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IEA/AMF ANNEX XXII: PARTICLE EMISSIONS AT MODERATE AND COLD TEMPERATURES USING DIFFERENT FUELS

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IEA/AMF Annex XXII: PARTICLE EMISSIONS AT MODERATE AND COLD TEMPERATURES USING DIFFERENT FUELS

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Summary

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ABSTRACT

Major part of the research work on particulate emissions has been carried out at normal ambient temperature. In real life, the average day temperatures, especially in the winter season, are far below the "normal" temperature (about +23 °C) of the exhaust emission test procedures. For many years, it has been obvious that the knowledge of the total particulate mass emissions is not enough. Quality of these particulates, e.g. polyaromatic hydrocarbon content and mutagenicity, has been studied. Now there is also a need to gain more information on fine particles, which can penetrate the lungs more easily. International Energy Agency's Committee on Advanced Motor Fuels sponsored this study of the possible effect of ambient temperature on particle emissions. Also aldehydes and speciated hydrocarbons were studied.

Several different engine and fuel technologies were covered, including gaseous fuels and biodiesel. Research work focused on light-duty technologies. Test vehicles were as follows: two diesel cars (direct and indirect-injection), stoichiometric gasoline fuelled car (multi-port-fuel-injection), direct-injection gasoline car, Flexible Fuel Vehicle running with E85 fuel, CNG and LPG cars. Four diesel fuel qualities were studied: European grade diesel fuel (EU2000), a blend of this fuel and 30% rape seed methyl ester (RME30), Swedish Environmental Class 1 fuel (RFD) and a blend of this fuel and 30% RME (RFD/RME).

The effect of temperature was dependent on the engine technology. Significant increase in particle mass and number emissions was seen with some technologies when -7 °C temperature was compared to normal test temperature. Some engine technologies were rather insensitive to ambient temperature, e.g. CNG car did not show any significant particle emission at normal or low temperatures. If an increase in particle emissions was seen, it typically appeared immediately after the cold start. With warmed-up engine the particle emissions were mainly at the same level at normal and low temperatures. In some cases RME indicated more particles and/or a shift at lower mean diameter at low temperatures after the cold start than in the tests at normal temperature.

CONTENTS

ABBREVIATIONS

BTEX	sum of benzene, toluene, ethylbenzene and xylenes
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
DNPH	dinitrophenylhydrazin
E85	85% ethanol and 15% gasoline
ECE1&2	Part One (urban cycle) of the European test cycle (former ECE-15)
EGR	Exhaust Gas Recirculation
ELPI	Electrical Low Pressure Impactor
EU2000	European grade diesel fuel
EUDC	extra-urban driving cycle (the last 400 s of the European test cycle)
FFV	Flexible Fuel Vehicle
G-DI	direct-injection gasoline car
HC	total hydrocarbons
HPLC	high performance liquid chromatography
IDI	indirect-injection
LPG	liquefied petroleum gas
LPI	low pressure impactor
MPI	multi-port-fuel-injection gasoline car with TWC
NO_x	nitrogen oxides
PM	particulate matter
RFD	Swedish Environmental Class 1 fuel
RFD/RME	a blend of RFD and 30% RME.
RME30	a blend of EU2000 and 30% RME
RME	rape seed methyl ester
SMPS	Scanning Mobility Particle Sizer
TDI	turbo-charged direct-injection diesel
TWC	three-way-catalyst

1 INTRODUCTION

There is a great interest in particulate emissions of road traffic all over the world. So far, most of the research work on particulate emissions has been carried out at normal ambient temperature. Even a slight reduction in temperature can increase particulate emissions. In real life, the average day temperatures, especially in the winter season, are far below the "normal" temperature (about +23 °C) of the exhaust emission test procedures. For many years, it has been obvious that the knowledge of the total particulate mass emissions is not enough. Quality of these particles, especially content of polyaromatic hydrocarbons and mutagenicity, has already been studied widely. Now there is also a need to gain more information on fine particles, which can penetrate lungs more easily. Research work on the particle size issues of engines and vehicles is still ongoing. In addition, there is no consensus about many basic aspects, like correct sampling conditions or whether the particle number, volume or mass is the most significant parameter. So far, the possible effect of temperature on particle size has not been studied much.

This project was targeted to cover different fuel and engine technologies, including gaseous fuels and biodiesel. Research work focused on different light-duty technologies. However, preliminary tests were conducted with a medium-duty engine to evaluate the suitability of different measuring techniques at low test temperatures. The preliminary tests with the medium-duty engine gave basis for the decisions made for the test conditions used in the light-duty vehicle tests.

The tests with the medium-duty engine, two diesel cars, one gasoline fuelled car and one CNG car are reported in three interim reports (1st May 2001, 2nd October 2001, 3rd April 2002). The tests continued with a E85 fuelled car, a LPG car and a direct injection gasoline car in 2002 - 2003.

An acknowledgement is given to the IEA/AMF participants, Canada, Finland, Italy, Japan (NEDO, LEVO), Sweden and USA, for the financial support which made possible to conduct this interesting Annex. In addition, also Honda R&D Europe and Ford Motor Company are acknowledged for their financial support. It is a pleasure to thank personnel of VTT Processes for their active contribution to the work on this Annex. Hannu Vesala deserves special appreciation for planning and installation of the measurement system for particles.

This project was linked to the University Research Program of Ford Motor Company. In this context, Tampere University of Technology and VTT studied different dilution systems for measurements at low temperatures. The results of this work will be published later on.

The results were published also as SAE Technical Paper [1].

2 TEST ENGINE, CARS AND FUELS

The tests were carried out with one engine and seven cars. The engine was medium-duty Valmet 620 tractor engine from 1980's (also used in the IEA/AMF Annex X [2]).

- vertical farm tractor engine
- turbo-charged, direct-injection
- rotary-type pump
- 6.6 liters, 6 cylinders
- power output: 130 kW at 2400 rpm, 630 Nm at 1500 rpm

Two diesel cars were tested, one of them was TDI car that represents direct-injection diesel technology for light-duty vehicles. It is equipped with the exhaust gas recirculation (EGR) and with an oxidation catalyst. The other car was an indirect-injection (IDI) car with EGR system, but without oxidation catalyst. As a 1999 model year car, it represents up-to-date indirect-injection engine technology.

Two gasoline fuelled cars were tested. One represented conventional stoichiometric multi-port-fuel-injection technology (MPI). The other car (G-DI) was a direct injection car. At the moment there are many options of gasoline direct injection technologies on market. These technologies may differ significantly from each other especially regarding fuelling strategies (stoichiometric/lean combustion). In this project only one gasoline-direct injection car was studied.

Stockholm Municipality lent a flexible fuel vehicle for the tests.

The CNG car was a dedicated, commercially available car, which was provided for the tests by the manufacturer.

The LPG car was provided for the tests by the manufacturer. The car individual tested was a prototype. The LPG car starts on gasoline, but automatically switches on gas shortly after start.

There was a certain spread in both model year and mileage, the model year ranging from 1996 to 2002 and mileage from 6 000 to 114 000 km. This was due to the fact that project was active from 2000 to 2003.

Diesel fuel fulfilling the specification of the European Directive 98/70/EC (EU2000) and a blend of this fuel and 30% rape seed methyl ester (RME30) were used in the tests. In addition, selected tests were run by using Swedish Environmental Class 1 fuel (RFD) and a blend of this fuel and 30% RME (RFD/RME). The analysed properties of the EU2000 fuel and selected properties from the Swedish specification for RME and Swedish Environmental Class 1 fuels are shown in Table 2. Additional pre-tests to study the dilution conditions were carried out with a diesel fuel with sulphur content of 300 ppm.

Gasoline fulfilling the Directive 98/70/EC was used for the gasoline fuelled cars. The gasoline did not contain oxygenates. RON was 98, MON 85, density 754 g/l, Reid vapour pressure 59 kPa, distillation FBP 199 °C, E100 57 vol-%, E150 85 vol-%, olefins 9 vol-%, aromatics 34 vol-%, benzene 0.4 vol-%, sulphur content 40 mg/kg and lead content below 0.005 g/l.

E85 fuel was blended from absolute ethanol by adding 15% of the same gasoline quality that was used with the MPI and G-DI cars.

The methane content of CNG was about 98%, ethane content about 1%, propane and heavier hydrocarbons max. 0.5%, nitrogen content max. 1% and sulphur content max. 1 mg/Nm^3.

LPG with 95% propane content was used. The LPG car starts on gasoline. Tests were conducted with the gasoline in the tank of the car (not analysed).

Table 1. Characteristics of the light-duty cars.

	TDI car	IDI car	MPI	G-DI	FFV	CNG	LPG
Model year	1996	1999	2001	2002	2002	1998	2001
Fuel injection	direct injection	indirect injection	multi-port-fuel-injection	direct injection	multi-port-fuel-injection	gaseous Injection	gaseous injection
Displacement	1.9	2	1.6	2	1.6	1.6	2.5
Gears	automatic	manual 5	manual 5	manual 5	manual 5	automatic	automatic
Emission control	EGR oxidation cat.	EGR	TWC catalyst	catalyst	TWC catalyst	TWC catalyst	TWC catalyst
Mileage, km	33 800	114 000	6 420	6 300	9 500	10 140	20 400
Origin	Europe	Japan	Europe	Europe	Europe/USA	Japan	Europe

Table 2. The analyzed properties of the EU2000 fuel and selected properties of the Swedish specifications for RME and Swedish Environmental Class 1 fuels.

	EU2000 analyzed	RME SS 15 54 36	MK1 SS 15 54 35
Density +15 °C, kg/m^3	838.5	870-890	800-820
Sulphur content, ppm	306	<10	max 10
Cetane number	51		min 50
Viscosity +40 °C, mm^2/s	2.6	3.5-5	1.4-4.0
Cloud point, °C	-10		-16*
Aromatics IP391, vol-%			
total	21.4		max 5
mono	20		
poly	1.4		
Distillation, °C			
IBP	187		min 180
95 vol-%			max 285
FBP	361		

* *winter quality*

2.1 TEST SET-UP, REGULATED EMISSIONS AND TOTAL PARTICULATE MASS

2.1.1 Test matrix

The summary of the test matrix is shown in Tables 3 and 4. At least two tests with each engine/car/temperature combination were carried out, except for the RFD, RFD/RME fuels and Japanese test cycles. Some additional tests were run especially with diesel engine and diesel cars.

Table 3. The test matrix for the medium-duty engine using selected steady-state loads.

Preparatory work	**Tests at normal test temperature (+23 °C)**	**Tests at moderate test temperature (+0 °C)**	**Tests at low test temperature (-7 °C)**
• installations (engine and particle sizing) • determination of suitable load combination	• 2 tests with EU2000 • 2 tests with RME30 • One test with RFD • One test with RFD/RME	• 2 tests with EU2000 • 2 tests with RME30	• 2 tests with EU2000 • 2 tests with RME30 • One test with RFD • One test with RFD/RME
	CO, HC, NO_x, aldehydes, total particulates, particle number distributions (ELPI), particle mass distributions (LPI)*)		

*) *One LPI measurement with each fuel/temperature combination.*

Table 4. Test matrix for the light-duty cars.

	IDI and TDI cars	**SI, G-DI and FFV(E85)**	**CNG and LPG cars**
Preparatory work	• installations (particle sizing instruments) • determination of suitable conditions for sampling • determination of correct collecting period for particle mass size measurement		
European test cycle	**+23 °C, +5 °C, -7 °C:** • 2x2x3 tests with EU2000 • 2x2x3 tests with RME30 • RFD and RFD/RME at +23 and –7 °C without replicate tests	**+23 °C, +5 °C, -7 °C:** • 2x3x3 tests (two tests with each car/temperature combination)	**+23 °C, +5 °C, -7 °C:** • 2x3x3 tests (two tests with each car/temperature combination)*)
	CO, HC, NO_x, aldehydes, speciated hydrocarbons*), total particulates, particle number distributions (ELPI), particle mass distribution (LPI)**)		
Japanese test cycle	**+23 °C, -7 °C:** • One test with each car/temperature	**+23 °C, -7 °C:** • One test with each car/temperature	**+23 °C, -7 °C:** • One test with each car/temperature
	CO, HC, NO_x, aldehydes, speciated hydrocarbons*), total particulates, particle number distributions (ELPI)		

**) Speciated hydrocarbons not measured with diesel vehicles **) LPI at two temperatures (+23 and –7 °C). One LPI measurement with each vehicle/fuel/temperature combination.*

2.1.2 Engine tests

The engine was installed in a cold test cell. Description of the dynamometer and the equipment used for recording the test parameters are described in Table 5. The following parameters were recorded in one-second time-intervals: engine speed, torque, battery charge, carbon monoxide (CO), total hydrocarbons (HC), nitrogen oxides (NO_x), temperature of the test cell, temperature of intake air, mass flow of intake air, oil pressure, temperatures of engine oil, exhaust gas, coolant and engine manifold. CO, HC and NO_x were measured from raw exhaust gas. In addition, NO_x of the diluted exhaust gas was recorded to define the dilution ratio of the particle measurements. Humidity of the test cell and ambient pressure were recorded manually during each test. The analysers were located in the control room at normal ambient temperature.

Table 5. The equipment used in the tests with the medium-duty engine.

Equipment	Type, manufacturer	Properties
Dynamometer (M450043)	EC 38 TD, Froude Consine Ltd.	max. 165 kW at 3300-8000 rpm
Intake air flow	Sensyflow VT2, Hartman & Braun Sensycon	0-1600 kg/h, ±1,5%
CO (M870504)	RF2G, ADC/GWB	0-500 ppm and 0-0.5%, ±1%FS
HC (M870503)	FID VE7, J.U.M. Engineering	0-100 000 ppm, ±1% FS
NO_x (M800502)	10AR, Thermo Electron Instruments	0-10 000 ppm, accuracy ±1% FS
NO_x (M990510)	CLD 700 REht, ECO Physics	0-10 000 ppm

The tests at ambient temperature were run with engine fully warmed-up as normally in the heavy-duty exhaust emission tests. In addition, a stabilisation period of at least one hour was run after the change of test fuel to avoid any trace-effect of the previous fuel quality.

The tests at low temperatures were started with cold engine conditioned at the test temperature overnight. Battery was fully charged before each test at low temperature. The engine was fully warmed-up after each cold test.

The test cycle used with the medium-duty engine is shown in Table 6. Loads were relatively low, namely 0%, 25% and 50% of maximum load with two engine speeds. In real-life, relatively low loads are used to warm-up the engine after the cold-start. Cold starts at low temperatures in combination with low loads represent extreme conditions, and such running conditions have not been extensively studied. In fact, hardly any data can be found of particulate mass or number emissions of medium-duty or heavy-duty diesel engines in these conditions.

The regulated gaseous mass emissions (CO, HC and NO_x) over the test cycle were calculated by using average values of last minute at each load mode. This follows the principle in the procedures for the emissions tests with the heavy-duty engines.

Table 6. Test cycle used in the tests with medium-duty engine.

Mode	Engine speed (rpm)	Torque (Nm)	Duration (s)	Cumulative duration (min)
1	idle		240	4
2	1500	160	180	5-7
3	1500	315	180	8-10
4	1800	160	180	11-13
5	1800	315	180	14-16

2.1.3 Light-duty cars

Cars were tested in a climatic test cell. Description of the dynamometer and the equipment used for recording the test parameters are described in Table 7. All equipment used for measurement of the regulated emissions (exhaust dilution and collection, concentration analysis etc.) conforms to the specifications of the Directive 70/220/EEC (European test).

The total particulate matter is not regulated emission for spark-ignition vehicles. The particulate mass emissions from these cars are low when compared to diesel cars. Hence, the diesel particulate collection system cannot be used. In addition, the possible contamination risk of diesel particles is avoided using a separate collection system. The total particulate mass for low-particle-emission cars was measured by collecting the particles with the high-capacity sampler used only for spark-ignition vehicles, which is specially developed at VTT for testing gasoline cars [3, 4]. The high-capacity particulate collection system used only for SI vehicles includes a dilution tunnel, probes, filter holders, a blower, a flow meter and an inverter to maintain constant flow of diluted exhaust gas through filters. Two large filter holders for filters (Ø 142 mm) were used in parallel. In these measurements, the flow through filters was 1600 l/min, which is about 60 times higher than that of the standard diesel sampling system at VTT. A significant amount of diluted exhaust gas by-passing the CVS system is taken into account when calculating the emission results.

Several parameters were recorded in one-second time-intervals e.g. speed, carbon monoxide (CO), total hydrocarbons (HC), nitrogen oxides (NO_x), temperature of the test cell, temperature of exhaust gas and humidity of the test cell. CO_2 of the diluted exhaust gas was recorded to define the dilution ratio in the particle size measurements. The analysers were located in the control room at normal ambient temperature.

The major part of the tests was carried out according to the European test cycle (Figure 1). Selected tests were run also with Japanese 10-15-mode test cycle (Figure 2).

The European test cycle was divided in three sub-cycles for sampling. The first part of the European test included the first two elementary sub-cycles of the urban cycle ECE15 (marked as ECE 1), the second phase was the rest of the ECE15 cycle (marked as ECE 2), and the third part was the extra urban portion (marked as EUDC).

The Japanese 10-15-mode test is a hot-start test. However, the 10-15 mode test was run as cold-start test at -7 °C temperature, as well as some selected tests at normal temperature.

Table 7. The basic equipment used in the tests with the light-duty cars.

Equipment	Manufacturer/type	Remarks
Chassis dynamometer	Froude Consine 1.0 m	DC, 100 kW
Constant volume sampler	Pierburg 12.5 WT	PDP-type with heat exhanger
CO, HC, NO_x, CO_2	Pierburg AMA 2000	regulated gaseous emissions, triple bench
particulate sampler diesel cars	dil. tunnel and Pierburg PS430	10" dil. tunnel and particulate sampler, filters ∅ 47 mm
particulate sampler other than diesel cars	dil. tunnel and high-capacity collection system	10" dil. tunnel and particulate sampler, filters ∅ 142 mm

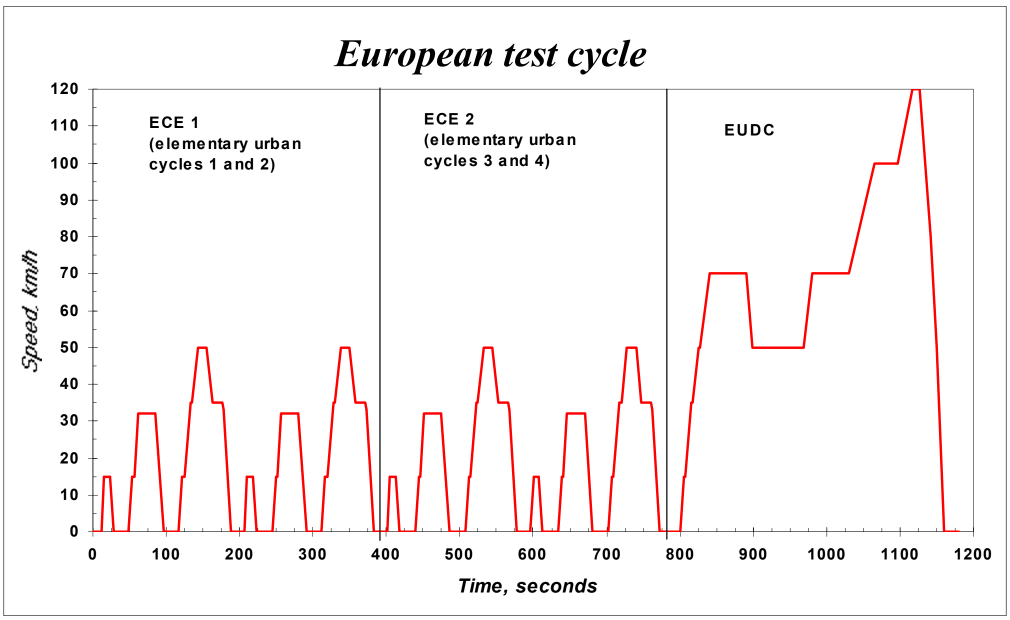


Figure 1. European test cycle.

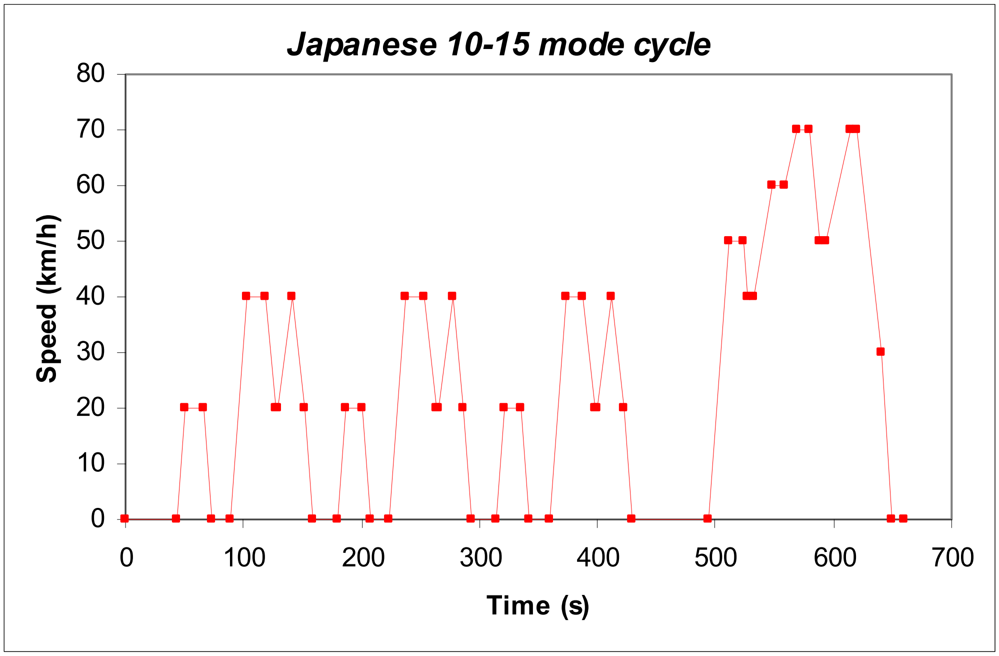


Figure 2. Japanese 10-15 mode test cycle.

