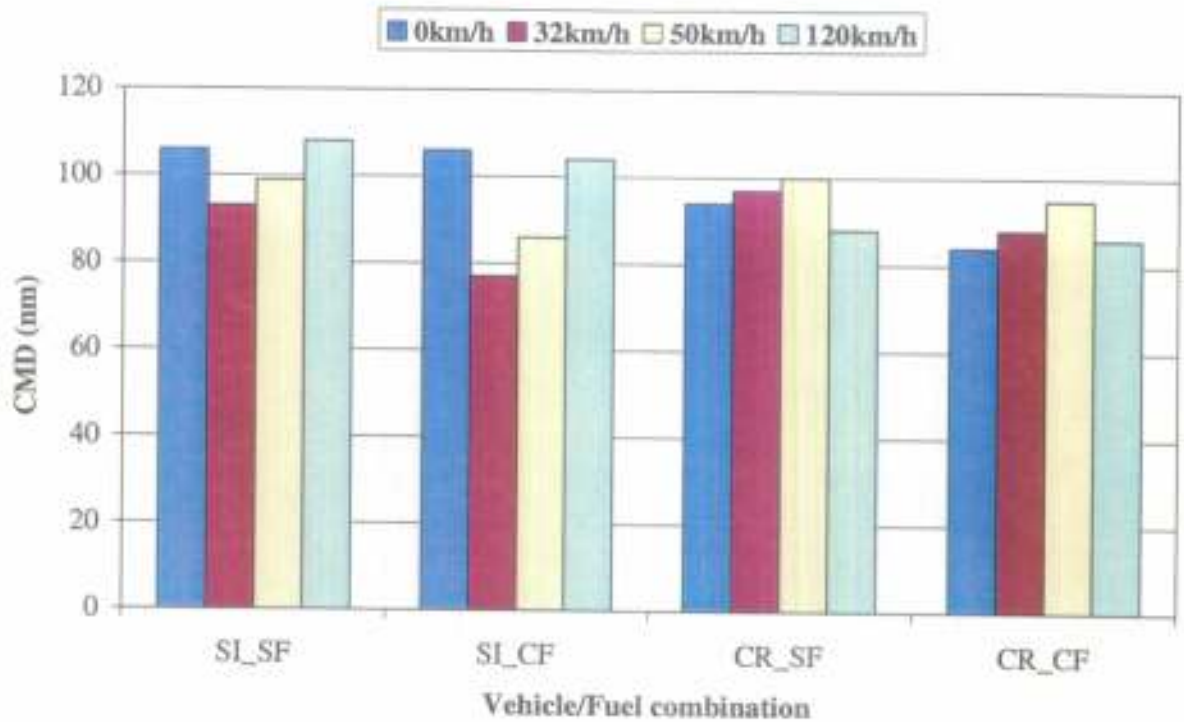




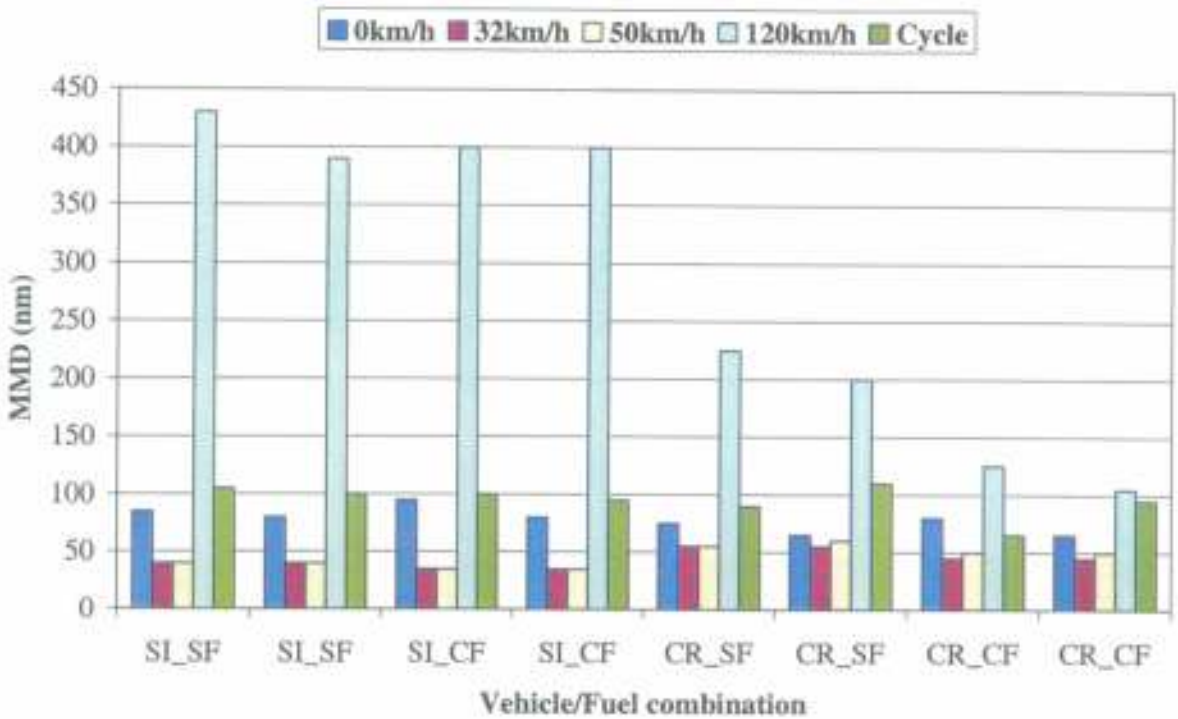




A8: Cumulative mass/size distributions of CR-vehicle particulate emissions derived from constant velocity tests and ECE15+EUDC test cycles.



A9: Count median diameters (CMD) derived from averaged SMPS cumulative number/size distributions for different vehicle/fuel combinations.



A10: Mass median diameters (MMD) derived from LPI-11 mass/size distributions.

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