2.2 ALDEHYDES AND C1-C8 HYDROCARBONS

With the heavy-duty engine aldehydes were collected from the porous-tube diluted exhaust gas (Chapter 2.3) by using dinitrophenylhydrazine (DNPH) cartridges. The aldehydes were collected with one cartridge over the 16-minute test cycle (Table 4). For the light-duty cars aldehyde samples were collected from the diluted exhaust gas (CVS) by using dinitrophenylhydrazine (DNPH) cartridges. The DNPH derivatives were extracted with acetonitrile/water mixture. Altogether 11 aldehydes (formaldehyde, acetaldehyde, acrolein, propionaldehyde, crotonaldehyde, methacrolein, butyraldehyde, benzaldehyde, valeraldehyde, m-tolualdehyde, hexanal) were analysed with the HPLC-technology (HP 1050, UV detector, Nova-Pak C18 column). The main attention was given to formaldehyde and acetaldehyde.

With the spark-ignition light-duty cars, hydrocarbons from C1 to C8 were measured from diluted exhaust gas with a HP 5890 Series II gas chromatograph (AL2O3, KCl/PLOT column). Samples of diluted exhaust gas were taken automatically through direct lines from the same CVS tedlar bags used for the analysis of regulated emissions. Thus the test was divided into the same sub-cycles as described previously for regulated emissions. The measured compounds were as follows: methane, ethane, ethene, propane, propene, acetylene, isobutene, 1.3-butadiene, benzene, toluene, ethylbenzene and xylenes. The main attention was given to methane, 1.3-butadiene, benzene and BTEX (sum of benzene, toluene, ethylbenzene and xylenes).

2.3 PARTICLE SIZE MEASUREMENTS

2.3.1 General

This project included both particle mass and number size measurements. Figure 3 shows an example of mass and number size distributions of diesel exhaust and the nomenclature of different size classes [5].

Particles below some 50 nm are called nucleation mode particles. They may consist of condensed hydrocarbons, sulfates, water, metals and ash. Nanoparticles tend to combine with other particles and grow in the atmosphere. Even if the number of nanoparticles would be high, mass of particles at that size class is low.

The particles from about 50 nm to 2.5 µm are called accumulation mode particles. They consist of soot, organic carbon, combustion derived sulphates, nitrates, adsorbed hydrocarbons, metals, ash, PAHs etc. The accumulation mode particles represent the major part of the particle mass emission from diesel engine. However, if nucleation mode exists, typically the number of accumulation mode particles is low when compared to the number of nanoparticles.

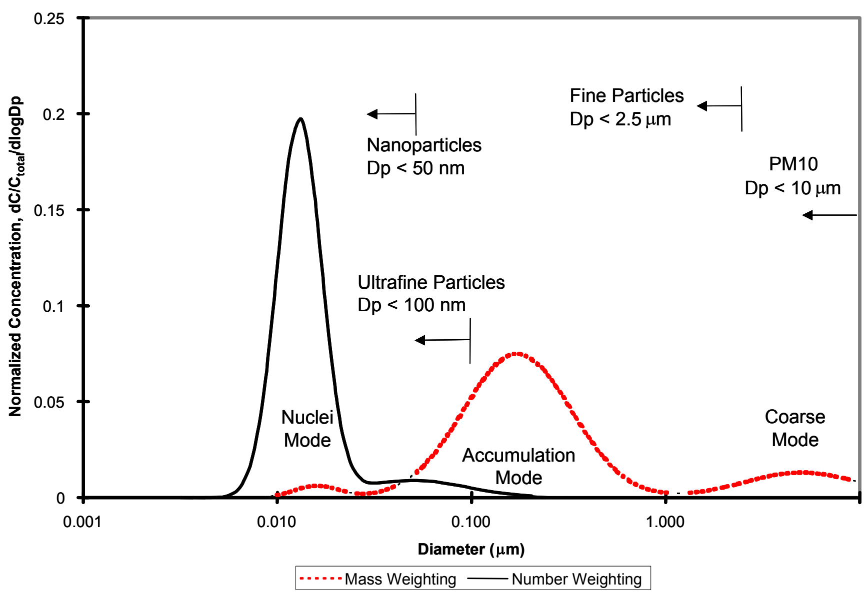


Figure 3. Schematic Figure of number and mass size distribution with both nucleation and accumulation mode, diesel exhaust gas [5].

2.3.2 Dilution system

There is a steady flow of reports published on the diluters and the effect of dilution parameters on the particle sizing results. There are several different diluter types that could be used to dilute the exhaust gas for the particle sizing measurements, e.g. full flow and partial flow dilution tunnels, ejector-type, rotating disk, and porous tube diluters. All of these different techniques have benefits and drawbacks. The standard dilution tunnel is not the best way to dilute exhaust gas in the particulate number measurements, as usually the dilution ratios are low and residence times long [5]. The ejector type diluters are capable to fast dilution with relatively short residence times, but one limitation is the requirement to heat the first diluter to avoid blocking of the nozzle.

The purpose of this research was to study the effect of low ambient temperature on particle emissions, and thus it was decided that cold dilution air should be used in the tests at low temperatures. The porous type diluter was chosen for these tests mainly due to feasibility of using cooled dilution air. The basic principle of porous diluter (PD) is described e.g. by Mikkanen [6]. The dilution air penetrates the wall smoothly through a wide area within PD. The PD that was used in these tests has been previously studied at VTT showing that the particle number results were rather insensitive to dilution ratio at higher dilution ratios [7].

For the medium-duty engine, both mass and number size distributions were measured from raw exhaust using a porous tube diluter (Figure 4). A similar arrangement was used for the number size measurements for the light-duty vehicles, however, mass size distributions were measured from the CVS diluted exhaust gas (Figure 5). Raw exhaust gas was drawn from the exhaust line (insulated) as close to the cold test cell as possible, but a significant length of transfer tube could not be avoided. However, the lines were as short as possible and only the materials suitable for particle measurements were used. The residence time from exhaust pipe to the measurement equipment was about 0.6 s (idle about 1 s) with medium-duty engine, and with the light-duty cars about 0.8-2.2 s depending on vehicle speed.

In the medium-duty tests, all temperature and fuel combinations were tested with the dilution ratio of 25, except some additional tests at +23 °C with the dilution ratio of 10 to collect enough particle mass. With light-duty cars, the target dilution ratio was 40. However, with gasoline fuelled cars dilution ratio of 10 was also screened due to low particle concentration. With diesel engine and cars the dilution ratio was calculated with NO_x concentrations measured from the raw and diluted exhaust gas in one-second intervals, and for other cars CO_2 concentrations were used. The concentrations were measured from the raw and diluted exhaust gas in one-second time intervals during the test cycle and the true dilution ratio was used in the calculations.

Dry and clean dilution air was used. Dilution air at room temperature was used in the tests at 23 °C. Dilution air was cooled in the tests at low temperatures to 0…-2 °C to mimic low ambient conditions. The effect of cold dilution air on the particle number results was studied in the pre-tests with the medium-duty engine (Figure 6). It was noted that the number of particles below 30 nm was higher with cold dilution air than without cooling. Pre-tests were conducted also to study the porous diluter used in these tests (Figure 7). The particle number size results were rather similar with the dilution ratios of 25 and 55 with only slight difference in the size class below 30 nm.

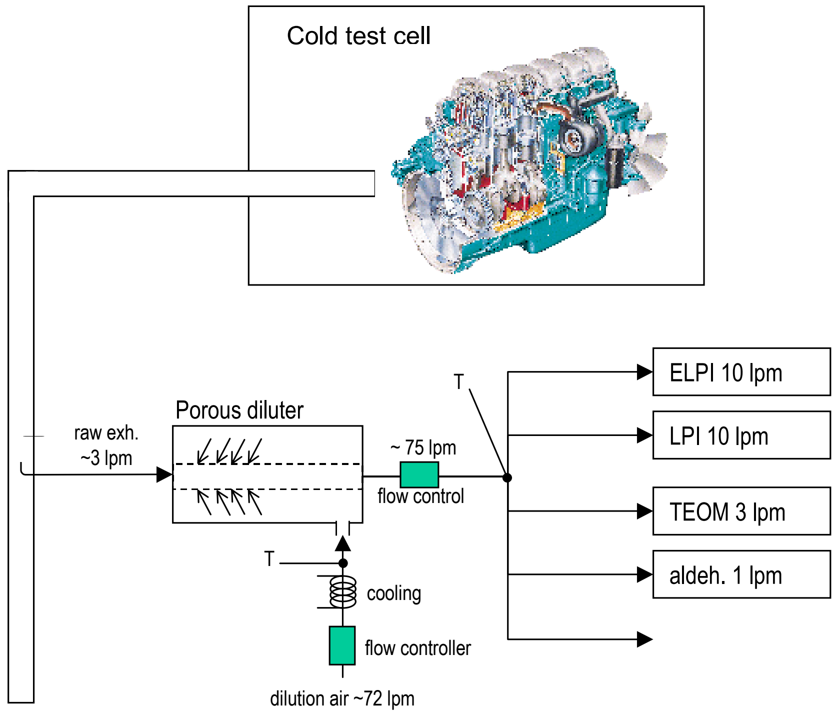


Figure 4. Medium-duty engine, schematic figure of the dilution system.

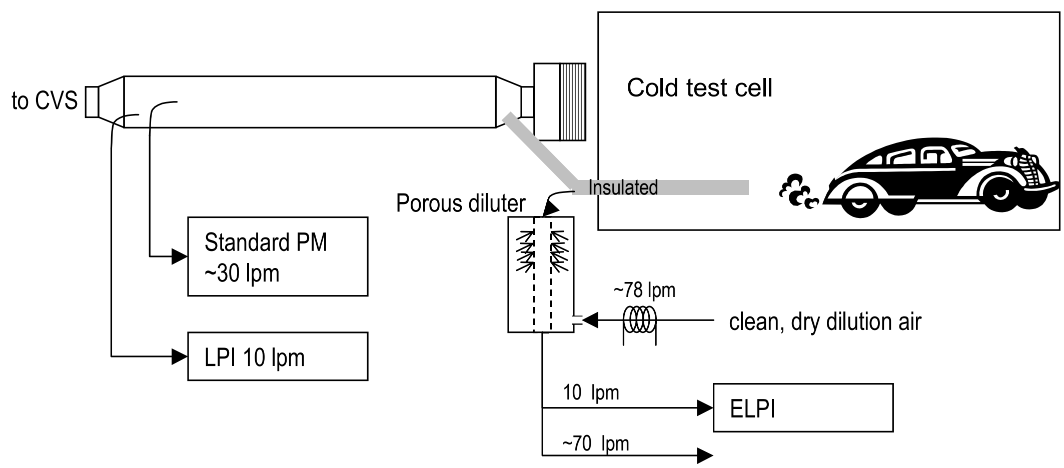


Figure 5. Light-duty cars, schematic figure of the dilution system.

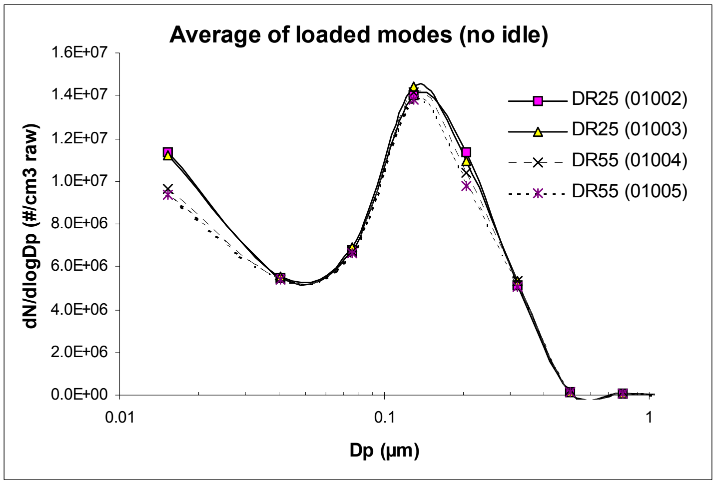


Figure 6. The particle number distribution with two dilution ratios using porous tube diluter (average values of last minute of each load mode). Medium-duty engine.

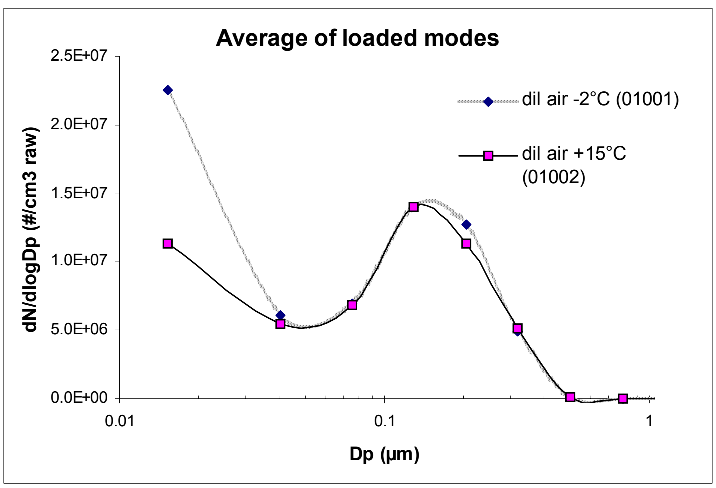


Figure 7. The effect of cooling of the dilution air on the particle number distribution over the test cycle at normal test temperature (average of last minute of each load mode).

2.3.3 Electrical Low Pressure Impactor (ELPI) and Low Pressure Impactor (LPI)

Particle number distributions were measured with the ELPI (Electrical Low Pressure Impactor) manufactured by Dekati Ltd. The principle of ELPI is based on charging, inertial classification and electrical detection of aerosol particles. The ELPI is a real-time particle size spectrometer, which measures airborne particulate size distribution in the size range of 30 nm – 10 µm. When equipped with a "Filter Stage" the lowest cut diameter is about 8 nm (geometric mean diameter about 15 nm at the filter stage). Technical data of the impactor used with ELPI is shown in Table 8.

The performance of ELPI has been extensively studied. The studies include comparisons to e.g. SMPS [i.a. 8, 9, 10, 11]. There are certain differences between the results obtained by ELPI and SMPS due to different measurement principles. SMPS system was not an option in this study as cold start is a transient condition, which practically cannot be monitored with the SMPS system.

The particle mass distribution measurements were conducted with a low pressure impactor (LPI) manufactured by Dekati Ltd. Technical data of the impactor is shown in Table 9. An "end-filter" was used in LPI to collect the particles below 30 nm.

Table 8. Technical data of the impactor (#2137) used in the ELPI measurements.

Stage	Cut diameter D50% (µm)	Geometric* D_g (µm)	dlogD50%	Pressure (kPa)
filter stage	0.008	0.015	0.559	
1	0.029	0.041	0.293	10.00
2	0.057	0.076	0.248	21.94
3	0.101	0.129	0.213	37.66
4	0.165	0.205	0.189	68.31
5	0.255	0.317	0.188	89.41
6	0.393	0.500	0.210	97.45
7	0.637	0.794	0.191	99.73
8	0.99	1.26	0.211	100.57
9	1.61	1.99	0.184	101.04
10	2.46	3.13	0.208	101.20
11	3.97	5.15	0.227	101.24
12 (not in use)	6.69			101.29
	10.15			101.32

* *geometric mean diameter*

Table 9. Technical data of the LPI (# 247) used in the particle mass distribution measurements.

Stage	Cut diameter D50% (µm)	Geometric* D_g (µm)	Pressure (kPa)
1	0.029	0.042	10.00
2	0.059	0.079	21.83
3	0.103	0.132	38.37
4	0.166	0.207	68.32
5	0.256	0.319	89.01
6	0.395	0.503	97.17
7	0.641	0.800	99.72
8	1.00	1.270	100.56
9	1.62	1.995	100.04
10	2.47	3.137	101.20
11	4.00	5.177	101.26
12	6.73	8.267	101.30
	10.21	12.360	101.32

* *geometric mean diameter*

2.3.4 Particle mass concentration, TEOM and ELPI

A TEOM 1400a instrument was used with the medium-duty engine to evaluate the suitability of this instrument to monitor continuous particulate mass concentration. The weighing principle used in TEOM is based on the tapered element, which vibrates at its natural frequency. An electronic control circuit senses the vibration and adds sufficiently energy to the system to overcome losses, so that the vibration stays at constant amplitude. The calibration constant for the equipment has been determined by measuring vibration with and without a known mass. TEOM 1400a has been developed for the measurements in the ambient air. It is capable to measure mass concentrations from below 5 $\mu g/m^3$ to several g/m^3. Another model, namely TEOM 1105, is developed specially for the exhaust emission tests, and it has been used successfully in the transient tests with the light-duty cars (data from the representative of manufacturer). However, TEOM 1105 was not available for the tests.

In principle, TEOM 1400a can monitor mass concentrations every two seconds. However, TEOM 1400a appeared to be too slow to monitor particle concentration in the transient conditions. A number of measurements were conducted showing only a few reasonable results. Even the most successful experiments (Figure 8) showed that TEOM 1400a did not response fast enough. The particle concentration seemed to be too low in the conditions other than cold start with 2-seconds monitoring frequency. Thus TEOM 1400a was not suitable for these measurements.

The ELPI particle number results can be converted to mass results. However, this calculation requires information on the particle density. Research on particle density and effective density at different size classes from the exhaust gas has been carried out [e.g. 9, 10, 12]. These studies have shown that the density of particles depends on the size class. In addition, density probably depends on the quality of exhaust gas, which vary with different engine/aftertreatment technologies, loads and test conditions.

Research work comparing TEOM and ELPI mass concentrations have shown rather good comparability for the emissions from boilers [13, 11]. In this study, total particle mass concentration was monitored based on ELPI results (particles below 2.5 µm) using unit particle density (1 g/cm^3) in the conversation. An example of the TEOM result compared to converted ELPI results is shown in Figure 8. In this case the mass concentration based on the ELPI results was at the same level as the results measured with TEOM 1400a. However, the absolute values of number to mass converted ELPI results cannot be considered accurate, even though they are useful in screening some general trends.

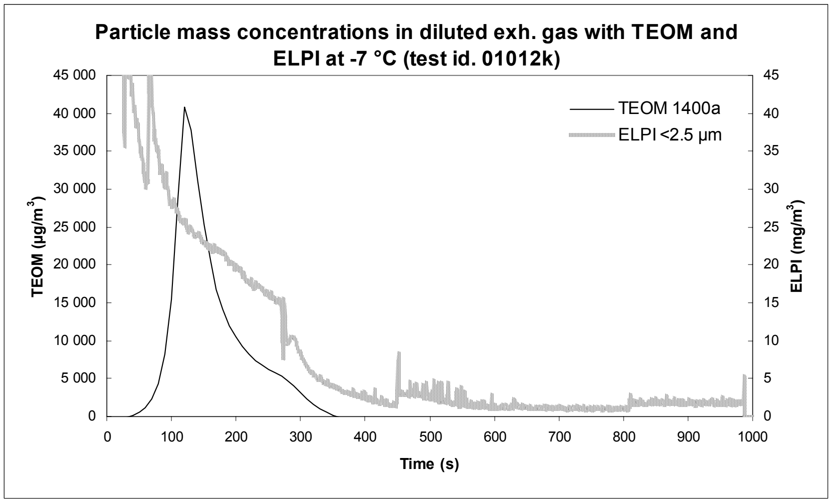


Figure 8. Particle mass concentrations in diluted exhaust gas measured with TEOM 1400a and ELPI (number converted to mass).

3 RESULTS WITH MEDIUM-DUTY ENGINE

3.1 TEST PARAMETERS AND GASEOUS EMISSIONS

Selected engine parameters, regulated gaseous emissions and aldehydes are shown in Figures 9-12. Normal stabilised temperature of engine oil was about 80 °C, which was not reached at 0 and -7 °C over the 16-minute test cycle. Similarly, the temperature of exhaust gas stayed at lower level at 0 and -7 °C than at normal temperature over the cycle. Temperature of coolant reached the normal temperature after 10-minute running.

The CO and HC emissions after the cold-start at low test temperatures were high when compared to the stabilized emission level at +23 °C. The HC concentration exceeded 1400 ppm in the beginning of the test at -7 °C (well below 200 ppm at +23 °C), and the CO emission reached even 5000 ppm values. However, the CO and HC concentrations at low temperatures decreased sharply as engine warmed up being rather close to the "normal" after some 5-minute running period. On the average the HC emission was 1.3-1.9 and the CO emissions 1.9-2.3 times higher at -7 °C than at +23 °C over the 16-minute test cycle. The effect of temperature on the HC and CO emissions was generally consistent with all fuels studied (some benefit in HC for the RFD and RFD/RME fuels).

The NO_x concentrations were lower at low test temperatures than at +23 °C. This trend was not seen in the NO_x mass emissions over the test cycle due to humidity correction factor, which was used only at +23 °C.

Formaldehyde, acetaldehyde and total aldehydes were about 10 times higher at -7 °C than at +23 °C with all fuels studied. Formaldehyde and acetaldehyde represented about

80 % of the total aldehydes. In some cases the RME blended fuels seemed to produce slightly higher aldehyde emissions than the base fuels.

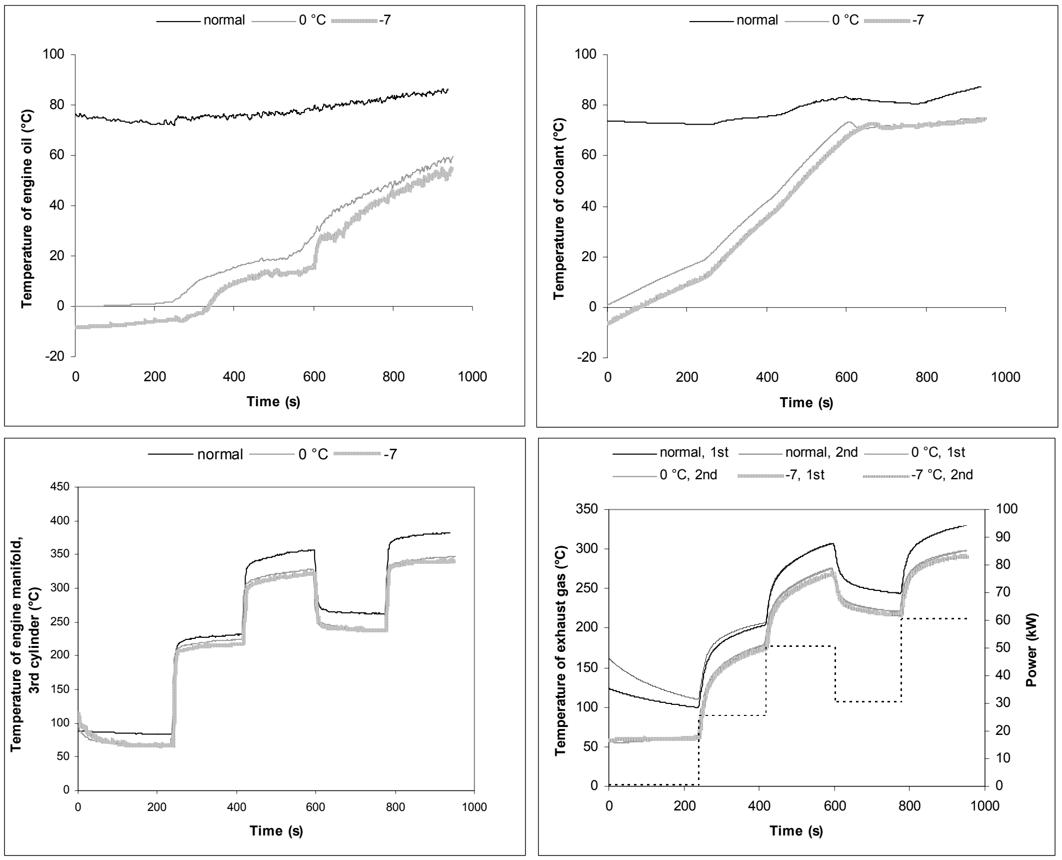


Figure 9. Selected engine parameters, the medium-duty engine with the EU2000 fuel.

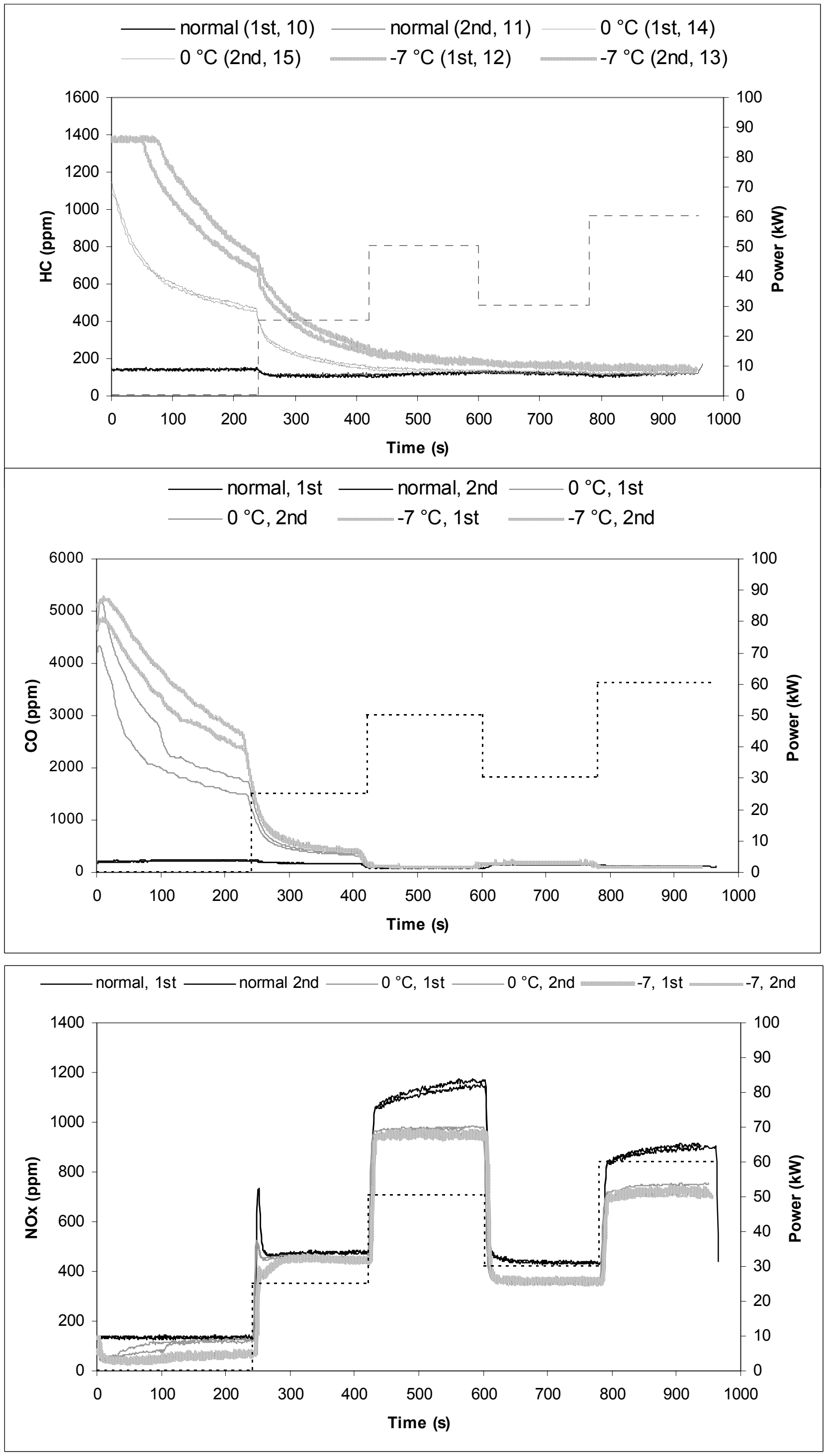


Figure 10. CO, HC and NO_x concentrations, medium-duty engine.

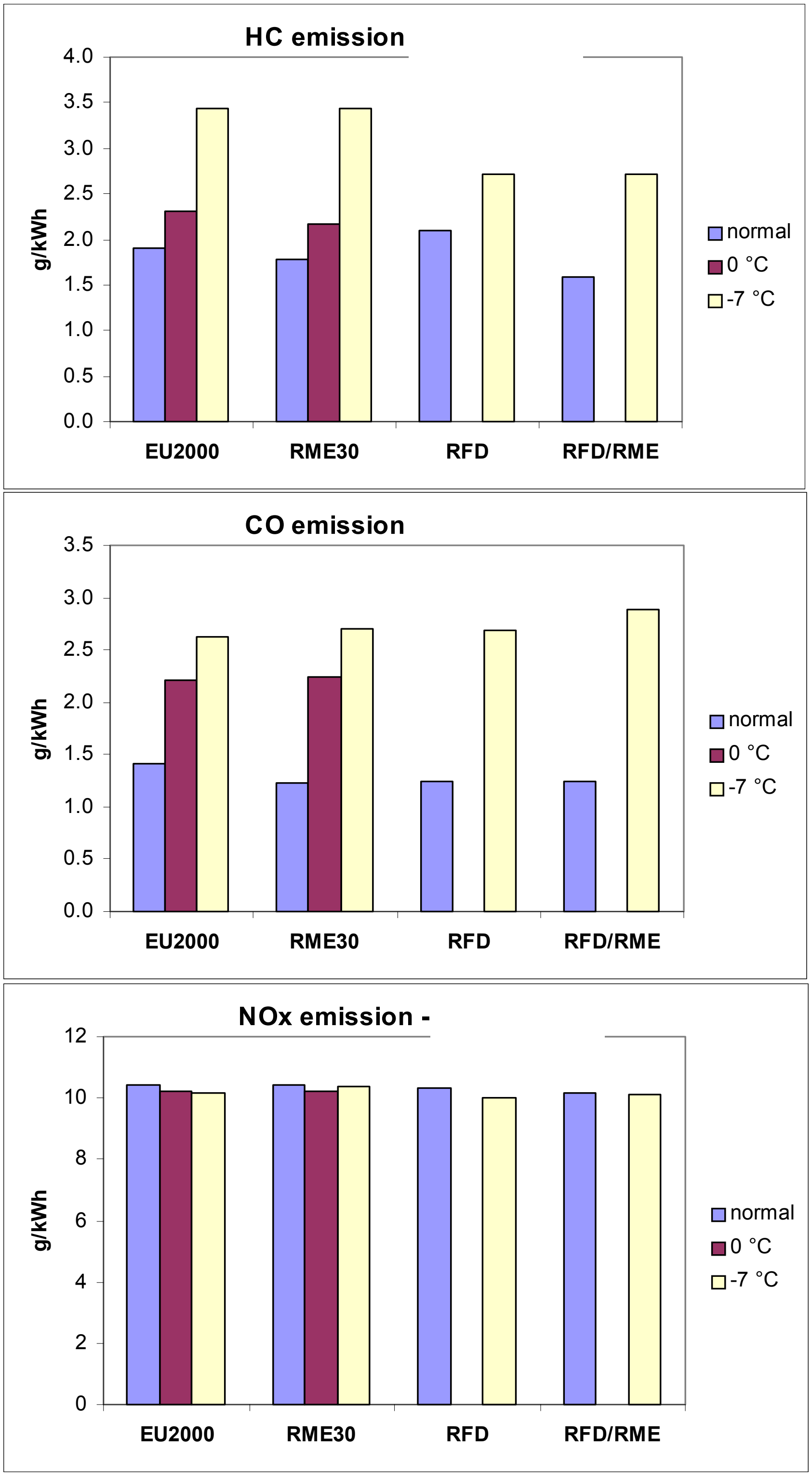


Figure 11. Regulated gaseous emissions, medium-duty engine.

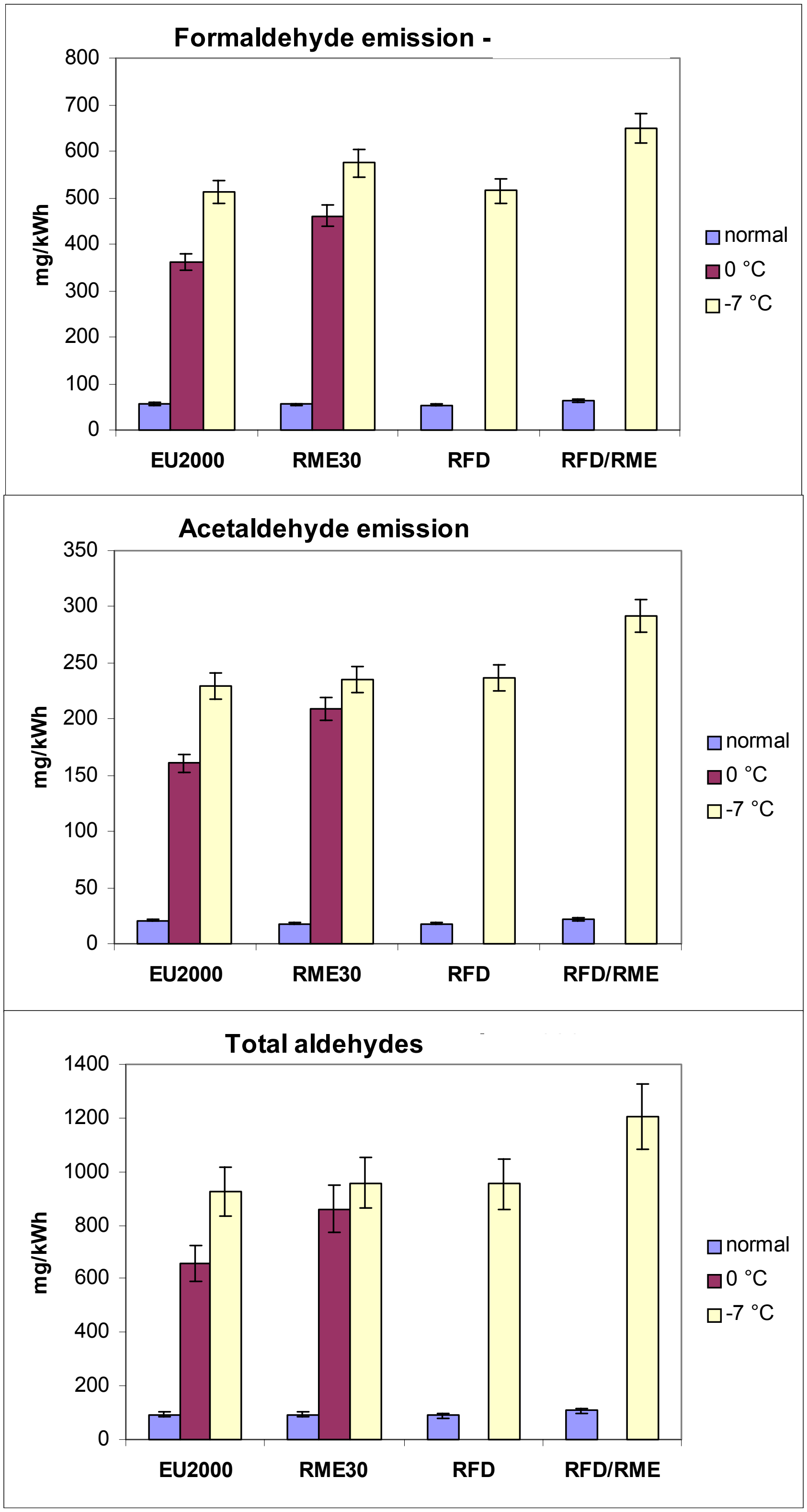


Figure 12. Aldehyde emissions with the medium-duty engine.

3.2 PARTICLE MASS EMISSIONS

The total particle mass emissions measured with impactor are shown in Figure 14. The particle mass emission level was about 7 times higher with the hydrocarbon fuels and about 11 times higher with the RME blended fuels at -7 °C than at +23 °C over the 16-minute test cycle. The RME blended fuels produced lower particle mass emissions than respective hydrocarbon fuels at +23 °C.

The particle mass flow results (ELPI number to mass conversion) are shown in Figure 13. The particle mass flow was high after the cold start at -7 °C and decreased sharply as engine warmed up reaching the normal level after about 5-minute running. At +23 °C test temperature the RME blends seemed to produce lower particle emission than the base fuels, but higher emission at low test temperature after cold-start.

The particle mass distribution results with the low pressure impactor are shown in Figure 15. The peak of particle mass distribution was around 0.2 μm regardless of the test temperature or fuel. The high particle mass emissions at low temperatures were seen as higher peak values. The EU2000 resulted in a “shoulder” in the distribution curve at -7 °C temperature.

Some differences in particles were seen visually from the impactor plates: particles were like dry “soot” at normal test temperature (Figure 16). The particles with the EU2000 fuel at -7 °C temperature were widely spread, which might indicate high share of hydrocarbons (“wet” particles). The particles with the RME30 fuel at -7 °C were spread as well, but not as smoothly as with EU2000 fuel. RME is an ester of long chain fatty acids, which may not spread so easily.

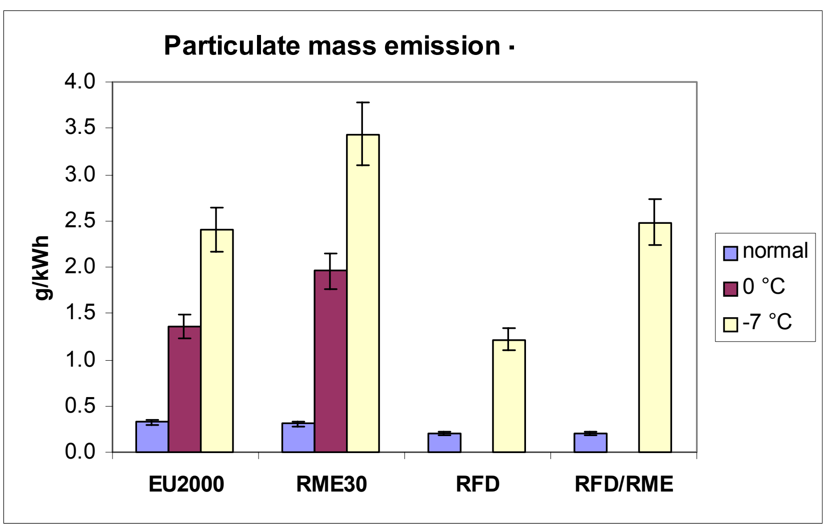


Figure 13. Particle mass emission over the 16-minute test cycle,medium-duty engine.

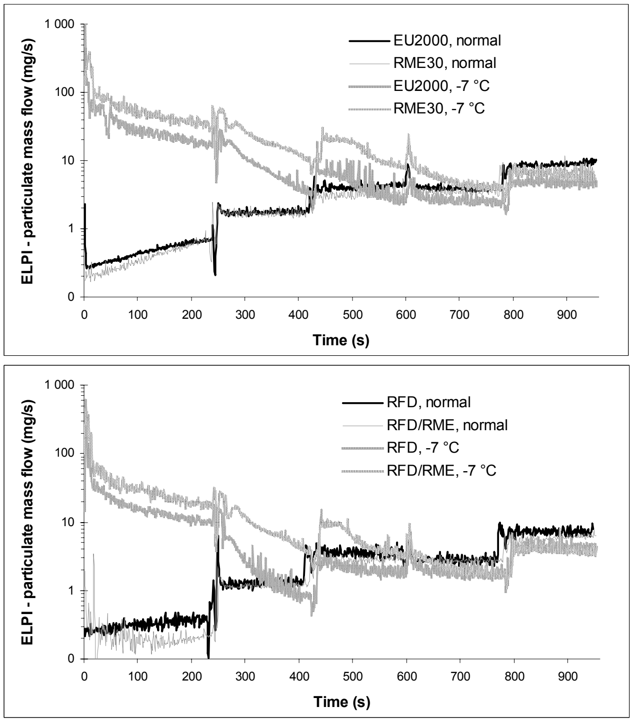


Figure 14. Particle mass flow (ELPI number to mass,) medium-duty engine.

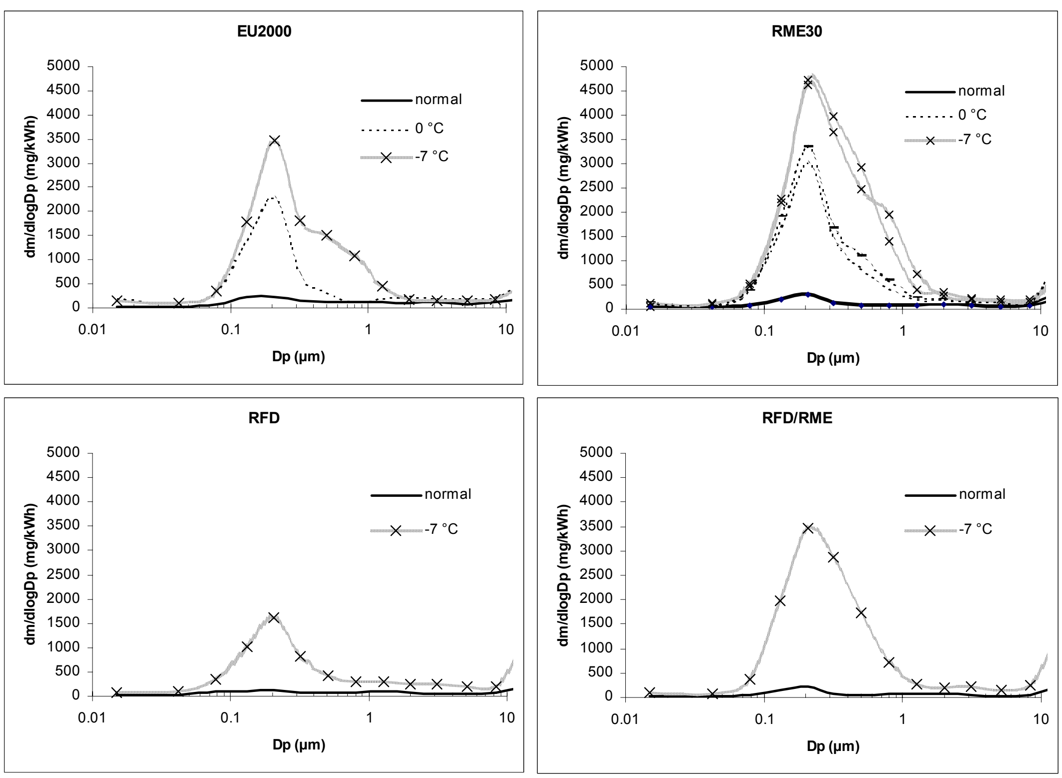


Figure 15. Particle mass distribution results, medium-duty engine.

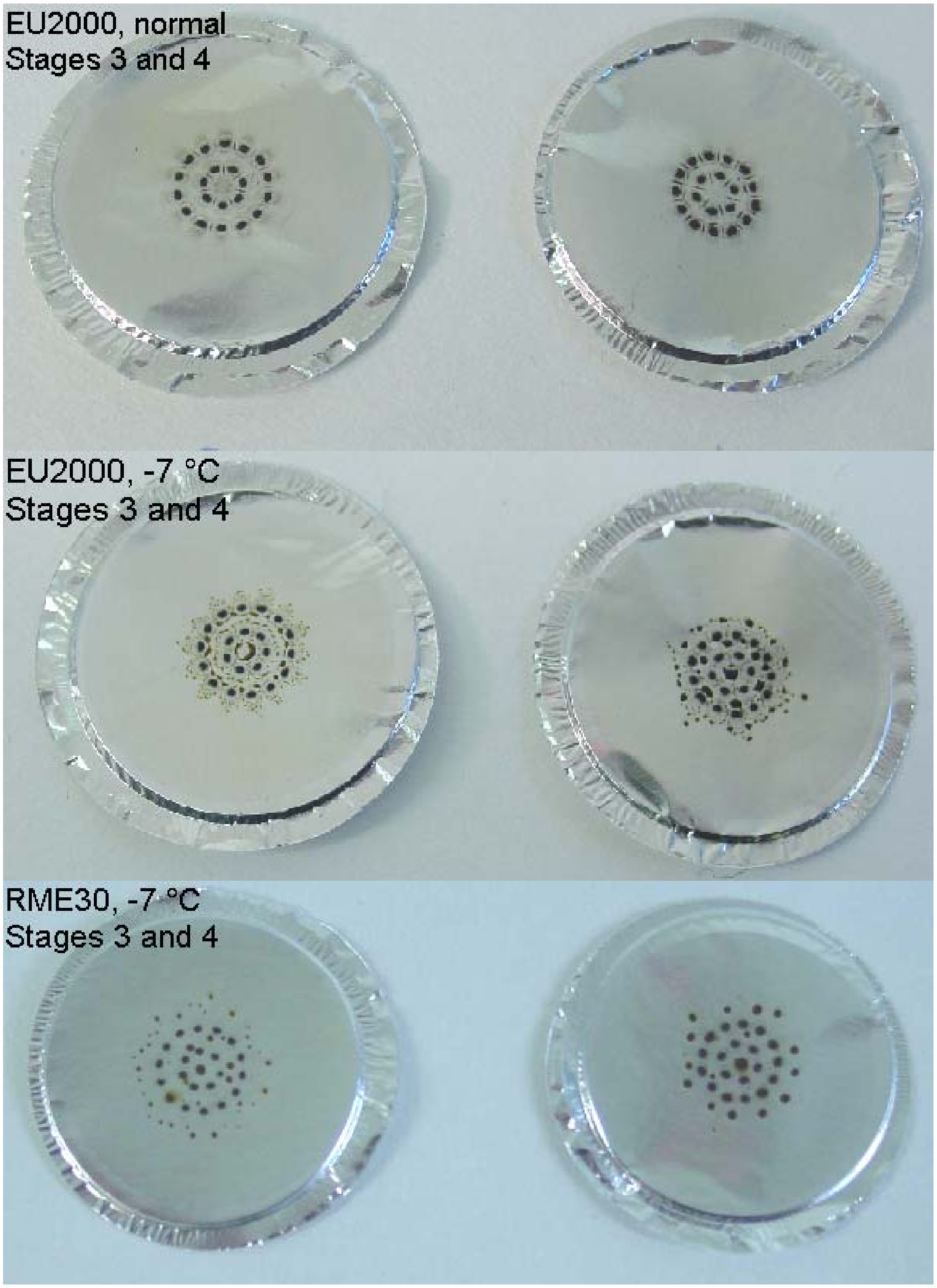


Figure 16. The stages 3 and 4 from low pressure impactor measurements with the medium-duty engine.

3.3 PARTICLE NUMBER EMISSIONS

3.3.1 The effect of load

The total particle number results with the EU2000 and RFD fuels at normal temperature with engine fully warmed-up are shown in Figure 17. The RFD fuel acted differently from EU2000 fuel producing a low number of nanoparticles at idle. A closer look at the different loads (idle excluded) using the EU2000 fuel is shown in Figure 18. The number of particles in the accumulation mode was higher at higher engine speed.

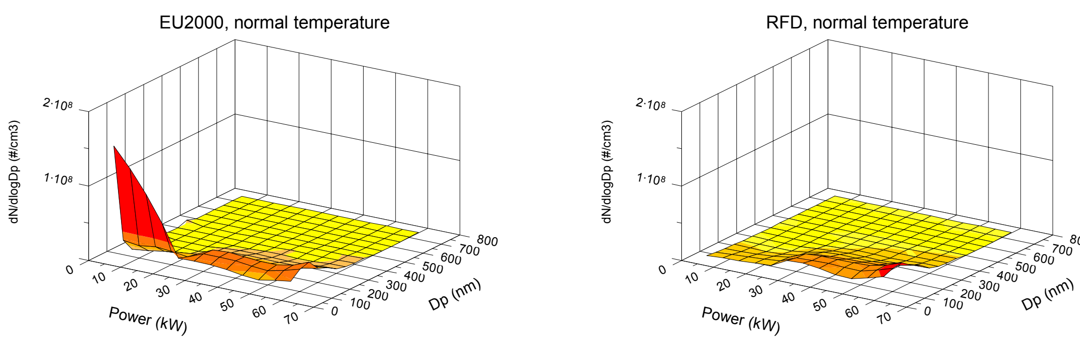


Figure 17. Number of particles at different loads tested, medium-duty engine.

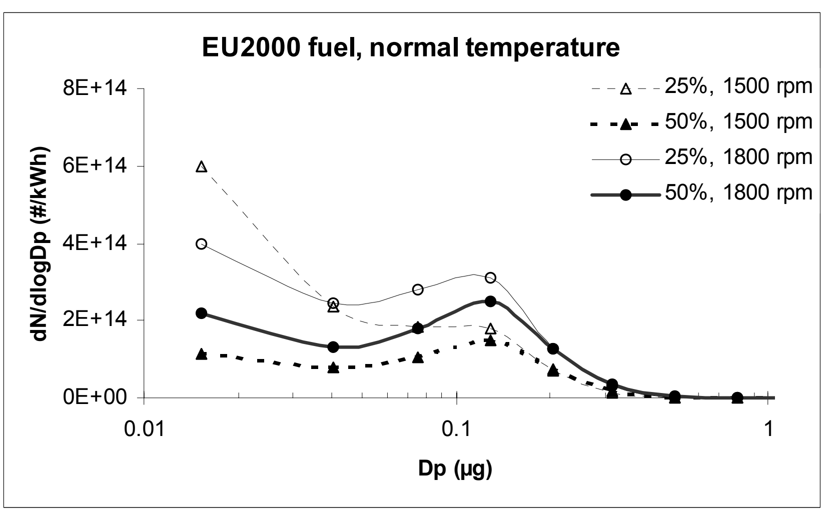


Figure 18. Particle number results at different loads, medium-duty engine.

3.3.2 The effect of temperature and fuel

The particle number level was high after the cold-start at low test temperatures, and it took about 10 minutes before the level decreased near to normal (Figure 19). The particle number flow was at higher level with the RME blends than with respective hydrocarbon fuels at some loads conditions (especially at 50% load).

Figures 20 and 21 show the particle number results at different size classes. The increase in the number of particles at low test temperatures was seen for particles both below and over 60 nm (nucleation and accumulation mode). The number of particles below 60 nm was about twice as high at -7 °C as at normal test temperature, and about 5-9 times higher in the size class over 60 nm, respectively.

When the smallest particles (<60 nm) were concerned the effect of temperature seemed to be more emphasized for RFD than for other fuels, and RME30 seemed to produce more particles than the EU2000 fuel. For the accumulation mode (>60 nm) the RME blends showed higher number of particles than the respective hydrocarbon fuels at low temperatures, whereas at +23 °C no significant difference was seen. The RFD fuel showed the lowest number of accumulation mode particles.

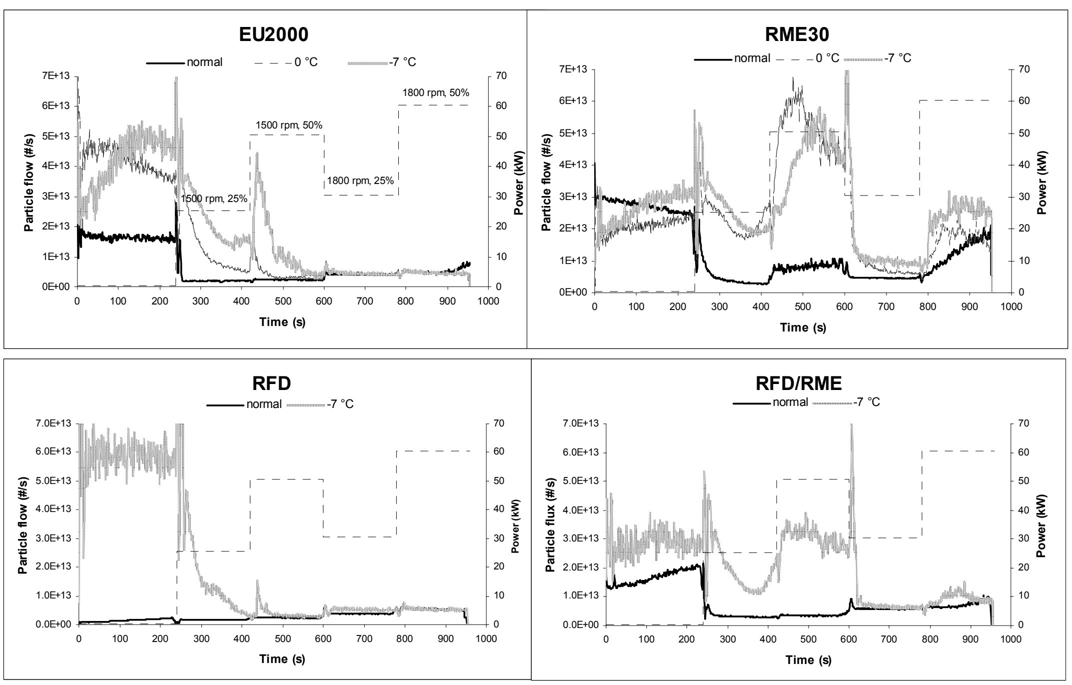


Figure 19. Particle number flow, medium-duty engine.

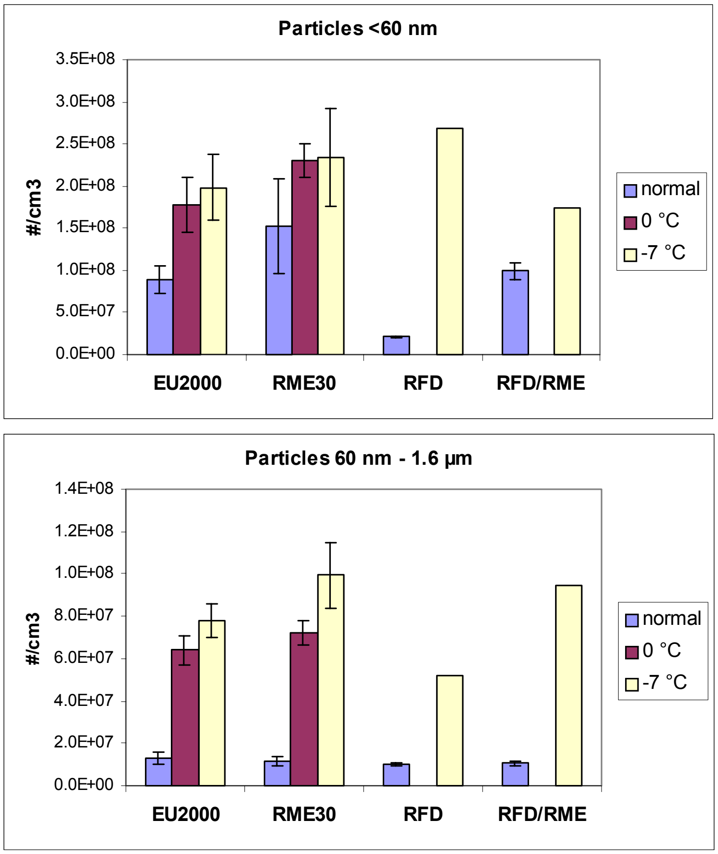


Figure 20. Number concentration of particles in two size classes, medium-duty engine.

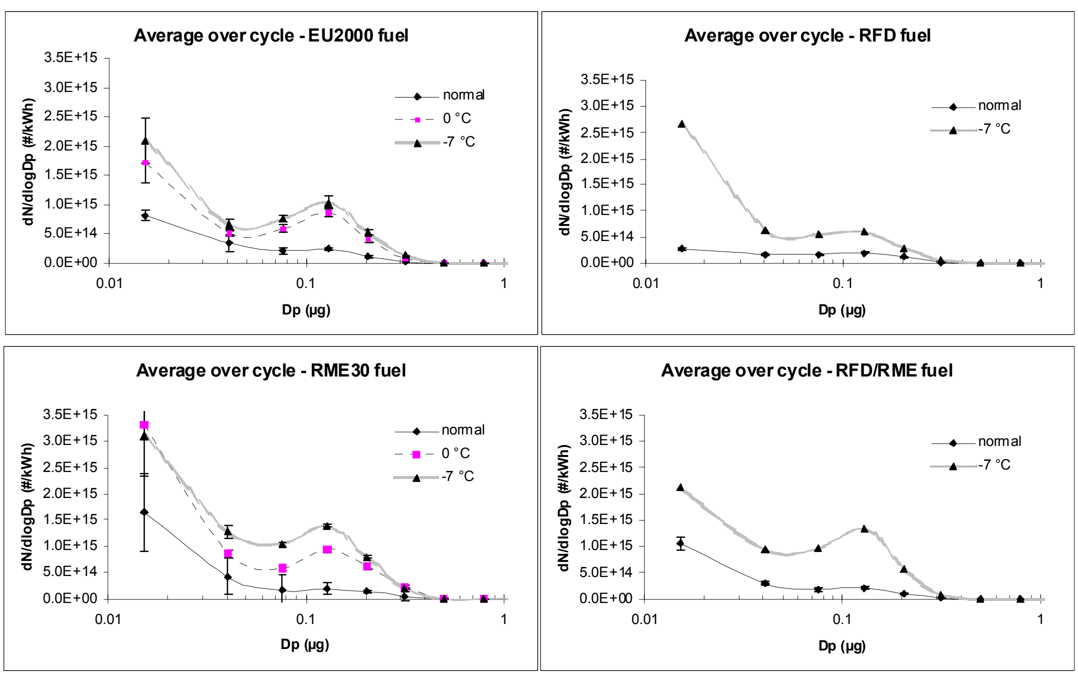


Figure 21. Particle number distributions over the 16-minute cycle, medium-duty engine.

The results were not consistent over the warm-up period of engine, which can not be seen in the average results (Figures 20-21). Thus the distributions at two selected load modes are shown in Figures 22 and 23. In several conditions RME blended fuels produces a higher number of particles below 60 nm than the respective hydrocarbon fuels, but not in the beginning of the test at low temperatures. RFD fuel resulted in higher number of the smallest particles (<60 nm) than the other fuels in the beginning of the test at -7 °C, but the lowest level after about 7 minutes. The relationship between the fuel and the particle number results seems to be complicated. The benefits obtained in the beginning of the test could be lost after some 10 minutes.

As a summary, it can be concluded that the effect of temperature on particles with the medium-duty engine was clear and seen both in the particle mass and number results. The total hydrocarbon emissions were huge in the beginning of the test at low temperatures. It is assumed that an increase in particle mass and number emissions at low temperatures was related to the condensed hydrocarbons.

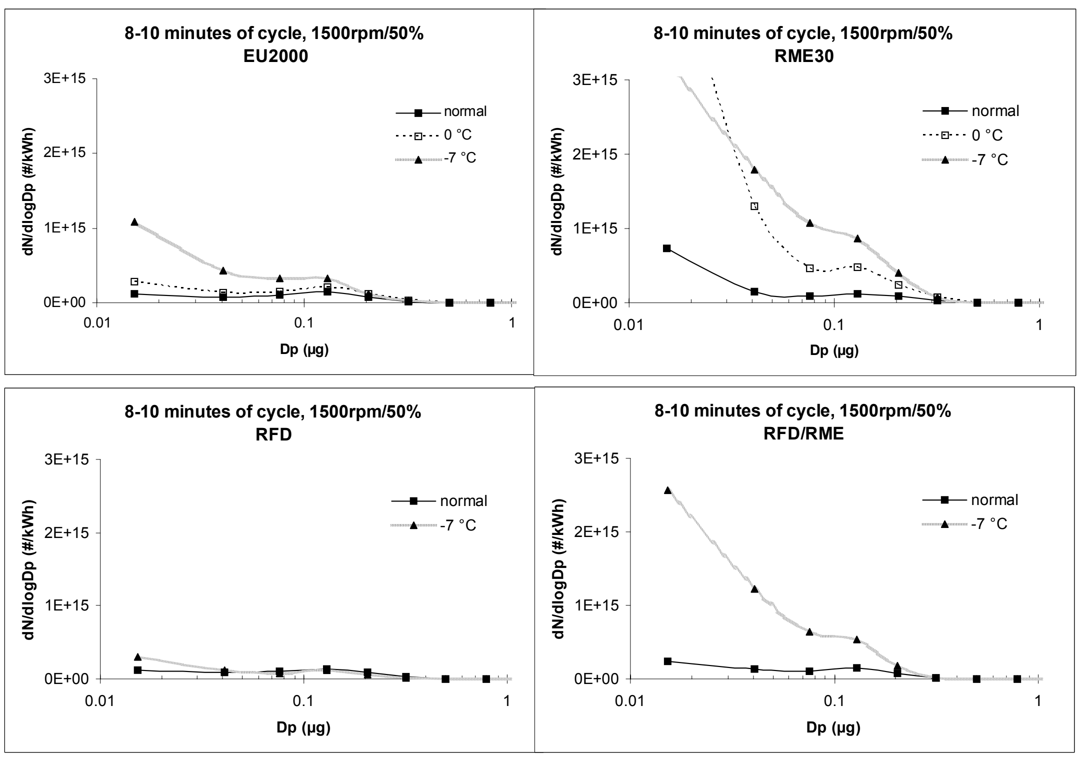


Figure 22. Particle number distributions after 8 minutes at 1500 rpm/50% load.

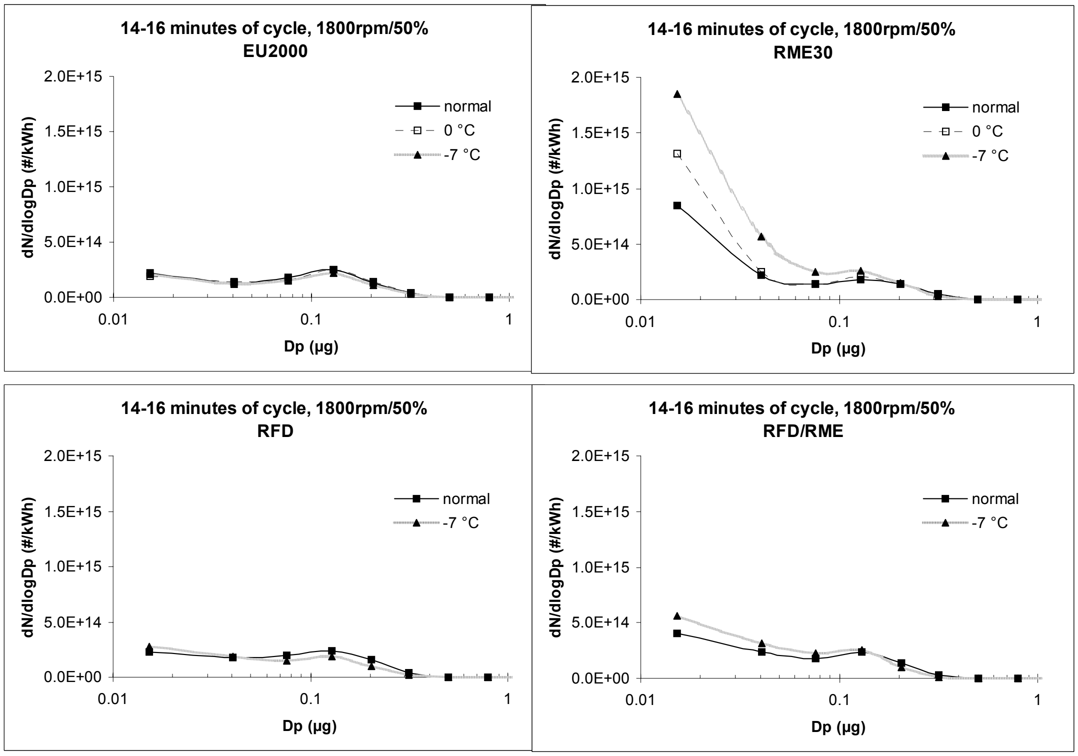


Figure 23. Particle number distributions in the end of the tests at 1800 rpm/50% load.

4 RESULTS WITH CARS

4.1 GASEOUS EMISSIONS

4.1.1 CO, HC and NO_x emissions

The CO, HC and NO_x emissions at different temperatures over the European test cycle are shown in Figure 25.

The CO and HC emissions were at low level at normal temperature with all cars tested. Diesel and CNG fuelled cars were more or less insensitive to test temperature, whereas gasoline, E85 and LPG fuelled cars showed drastically higher CO and HC emission level at +5 and -7 °C than at +23 °C due to enrichment of fuel to air ratio and operation of catalyst.

NO_x emission level of diesel cars is higher than for the gasoline, ethanol or gas fuelled cars. The NO_x emission increased as the test temperature decreased with the major part of the cars. Conventional diesel cars typically show a decrease in NO_x emission at low temperatures. However, these diesel cars were equipped with the EGR system, which does not operate properly when engine is cold.

For cars other than diesel, the higher CO, HC and NO_x emissions at low temperatures are typical due to operation of three-way catalyst. However, E85 fuelled FFV car did not produce more NO_x at low than at normal temperature. Low temperature and enrichment of fuel to air ratio diminish formation of NO_x emission. For FFV car enrichment of fuel to air ratio was highest (seen from CO and HC emissions), which may explain low NO_x emission at low temperatures. For CNG car, there is no enrichment, which is seen as high increase in NO_x emissions when lowering the test temperature.

Continuous HC concentration is shown as an example for diesel, MPI and CNG cars in Figure 27. The peak in HC emission was seen during the first minutes of the test. If the effect of temperature was seen, it took also place immediately after the start of the car. Figure 27 shows how insensitive the CNG car was towards temperature even in the beginning of test.

Extensive study of alternative fuel/engine concepts was carried out within IEA/AMF Annex V [14]. It was interesting to compare the regulated emissions of the cars studied in this work to older cars studied in Annex V. The regulated emissions for MPI, E85 and CNG cars in this work were significantly lower than the emissions from the respective cars studied in Annex V. For diesel cars, the regulated gaseous emissions observed in this work and in Annex V were at the same level. LPG car of this work showed similar emission level at normal test temperature, but worse performance at cold temperature, than the LPG cars of Annex V.

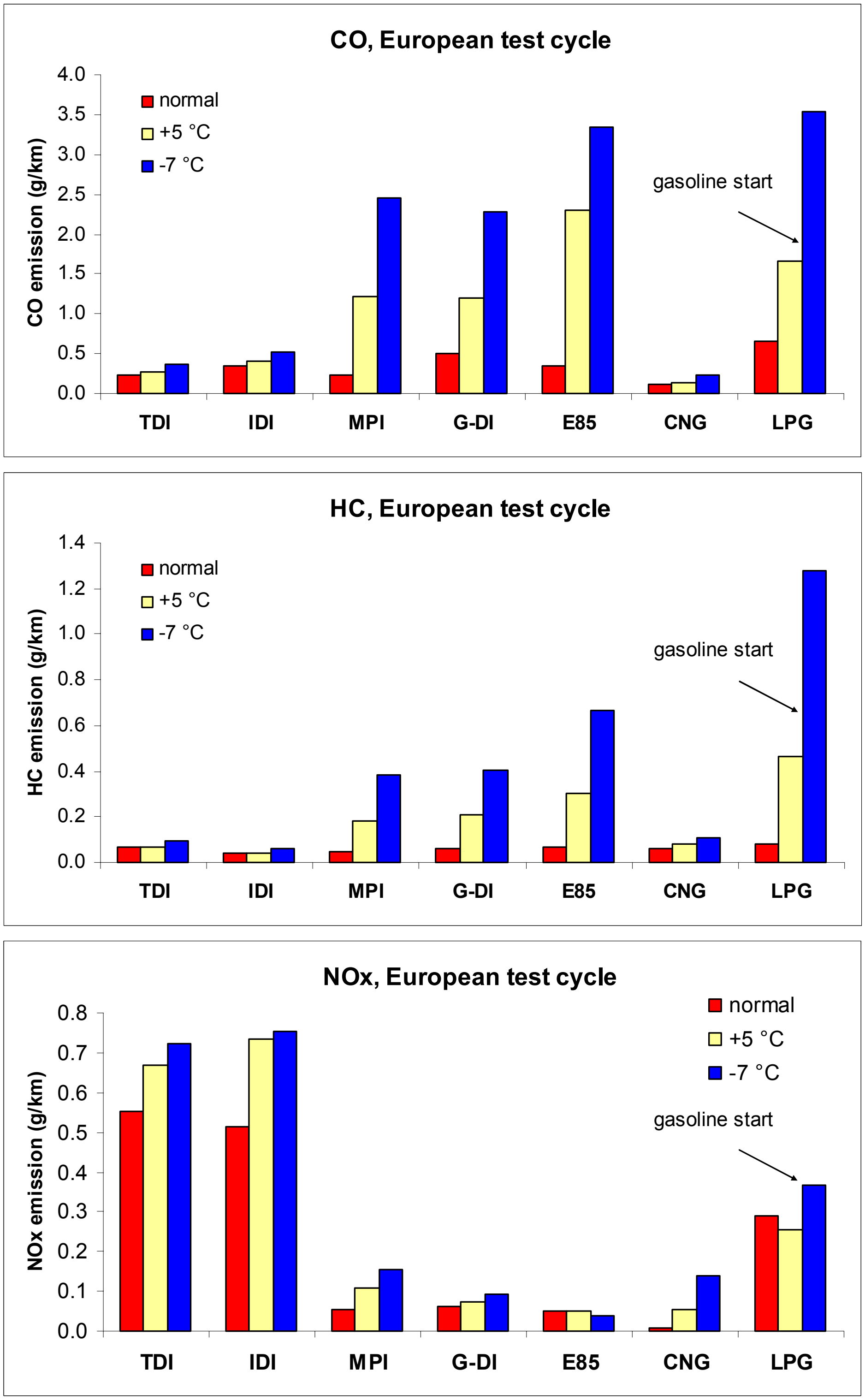


Figure 24. Regulated gaseous emissions over the European test cycle, light-duty cars.

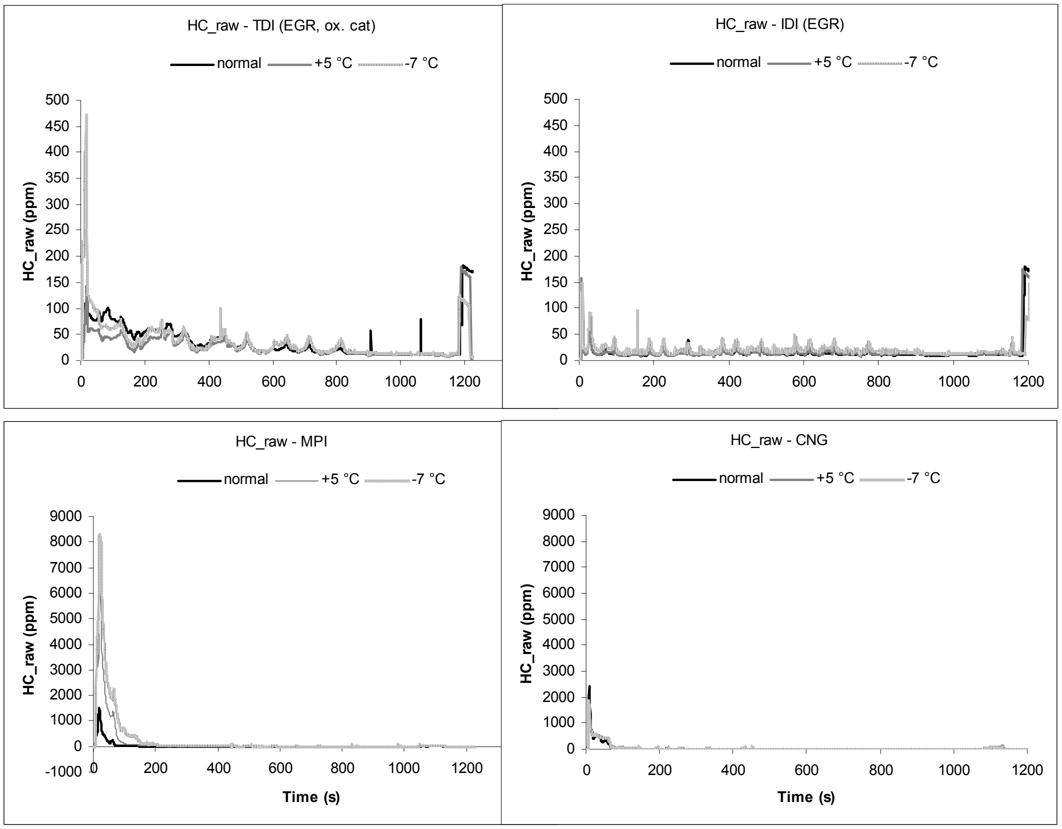


Figure 25. Continuous raw exhaust gas concentrations of CO, HC and NO_x during the European test cycle.

4.1.2 Aldehydes and speciated hydrocarbons

Aldehyde emissions were low, except acetaldehyde emission with E85 fuelled FFV car. Figure 26 shows that formaldehyde emission was below 2.5 mg/km with all cars at all temperatures. The Californian standard gives maximum formaldehyde limit of 8 mg/mile (~5 mg/km) for ULEV cars. This limit cannot be directly compared to these tests as the test cycle is different, but it gives a view of the lowness of formaldehyde level from the cars tested. Typically formaldehyde and acetaldehyde represented about 85-95% of the total aldehydes analyzed.

Probably due to low aldehyde emission level, the effect of temperature was not consistent in all cases. For diesel and E85 fuelled cars formaldehyde emission increased as the test temperature decreased. However, gasoline, CNG and LPG fuelled cars showed even lower formaldehyde emission at low test temperature than at normal temperature.

The effect of temperature on acetaldehyde emission followed in general similar patterns as was seen for formaldehyde emission. However, acetaldehyde emission with E85 fuelled FFV car was naturally higher already at normal test temperature than with other cars and increased up to almost 16 mg/km at -7 °C.

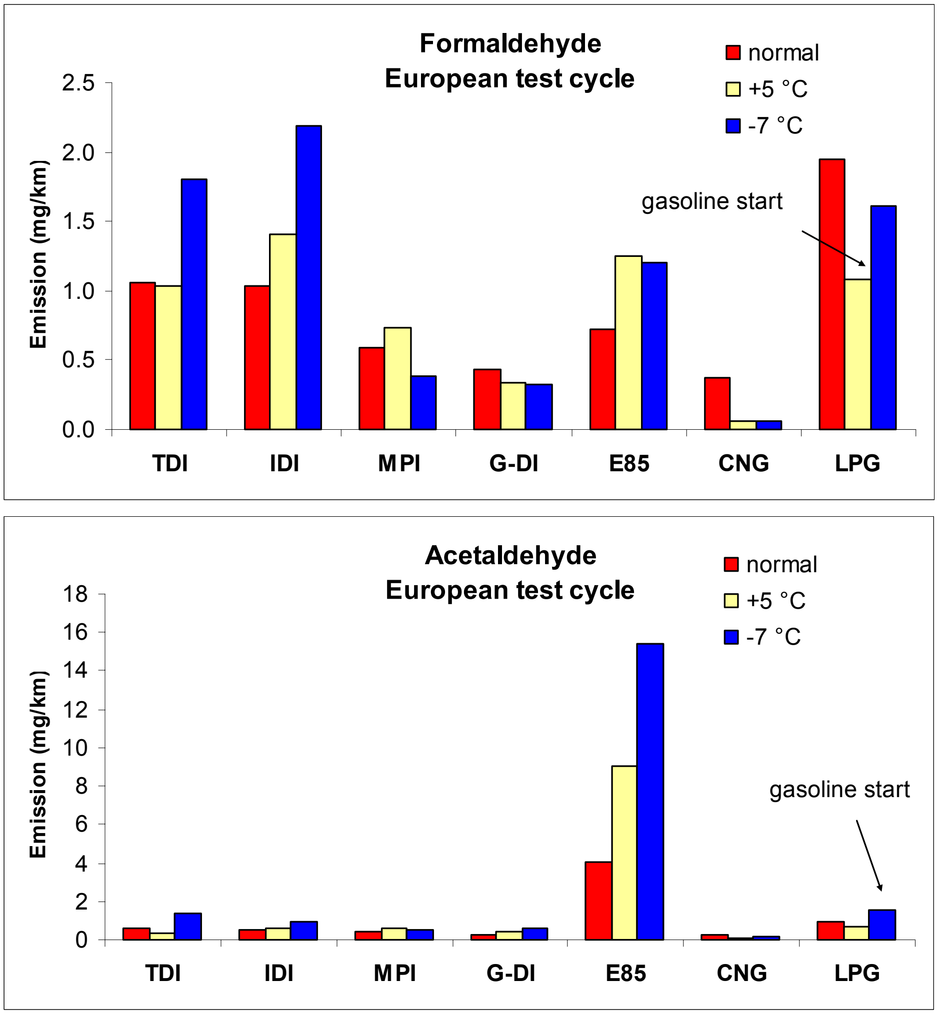


Figure 26. Formaldehyde and acetaldehyde emissions, light-duty cars.

Methane emission from the CNG car was higher than that from the gasoline, E85 or LPG fuelled cars (Figure 27). The total hydrocarbon emission, on the other hand, was at the same level as with the other cars (previous Chapter). The total hydrocarbon emission with CNG car consisted almost solely of methane.

1,3-butadiene emission was negligible for the CNG car. LPG car showed lower 1,3-butadiene emission than MPI, G-DI or E85 cars at normal temperature, but at -7 °C vice versa. BTEX emissions were negligible for the CNG car. MPI, G-DI and E85 cars showed similar level of BTEX emissions at normal temperature. BTEX emission with LPG car was lower than with gasoline or E85 fuelled cars at normal temperature, but opposite was seen at low test temperature.

When the individual hydrocarbons from MPI, G-DI, E85, CNG or LPG cars are considered, they were strongly influenced by the test temperature before the warm-up of the catalyst. The influence of test temperature was highest for the LPG car.

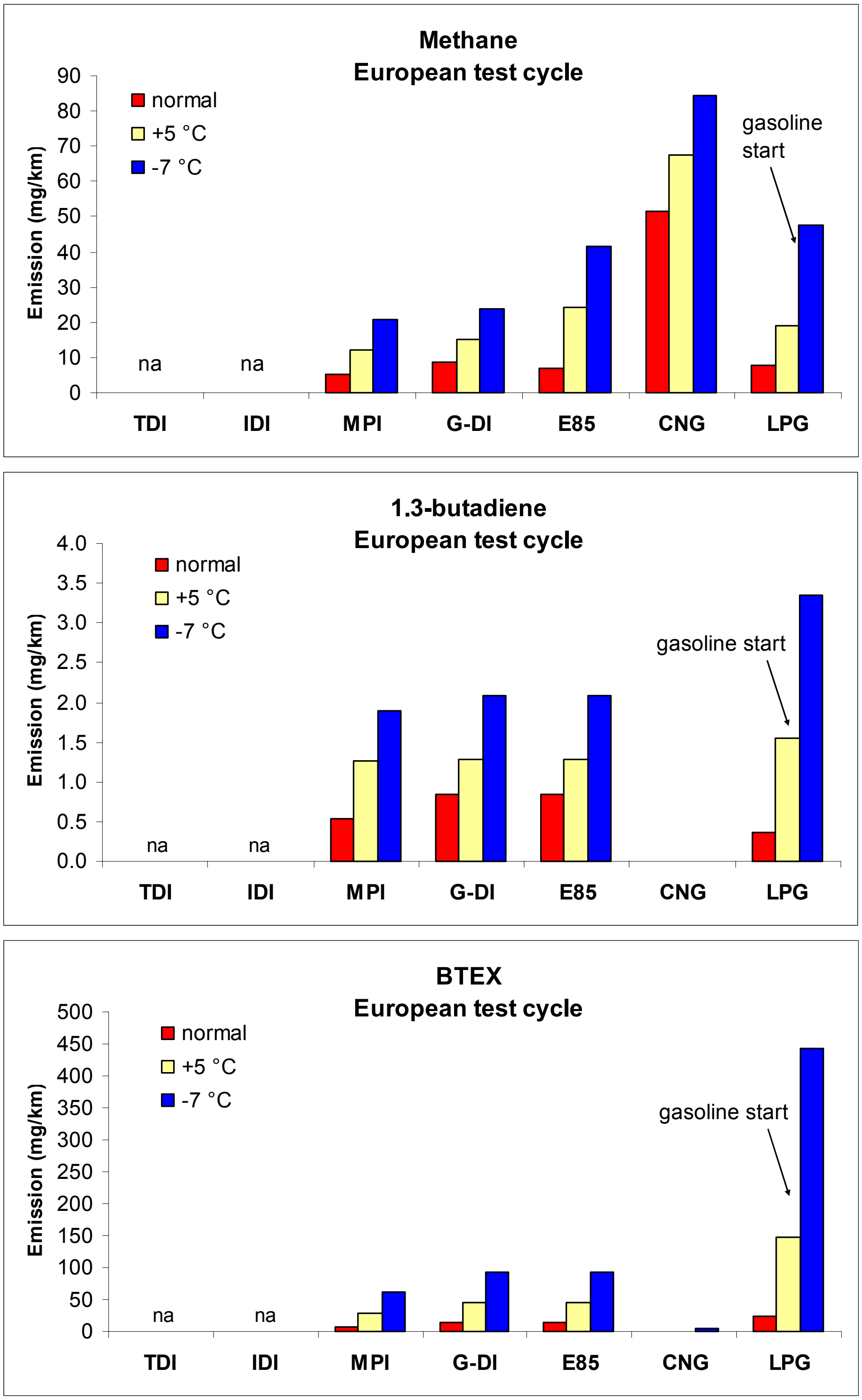


Figure 27. Methane, 1,3-butadiene and sum of benzene, toluene, ethylbenzene and xylenes over the European test cycle, light-duty cars.

4.2 PARTICLE EMISSIONS

4.2.1 Particle mass emissions

The total particulate mass results over the European test cycle are shown in Figure 28, and in the different test phases for diesel cars in Figure 29.

The particulate mass emissions were higher with diesel cars than with gasoline, E85, CNG or LPG fuelled cars. For MPI, E85, CNG and LPG cars the particulate matter emission was close to the detection level at normal test temperature. PM emission from G-DI car (~10 mg/km) was much higher than for MPI car (~1 mg/km).

The particulate mass emissions from the MPI, E85 and LPG cars were higher at -7 °C test temperature than at normal test temperature, whereas the emission from the CNG car stayed at the "zero" emission level at all temperatures. PM emission from G-DI car was not influenced by test temperature, which is better result than reported with some direct-injection gasoline cars [3]. PM emissions at +5 °C were close to emissions at normal temperature with other cars than IDI and LPG cars.

The particulate mass emission increased as test temperature decreased with the TDI car. With IDI car there was a decrease in PM or no effect as temperature decreased when the emissions over the test cycle were considered. When the emissions in the different test phases were studied, it was seen that the particulate mass emission increased as test temperature decreased in the beginning of the test (ECE 1) with both cars. With the TDI car the difference in PM emission at different temperatures diminished as the engine warmed up. For the IDI car, the low test temperature gave a positive effect on the particulate mass emission over the EUDC test phase when using EU2000 fuel.

A closer look on the particulate mass emission in the first and last 400 seconds of the test cycle is given in Figure 30 (ELPI particle numbers converted to mass emissions).

The first peak of particles with the TDI car was higher at low temperatures than at +23 °C. After the first acceleration the particulate flow level was only slightly higher at low temperature than at +23 °C temperature.

With the IDI car there was no huge peak of particulates in the beginning of the test at low test temperatures. The difference in PM emission at different test temperatures seemed to accumulate gradually over the test.

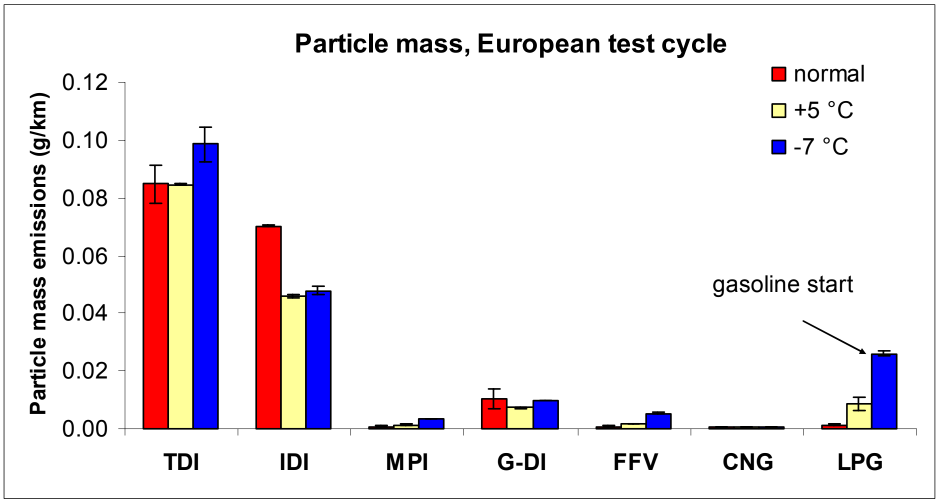


Figure 28. Total particulate mass emission over the European test cycle, light-duty cars.

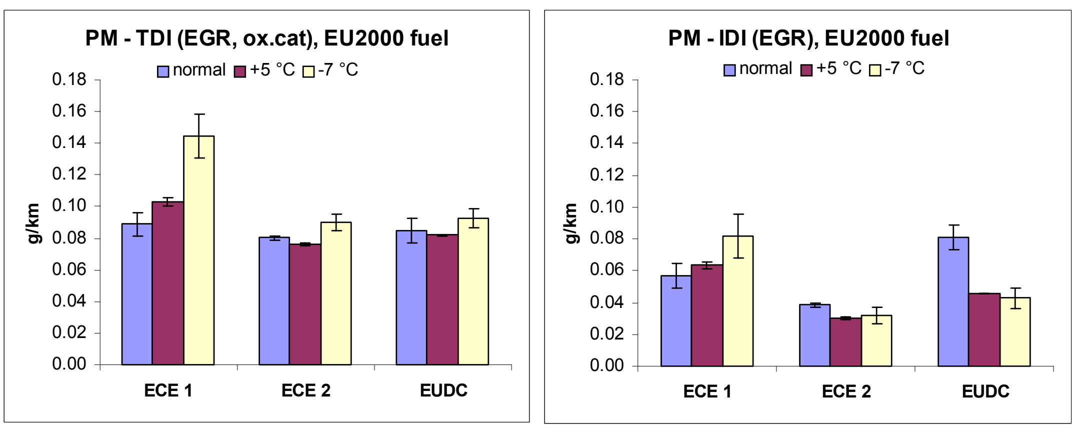


Figure 29. Particulate mass emission at different phases of the European test cycle with diesel cars (fuel EU2000).

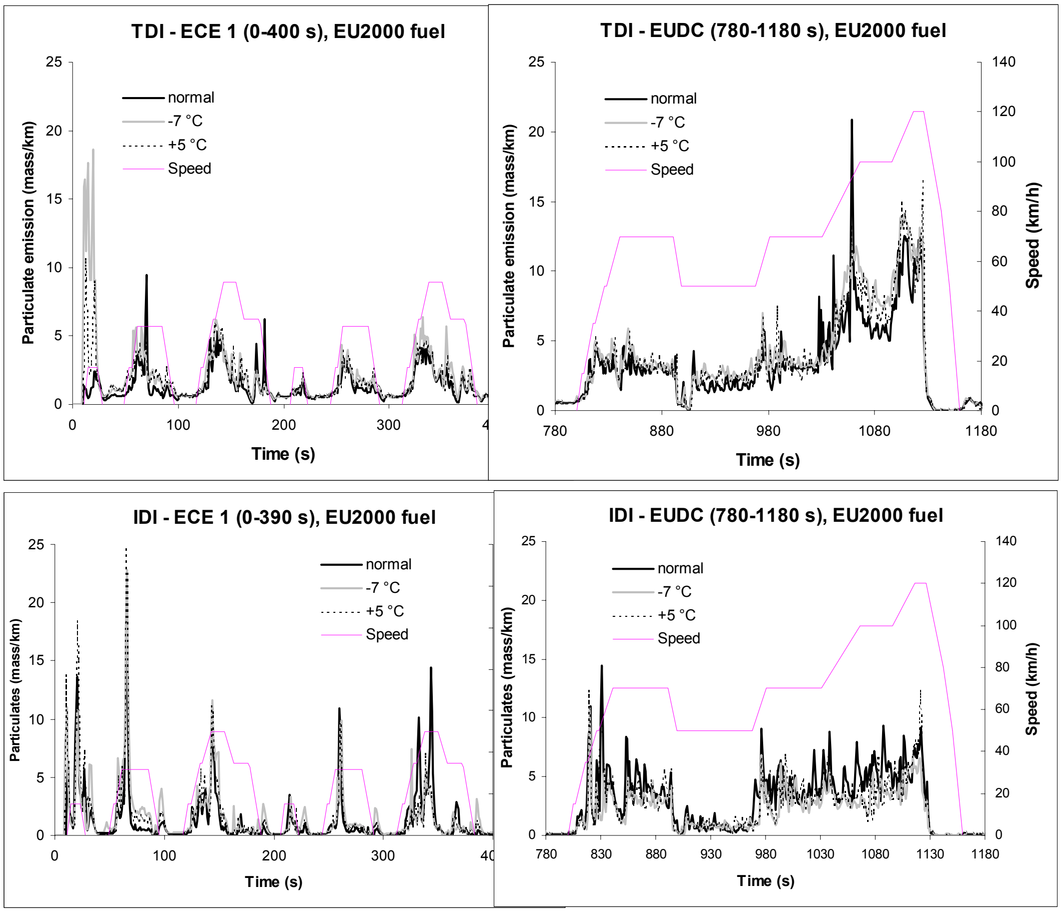


Figure 30. Particle mass emission with the TDI and IDI car in the beginning and in the end of the European test cycle at different test temperatures using EU2000 fuel (ELPI data converted to mass emissions).

The particle mass distribution measurements were conducted with the low-pressure impactor (LPI) by collecting the particulates of the first 13 minutes of the European test cycle (ECE 1&2). The EUDC part of the test cycle was excluded to emphasize the effect of cold-start.

With diesel cars particulate mass emissions calculated from the LPI stages 1-12 were compared with standard particulate mass emission result (Figure 31). Generally, the particle mass collected with LPI correlated well with the standard PM results from European test cycle phases ECE 1&2, which is an indication of reliability (quality) of the LPI measurements. The two measurements with the highest deviation were obtained with the TDI car at -7 °C using the RME30 and RFD/RME fuels.

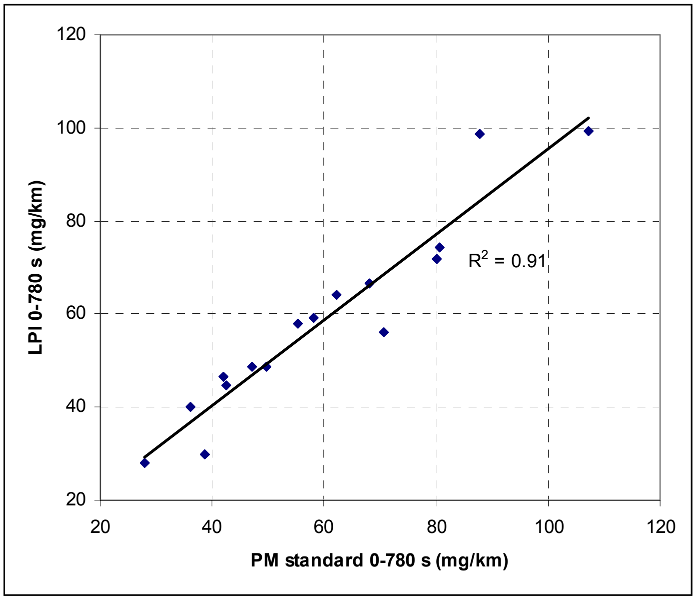


Figure 31. Correlation between the particle mass emission results (PM) obtained with standard collection system and LPI in the ECE 1&2 phases, 0-780 s.

The particle mass distribution results are shown in Figure 32. With diesel cars, the particle mass emission was higher and the peak broader shifting median to higher particle size at -7 °C when compared to the results at +23 °C temperature when using EU2000 fuel.

For other cars than diesel the particle mass distribution measurements indicated similar result as was seen for the total PM emission: G-DI showed measurable mass at all temperatures, whereas the MPI, FFV and LPG cars showed measurable masses only at -7 °C. CNG car did not show any measurable particle mass emission.

The shape of the distribution curve was not changed at lower temperatures with G-DI car. For MPI, FFV and LPG cars such comparison of shape is not possible as particle mass level was too low at normal temperature. However, the peak with these cars at –7 °C seemed to be at slightly higher size class than with diesel or GDI cars.

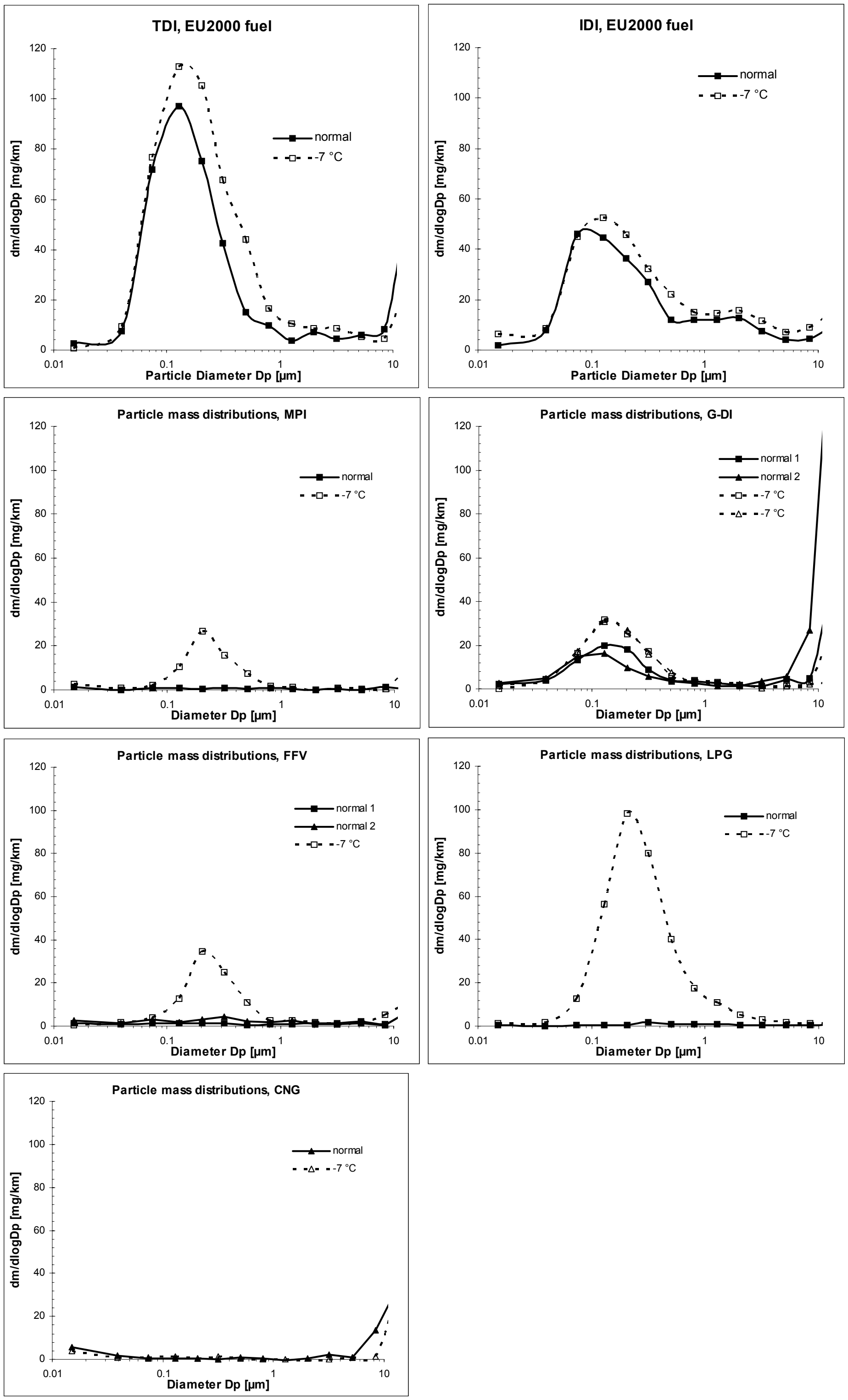


Figure 32. Particle mass size distributions with diesel, MPI, G-DI, E85 (FFV), CNG and LPG cars over ECE 1&2 phases of the European test cycle.

4.2.2 Particle number emissions

4.2.2.1 Results over the European test cycle

Figure 33 shows the number size distribution results and Figure 34 the total number of particles from the different cars over the European test cycle.

The number of the accumulation mode ("soot") particles over the European test cycle was really low with the other cars when compared to diesel cars. G-DI and LPG cars showed accumulation mode particles at –7 °C (G-DI also at +23 °C). Also MPI and E85 cars showed some particles at -7 °C, even though it is difficult to observe from Figure due to scale adjusted for diesel cars. The number of particles for the CNG car is considered to be insignificant at all test temperatures. Clear nucleation was not seen with any of the cars when the results over the test cycle are considered. The IDI car showed the highest number of particles at the lowest size class of ELPI (Dg ~15 nm).

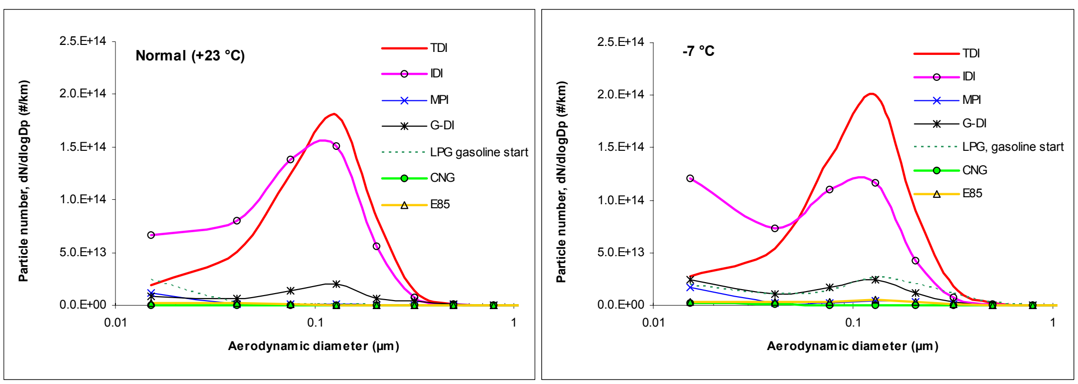


Figure 33. Particle number size distributions over the European test cycle at +23 °C and -7 °C temperatures, light-duty cars.

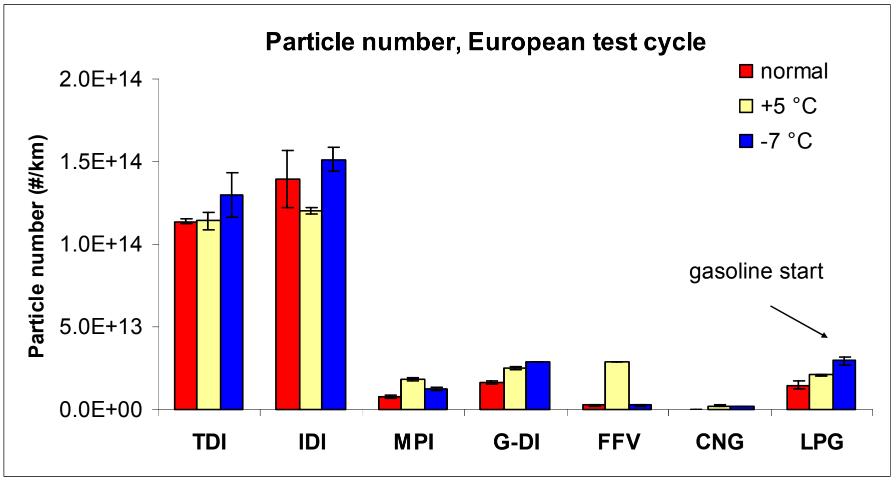


Figure 34. Total particle number emissions over the European test cycle at different temperatures, light-duty cars.

4.2.2.2 Particle number results at cold-start and with warmed-up engine

The flow of total particles and particle number distributions over the ECE 1 (cold-start) and EUDC (warmed-up engine) test phases of the European cycle are shown in Figures 35-37.

With both diesel cars, the flow of total particles followed in general the speed of cars. With the TDI car, a peak in the particle number flow was seen in the beginning of the test at -7 °C when using the EU2000 fuel, but after that very slight difference was seen.

With the IDI car, similar peak after cold-start at -7 °C as with the TDI was not seen. The difference in particle number flow between +23 and -7 °C temperatures seemed to accumulate gradually over the test cycle. However, a more detailed study showed that e.g. order of number of particles in the size class of 15 nm and 70 nm varied with driving conditions (different kind of particle number distributions).

With MPI, E85 and LPG cars peaks in particle number flow were seen in two conditions: after the start of the car and at high-speed of 120 km/h. G-DI car showed particles during accelerations, but the highest peak was seen at high speed in the EUDC test phase. With the CNG car only a small peak of particles was seen after the start of the car.

Particle number distributions from these TDI and IDI cars were significantly different from each other. The particles from the TDI car fell mainly into size classes over 60 nm. The IDI car produced more particles at lower size class than the TDI car. Even though this was not actual nucleation, it can be indication of tendency to form nanoparticles.

After the cold-start the number of particles slightly increased at all size classes as the test temperature decreased with the TDI car using the EU2000 fuel. With the IDI car the effect of temperature was clear for particles at the lowest size class (~15 nm). With spark-ignition G-DI, LPG, MPI and FFV cars, an increase in the number of accumulation mode particles was seen after cold-start as temperature decreased.

If the effect of temperature on particle number results was seen with gasoline, E85 and LPG fuelled cars, it occurred after cold start as an increase in the accumulation mode particles at low temperature. With warmed-up engine particles were seen only at the lowest size class, but this was not dependent on the test temperature.

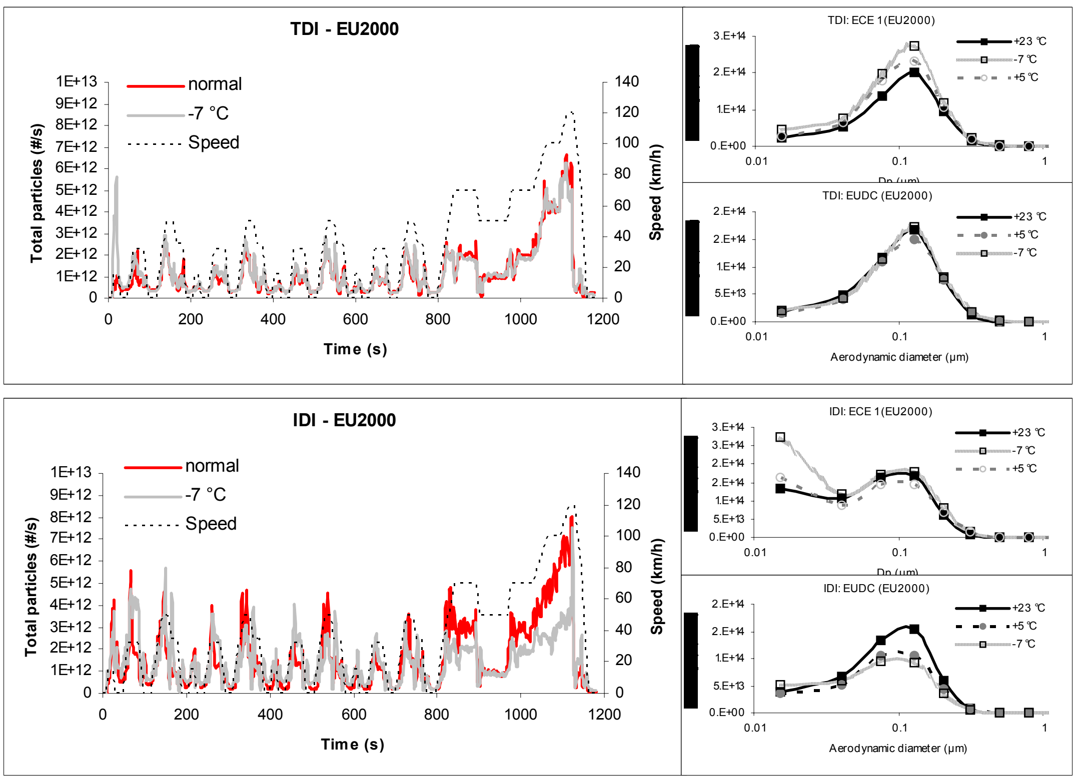


Figure 35. Particle number flow over the European test cycle with the TDI and IDI cars using EU2000 fuel.

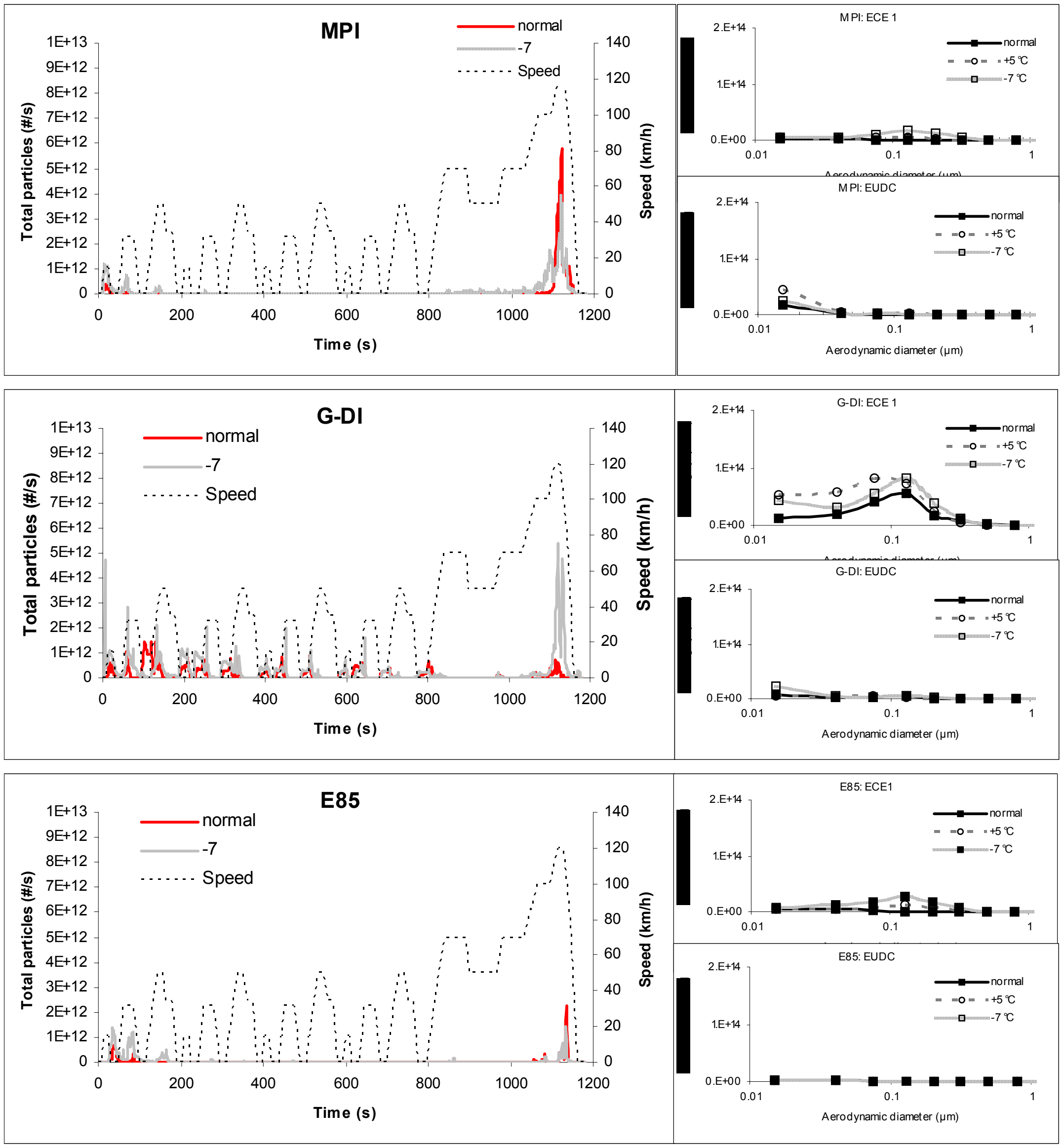


Figure 36. Particle number flow over the European test cycle with MPI, G-DI and E85 (FFV) cars.

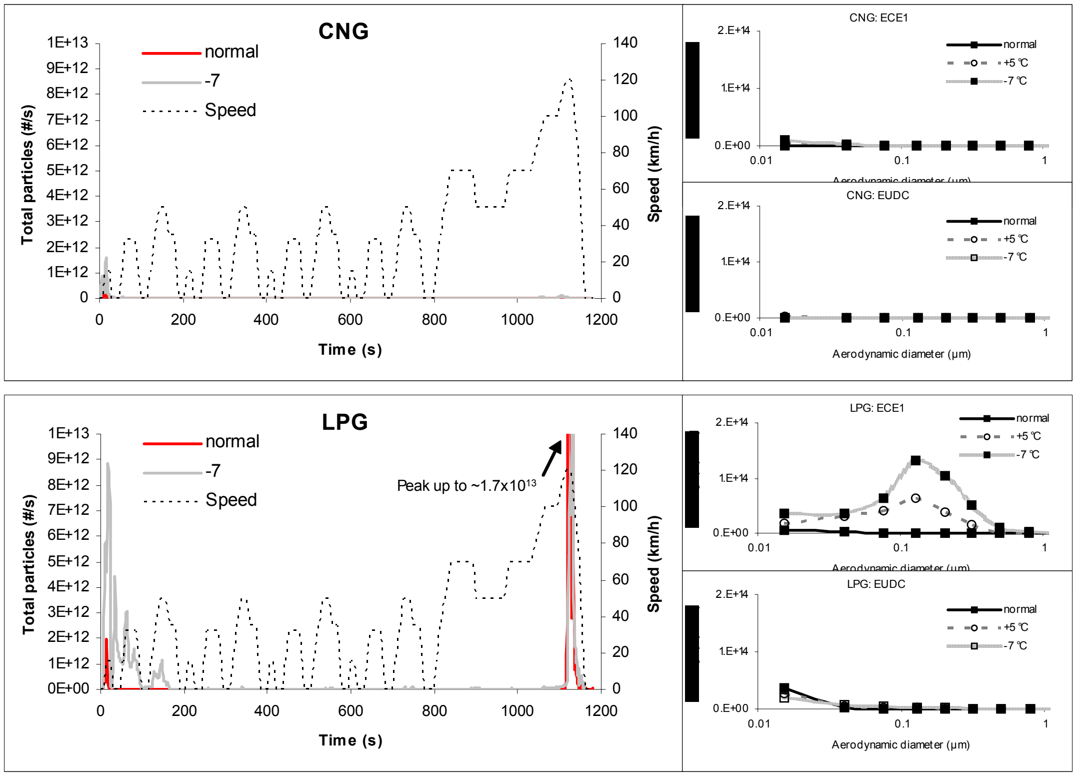


Figure 37. Particle number flow over the European test cycle with the CNG and LPG cars.

With the G-DI car additional constant speed tests were carried out at (Figure 38). These tests showed nucleation at high speeds of 100 and 120 km/h. The European test cycle showed that there was a tendency for nucleation at high speed phase with G-DI car (as well as with many other cars). However, this was not repeatable from test to test and not related to test temperature.

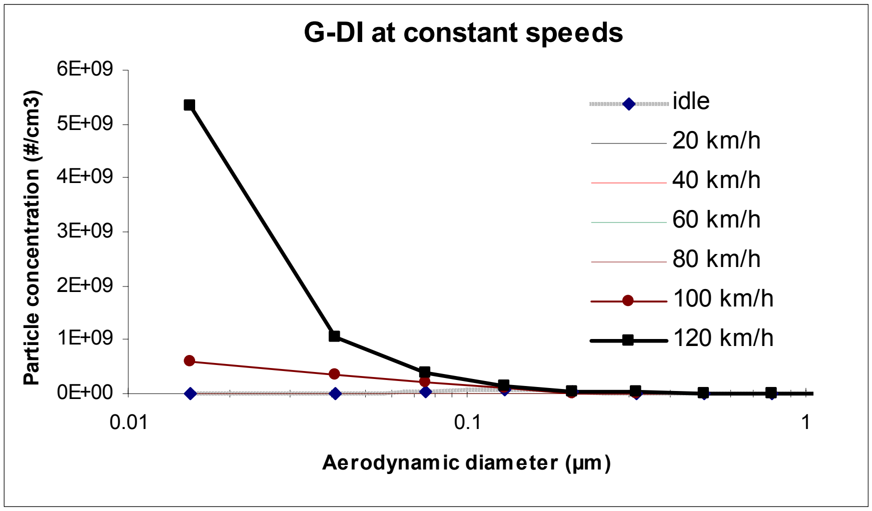


Figure 38. Particle number size distribution at constant speeds with G-DI car at normal temperature.

4.2.3 The results with RME blends, diesel cars

Diesel cars were tested with both hydrocarbon fuels and RME blends. Generally, the effect of fuel on regulated gaseous emissions was rather small (Figure 39). Slight benefit of using RFD or RFD/RME fuels was seen regarding CO and HC emissions. The NO_x emission increased as the test temperature decreased with these diesel cars. Conventional diesel cars typically show a decrease in NO_x emission at low temperatures. However, these diesel cars were equipped with the EGR system, which does not operate properly when engine is cold.

The effect of temperature on formaldehyde and acetaldehyde emissions with diesel cars using hydrocarbon fuels and RME blends are shown in Figure 40. Aldehyde emissions generally increased with hydrocarbon fuels and RME blends as temperature decreased with exception of RFD, which seemed to be rather insensitive towards test temperature with the TDI car. At +5 °C the emission level was close to normal temperature with both diesel cars. Higher increase in formaldehyde emission was seen for RME30 than for EU2000 fuel. Adding RME to reformulated diesel did not show consistent behaviour with both cars.

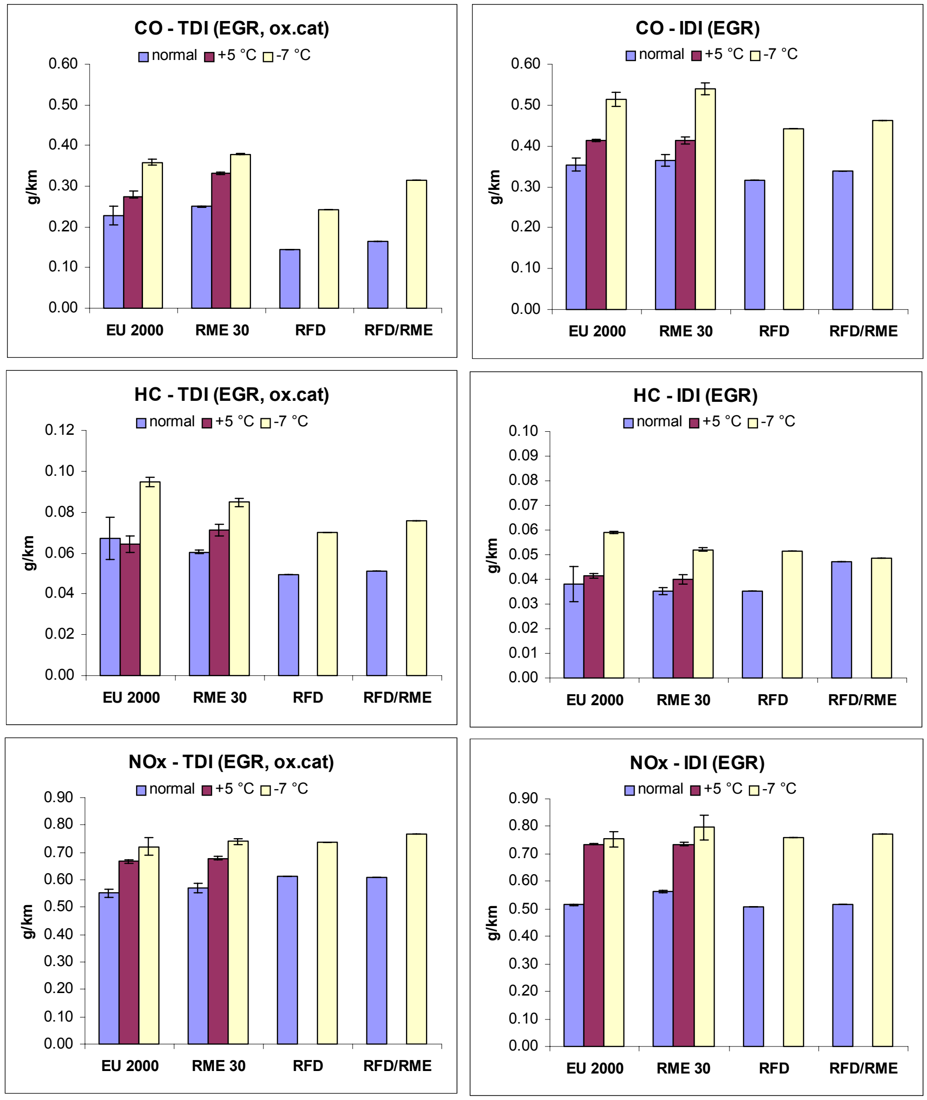


Figure 39. CO, HC and NO_x emissions over the European test cycle with the TDI and IDI cars.

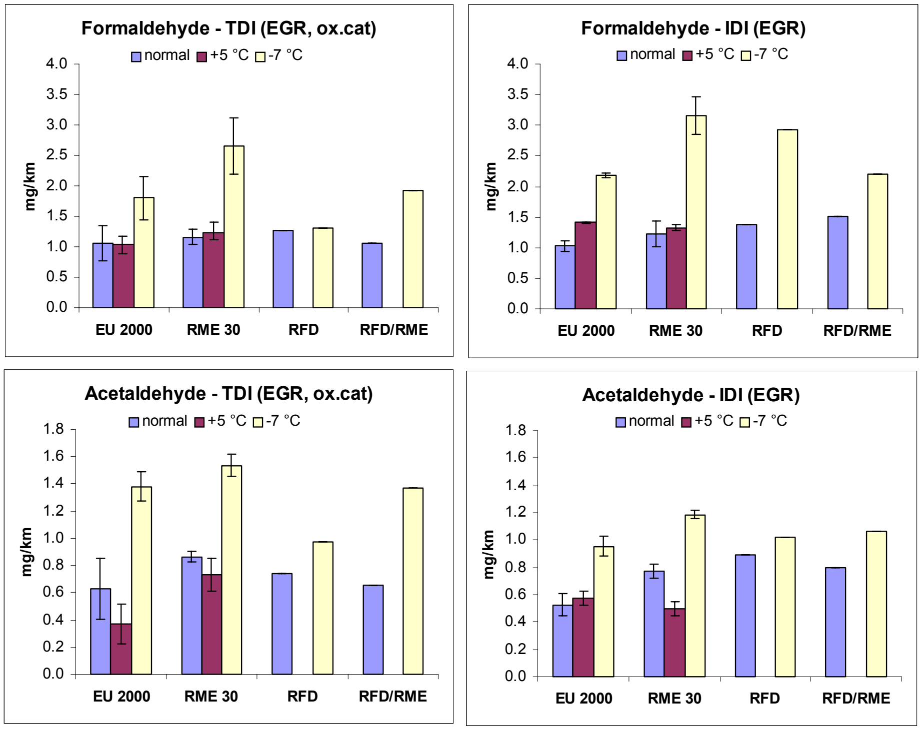


Figure 40. Formaldehyde and acetaldehyde emissions over the European test cycle with the TDI and IDI cars.

The EU2000 fuel resulted in the highest particulate mass emissions with both cars (Figure 41). At +23 °C for TDI car the particulate mass emission was 24% lower with RME30, 30% with RFD and 40% with RFD/RME than with the EU2000 fuel. For the IDI car at +23 °C the particulate mass emissions were about 40-50% lower for the RME30, RFD and RFD/RME fuels when compared to EU2000. The EU2000 fuel gave higher particulate mass emission than the other fuels also at +5 and -7 °C temperatures. There was a benefit of using RFD or RME when compared to EU2000 fuel, but blending RME to RFD fuel did not show so much effect on particulate mass emission.

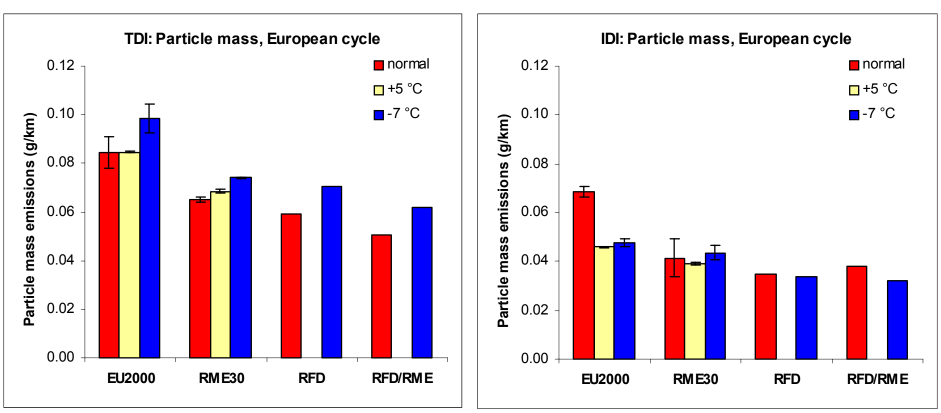


Figure 41. Particle mass emissions with TDI and IDI cars.

The particle mass distribution results are shown in Figure 42. With diesel cars, the particle mass emission was higher and the peak broader shifting median to higher particle size at -7 °C when compared to the results at +23 °C temperature when using EU2000 and RME30 fuels. The effect of temperature on particle mass distribution was only slight when RFD and RFD/RME fuels were used.

In the LPI measurements, an "end-filter" was used to collect the particles below 30 nm. It was noted that the mass of particles below 30 nm was higher at -7 °C than at normal temperature in many cases (TDI/RME30, IDI/EU2000, IDI/RME30), but not with RFD or RFD/RME fuels.

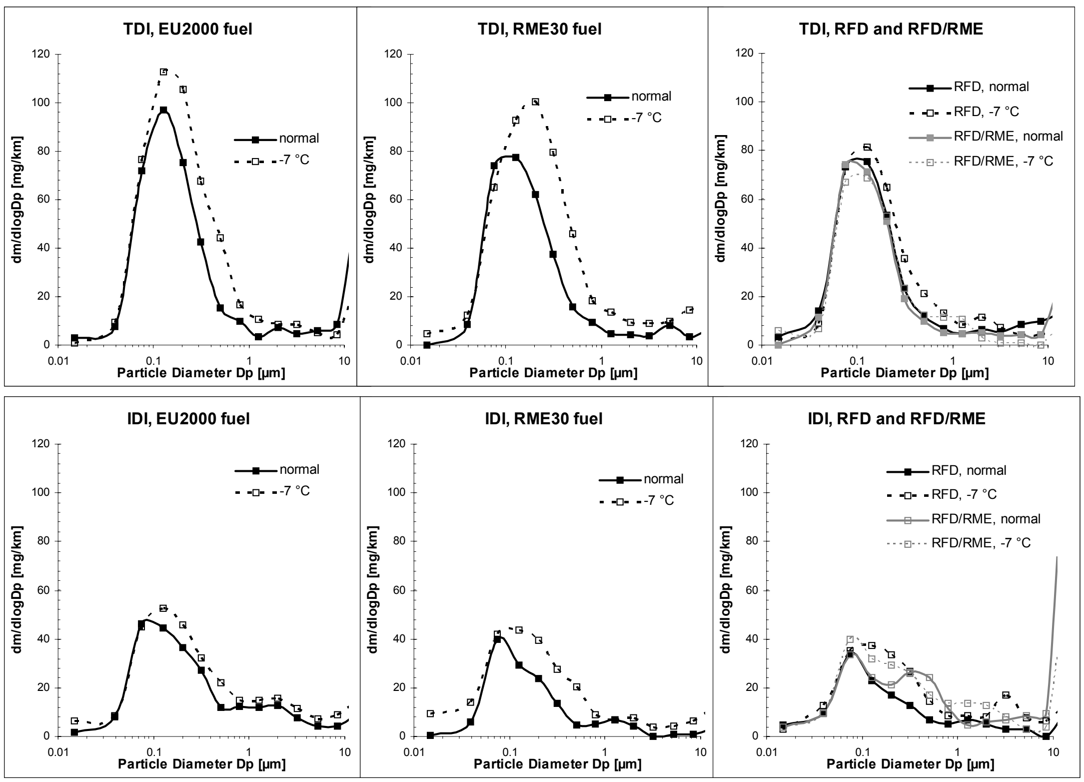


Figure 42. Particle mass size distributions with diesel cars over ECE 1&2 phases of the European test cycle.

The summary of the total particle number results over the European test cycle is given in Figure 43. Appendix 4 shows the distributions in the cold-start test phase (ECE 1) and with warmed-up engine (EUDC). The flow and number distributions over the European test cycle with RME30 fuel is shown in Figure 44.

For TDI car, the total number of particles increased as temperature decreased when using EU2000 and RME30 fuels, but such effect of temperature was not seen for the RFD and RFD/RME fuels. The temperature affected the number of particles below 60 nm more with the RME30 than with EU2000 fuel.

RME30 fuel shifted the size distribution to lower size class with the TDI car at low temperatures especially at cold start, but also in the EUDC part of the test (Appendix 4, Figure 44). When using EU2000, RFD or RFD/RME fuels the influence of temperature diminished as the TDI engine warmed up. For the TDI car the number of particles below 60 nm at +5 °C temperature was mostly in between the results obtained at normal and -7 °C temperatures.

For the IDI car the number of particles below 60 nm was higher at -7 °C than at +23 °C temperature with all fuels studied in the ECE 1 test phase, but the most significant increase was observed with the RME30 fuel (Appendix 4, Figure 44). With warmed-up engine the particle number at accumulation mode decreased as the test temperature decreased, especially when using the EU2000 fuel.

The RFD/RME fuel seemed to be less insensitive to test temperature than the RME30 fuel as concerns the total particle numbers.

With the TDI car a peak in the particle number flow was seen in the beginning of the test at -7 °C when using the EU2000 fuel, but after that the difference was very slight (Figure 35). Figure 44 shows that when using the RME30 fuel the total particle number flow was higher at -7 °C than at normal temperature throughout the test cycle with the TDI car.

With the IDI car, the particle number was similar or even lower (EUDC part) at -7 °C than at +23 °C when using the EU2000 fuel (Figure 35), whereas with the RME30 fuel the total particle number flow was higher at -7 °C than at normal temperature throughout the test cycle (Figure 44).

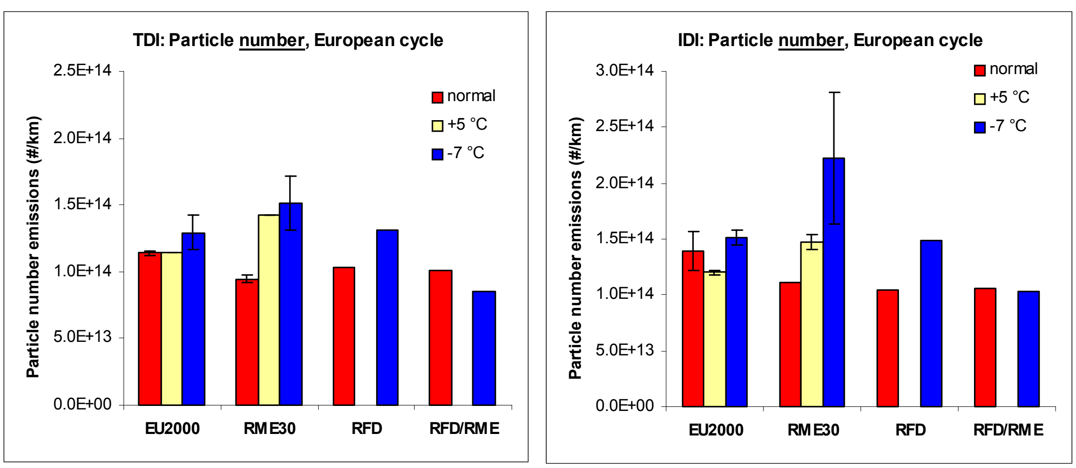


Figure 43. Total number of particles over the European test cycle, TDI and IDI cars.

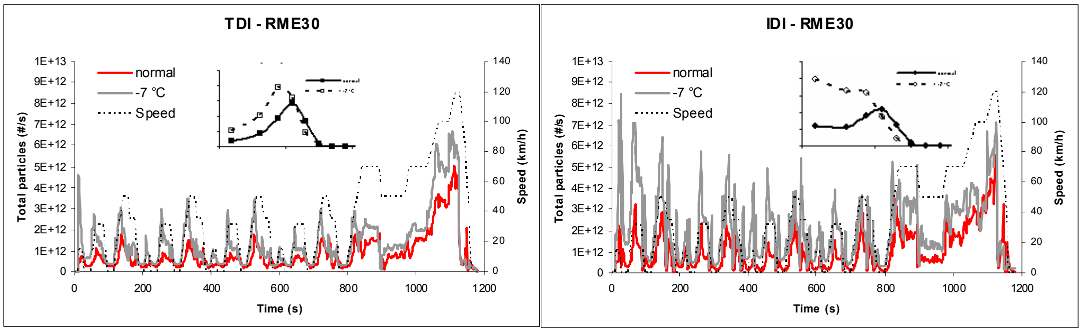


Figure 44. Particle flow and number distribution over the European test cycle using RME30 fuel, diesel cars.

Figure 45 shows the overall summary of particle mass and number results with tractor engine and diesel cars. With tractor engine the effect of temperature on particle mass and number results was clear. The increase in both particle mass and number results seemed to be more significant when using RME blends than respective hydrocarbon fuels. With diesel cars the particle mass results were higher with EU2000 fuel than with the other fuels at all temperatures studied. With diesel cars the number of particles at low test temperatures seemed to be higher for RME30 fuel than for the other fuels. However, when RME was blended with RFD such increase in particle number results with decreasing temperature was not seen.

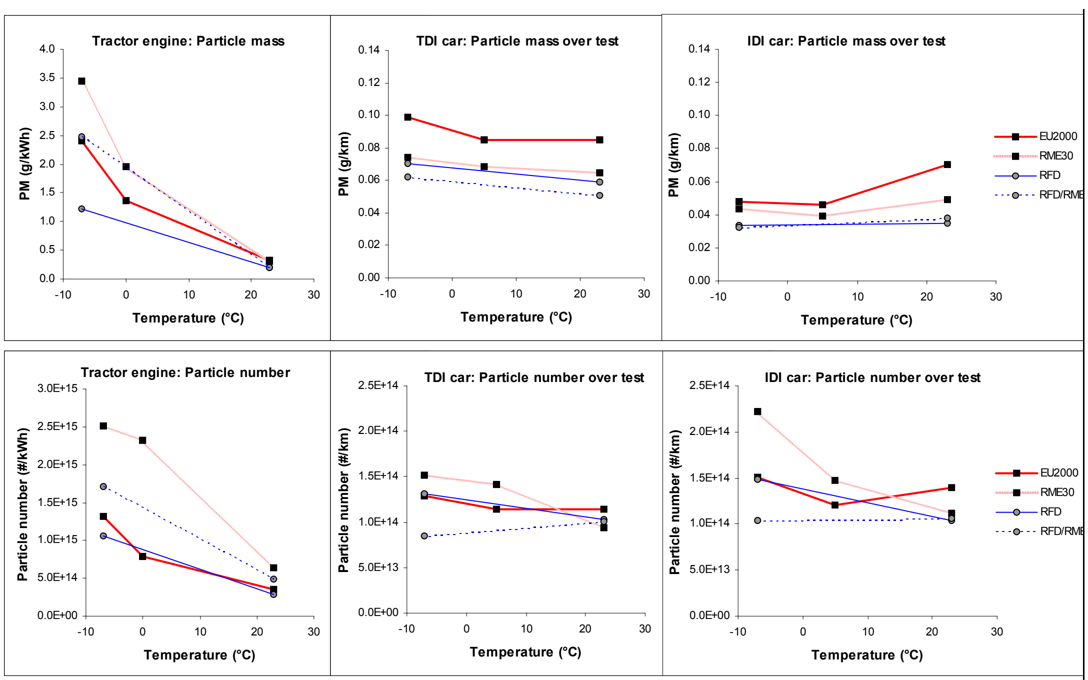


Figure 45. Summary of particle mass and number results with tractor engine and diesel cars.

5 RESULTS WITH THE JAPANESE 10-15 MODE CYCLE

Limited tests were carried out with Japanese 10-15 mode test cycle. The tests at -7 °C were conducted as cold-start tests. The tests at normal temperature were conducted both as cold-start and hot-start tests with a part of the cars, but only as hot-start for some cars (Appendices 1-3).

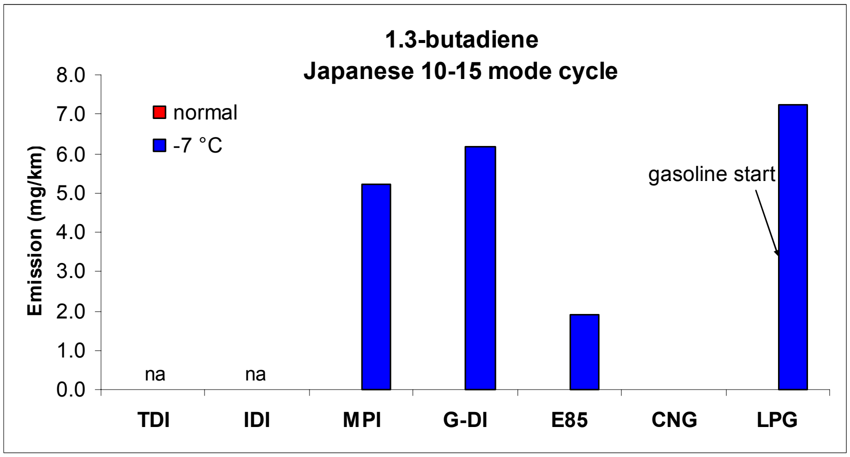
Table 10 shows that both regulated and unregulated emissions tend to be higher at -7 °C with the 10-15 mode test cycle than with the European test cycle.

Selected results with the Japanese 10-15 mode test cycle are shown in Figures 46-49. General trend seems to be that Japanese 10-15 mode test cycle can be more sensitive towards test temperature than European test cycle. When compared to the results over the total European test cycle, a more significant influence of test temperature is seen in some cases (e.g. for the G-DI car). However, it must be noted that major part of the tests at normal test temperature were conducted as hot-start tests with Japanese test cycle, whereas European test cycle includes always cold-start. The particle number distributions at normal temperature (hot-start) and at -7 °C (cold-start) gave similar patterns as was shown for the ECE1 part of the European test.

Table 10. Factors when Japanese 10-15 mode results are compared to European test cycle at -7 °C.

	CO	HC	NOx	PM	FA	AA	Methane	1.3-butad.	BTEX
TDI	2.4	2.2	1.5	1.0	12.4	12.4	na	na	na
IDI	1.1	1.1	1.5	1.4	6.4	6.9	na	na	na
MPI	2.8	2.3	2.8	0.7	2.0	5.4	2.0	2.8	2.4
G-DI	3.4	2.9	1.8	1.5	1.5	3.0	2.5	2.9	3.0
E85	3.0	2.0	2.6	0.4	1.7	3.1	2.3	0.9	3.0
CNG	0.9	2.7	2.6	1.0	2.5	1.2	2.7	bd	1.7
LPG	2.6	2.2	1.3	1.0	1.9	2.3	2.2	2.2	2.3

na = not analyzed, bd = below detection limit



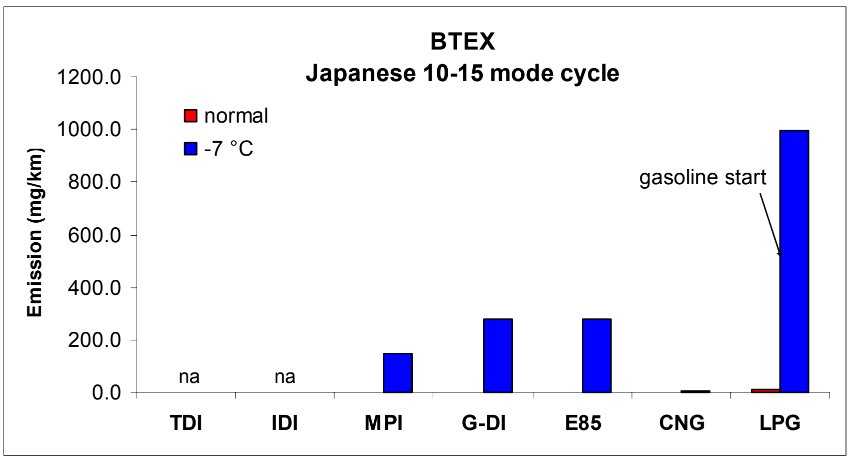


Figure 46. 1,3-butadiene and sum of benzene, toluene, ethylbenzene and xylenes over the Japanese 10-15 mode test cycle.

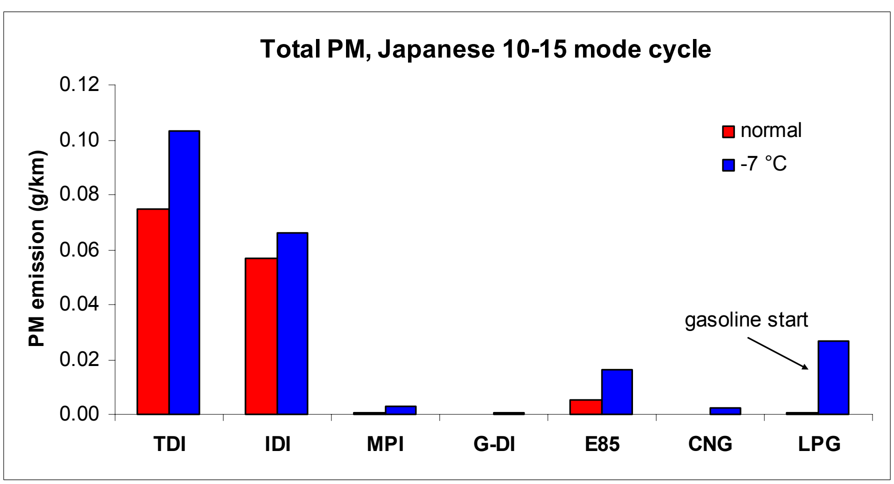


Figure 47. Total particulate matter emission over the Japanese 10-15 mode test cycle

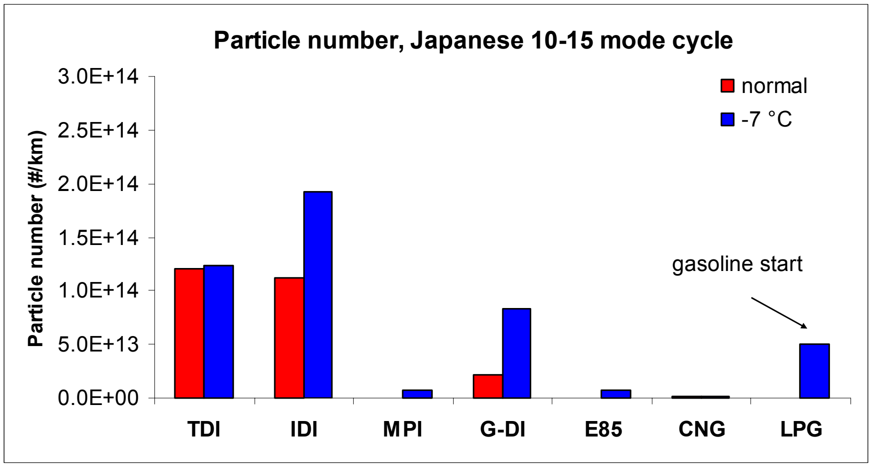


Figure 48. Particle number emissions over the Japanese 10-15 mode test cycle.

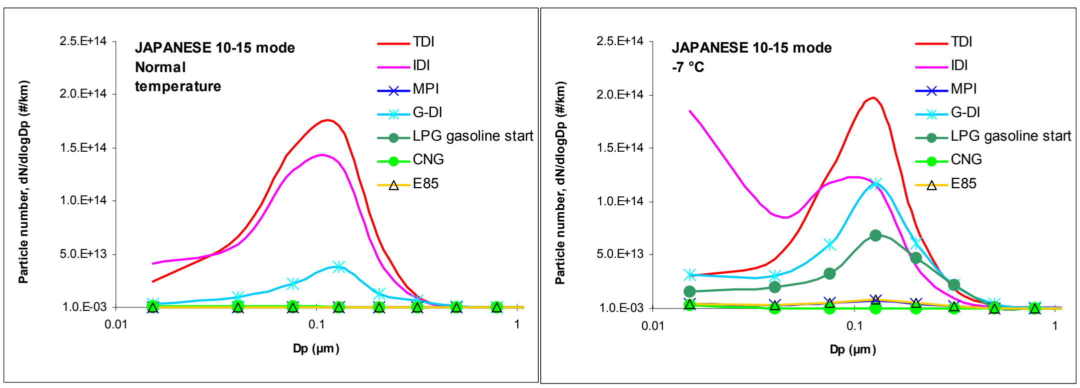


Figure 49. Particle number size distributions over the Japanese 10-15 mode test cycle.

6 SUMMARY

The objective of this work was to study particle emissions at moderate and cold temperatures. Several different engine and fuel technologies were covered, including gaseous fuels and biodiesel. Preliminary tests were conducted with a medium-duty farm tractor engine. The main test programme was run with two diesel cars (direct and indirect-injection), stoichiometric gasoline fuelled car, direct-injection gasoline car, Flexible Fuel Vehicle (E85), CNG and LPG cars. With diesel cars four fuels were studied: European grade (EU2000), a blend of EU2000 with 30% RME (RME30), reformulated fuel (RFD) and a blend of RFD and 30% RME (RFD/RME). The tests were conducted using the European test cycle with some additional tests with Japanese 10-15 mode cycle.

The CO and HC emissions were low at +23 °C with cars. Gasoline, E85 and LPG fuelled cars showed higher CO and HC emissions at low than at +23 °C temperature, whereas diesel and CNG cars were more or less insensitive to test temperature. Aldehyde emissions were low with all cars at all temperatures, except acetaldehyde for E85 fuelled FFV car. The test temperature had a strong impact on the emissions of individual hydrocarbons for the period before catalyst light-off. If an effect of temperature on gaseous emissions was seen, it took place immediately after the start of the car. However, CNG car was insensitive regarding temperature even in the beginning of test.

The major findings concerning particle emissions were as follows:

- The total effect of temperature comprises of the effect on the cold-start phase but also, although to a smaller extent, of the temperature effect on the operation of the stabilized engine.
- With tractor engine, the effect of temperature on particles was clear and seen both in the mass and number results, even though the emission level decreased sharply as engine warmed up. This was thought to be related to the condensed hydrocarbons (HC and aldehyde emissions were high after cold-start).
- For light-duty cars the effect of temperature was dependent on the engine technology. The particle emissions were generally low with spark-ignition cars when compared to diesel cars at all temperatures (Figure 50).
- Particle emissions increased as temperature decreased with both diesel cars after cold-start. MPI, E85 and LPG cars showed extremely low particle emission at +23 °C, but measurable level at -7 °C. The particle emissions from the CNG car was at “zero” level at all temperatures tested.
- G-DI car showed measurable particle emissions at all temperatures studied. G-DI car seemed to be insensitive to test temperature as concerns particle mass emissions, but an increase in particle number emission was seen with decreasing temperature.
- Typically, if an increase in particle emissions with decreasing temperature was seen, it appeared immediately after the cold start and the effect diminished as engine, catalyst and/or EGR system warmed up.
- The RME blends generally gave benefit on particle mass emissions. With diesel cars a blend of RME and European grade diesel fuel showed higher number of particles and/or a shift at lower mean diameter at -7 than at +23°C temperature, whereas a blend of RME and RFD was less sensitive with temperature.

Limited tests with Japanese test cycle (10-15 mode) indicated that higher influence of test temperature might be seen with the Japanese than with the European test cycle.

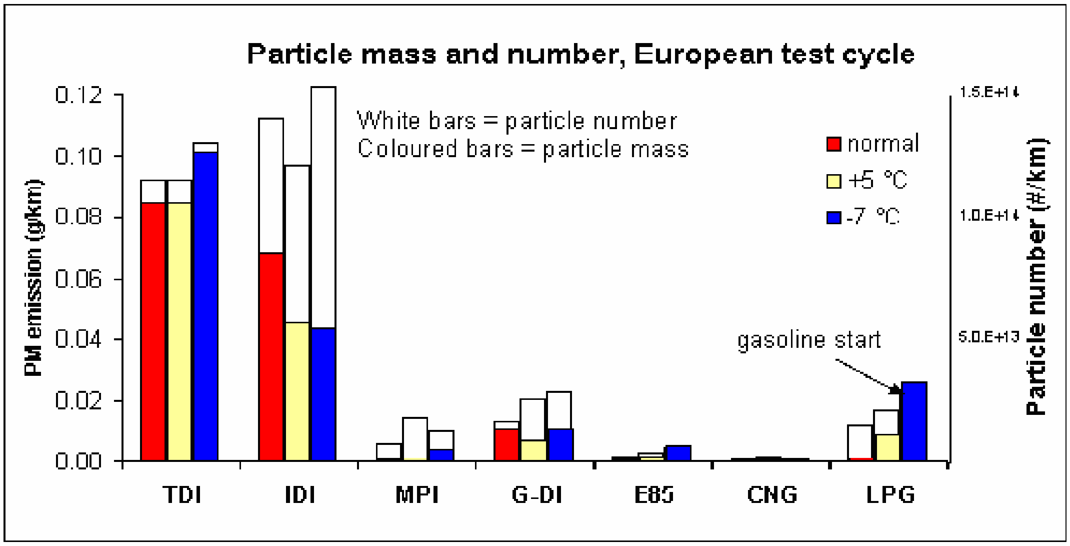


Figure 50. Overall summary of particle mass and number emissions with light-duty cars.

ACKNOWLEDGEMENTS

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Canada	*Natural Resources Canada*
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Japan	*NEDO, LEVO*
Sweden	*STEM*
USA	*US Department of Energy (DOE)*
Finland	*Ministry of Transport and Communications, VTT*

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Average results of the regulated emissions with cars, European test cycle.

Car	Temp °C	Fuel	CO g/km	HC g/km	NOx g/km	PM g/km
TDI	23	EU2000	0.23	0.07	0.55	0.085
TDI	23	RME30	0.25	0.06	0.57	0.065
TDI	23	RFD	0.14	0.05	0.61	0.059
TDI	23	RFD/RME	0.17	0.05	0.61	0.051
TDI	5	EU2000	0.27	0.06	0.67	0.085
TDI	5	RME30	0.33	0.07	0.68	0.069
TDI	-7	EU2000	0.36	0.09	0.72	0.102
TDI	-7	RME30	0.38	0.08	0.74	0.074
TDI	-7	RFD	0.24	0.07	0.74	0.070
TDI	-7	RFD/RME	0.31	0.08	0.77	0.062
IDI	23	EU2000	0.35	0.04	0.51	0.069
IDI	23	RME30	0.37	0.04	0.56	0.041
IDI	23	RFD	0.31	0.04	0.51	0.035
IDI	23	RFD/RME	0.34	0.05	0.52	0.038
IDI	5	EU2000	0.41	0.04	0.74	0.046
IDI	5	RME30	0.41	0.04	0.74	0.039
IDI	-7	EU2000	0.51	0.06	0.75	0.048
IDI	-7	RME30	0.54	0.05	0.80	0.044
IDI	-7	RFD	0.44	0.05	0.76	0.034
IDI	-7	RFD/RME	0.46	0.05	0.77	0.032
MPI	23	gasoline	0.24	0.05	0.06	0.001
MPI	5	gasoline	1.22	0.18	0.11	0.001
MPI	-7	gasoline	2.46	0.38	0.15	0.004
G-DI	23	gasoline	0.51	0.06	0.06	0.011
G-DI	5	gasoline	1.19	0.21	0.07	0.007
G-DI	-7	gasoline	2.27	0.40	0.09	0.010
FFV	23	E85	0.35	0.07	0.05	0.001
FFV	5	E85	2.30	0.31	0.05	0.002
FFV	-7	E85	3.33	0.67	0.04	0.005
CNG	23	CNG	0.12	0.06	0.01	0.000
CNG	5	CNG	0.14	0.08	0.05	0.001
CNG	-7	CNG	0.22	0.11	0.14	0.000
LPG	23	LPG, gasoline start	0.65	0.08	0.29	0.001
LPG	5	LPG, gasoline start	1.66	0.46	0.25	0.009
LPG	-7	LPG, gasoline start	3.53	1.28	0.37	0.026

Results of the regulated emissions, Japanese test cycle with cars.

Car	Temp °C	Fuel	CO g/km	HC g/km	NOx g/km	PM g/km	*Comment*
TDI	23	EU2000	0.06	0.03	0.75	0.075	*JAP 10-15 hot*
TDI	23	EU2000	0.53	0.12	0.71	0.086	*JAP 10-15 cold*
TDI	-7	EU2000	0.86	0.21	1.06	0.103	*JAP 10-15 cold*
IDI	23	EU2000	0.26	0.02	0.50	0.057	*JAP 10-15 hot*
IDI	23	EU2000	0.41	0.04	0.62	0.059	*JAP 10-15 cold*
IDI	-7	EU2000	0.59	0.06	1.14	0.066	*JAP 10-15 cold*
MPI	23	gasoline	0.11	0.02	0.08	0.000	*JAP 10-15 hot*
MPI	23	gasoline	0.14	0.01	0.07	0.000	*JAP 10-15 cold*
MPI	-7	gasoline	0.34	0.01	0.11	0.001	*JAP 10-15 hot*
MPI	-7	gasoline	6.89	0.90	0.43	0.003	*JAP 10-15 cold*
G-DI	23	gasoline	0.02	0.01	0.14	0.005	*JAP 10-15 hot*
G-DI	-7	gasoline	7.72	1.18	0.17	0.016	*JAP 10-15 cold*
FFV	23	E85	0.01	0.00	0.03	0.000	*JAP 10-15 hot*
FFV	-7	E85	9.94	1.31	0.10	0.002	*JAP 10-15 cold*
CNG	23	CNG	0.02	0.03	0.07	0.000	*JAP 10-15 cold*
CNG	-7	CNG	0.03	0.01	0.02	0.001	*JAP 10-15 hot*
CNG	-7	CNG	0.20	0.29	0.37	0.000	*JAP 10-15 cold*
LPG	23	LPG, gasoline start	0.05	0.01	0.12	0.000	*JAP 10-15 hot*
LPG	-7	LPG, gasoline start	9.23	2.85	0.49	0.027	*JAP 10-15 cold*

Average results of the aldehyde emissions with cars, European test cycle.

Car	Temperature °C	Fuel	Formaldehyde mg/km	Acetaldehyde mg/km	Sum mg/km
TDI	23	EU 2000	1.1	0.6	1.7
TDI	23	RME 30	1.2	0.9	2.1
TDI	23	RFD	1.3	0.7	2.1
TDI	23	RFD/RME	1.1	0.7	1.7
TDI	5	EU 2000	1.0	0.4	1.4
TDI	5	RME 30	1.2	0.7	2.1
TDI	-7	EU 2000	1.8	1.4	3.3
TDI	-7	RME 30	2.7	1.5	4.5
TDI	-7	RFD	1.3	1.0	2.4
TDI	-7	RFD/RME	1.9	1.4	3.5
IDI	23	EU 2000	1.0	0.5	1.8
IDI	23	RME 30	1.2	0.8	2.2
IDI	23	RFD	1.4	0.9	2.5
IDI	23	RFD/RME	1.5	0.8	2.5
IDI	5	EU2000	1.4	0.6	2.2
IDI	5	RME30	1.3	0.5	2.0
IDI	-7	EU2000	2.2	1.0	3.5
IDI	-7	RME30	3.2	1.2	4.8
IDI	-7	RFD	2.9	1.0	4.3
IDI	-7	RFD/RME	2.2	1.1	3.4
MPI	23	gasoline	0.6	0.4	1.4
MPI	5	gasoline	0.7	0.6	2.2
MPI	-7	gasoline	0.4	0.6	1.5
G-DI	23	gasoline	0.4	0.3	0.9
G-DI	5	gasoline	0.3	0.4	1.1
G-DI	-7	gasoline	0.3	0.6	1.4
FFV	23	E85	0.7	4.0	5.0
FFV	5	E85	1.2	9.0	10.8
FFV	-7	E85	1.2	15.4	17.6
CNG	23	CNG	0.4	0.2	0.6
CNG	5	CNG	0.1	0.1	0.2
CNG	-7	CNG	0.1	0.2	0.2
LPG	23	LPG, gasoline start	1.9	0.9	3.0
LPG	5	LPG, gasoline start	1.1	0.7	2.4
LPG	-7	LPG, gasoline start	1.6	1.5	4.1

Results of the aldehyde emissions, Japanese test cycle with cars.

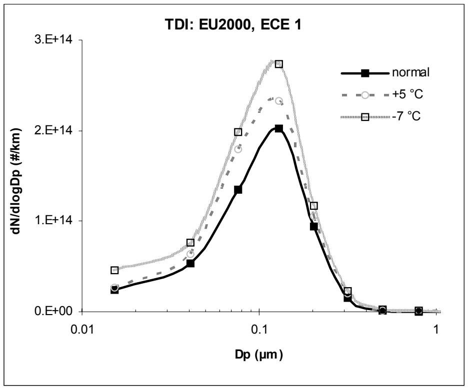
Car	Temperature °C	Fuel	Formaldehyde mg/km	Acetaldehyde mg/km	Sum mg/km	*Comment*
TDI	23	EU2000	4.6	2.6	7.7	*JAP 10-15 cold*
TDI	-7	EU2000	22.3	17.2	46.9	*JAP 10-15 cold*
IDI	23	EU2000	3.9	1.2	5.3	*JAP 10-15 cold*
IDI	-7	EU2000	13.9	6.6	24.6	*JAP 10-15 cold*
MPI	23	gasoline	0.3	0.2	0.5	*JAP 10-15 cold*
MPI	-7	gasoline	0.8	3.0	5.8	*JAP 10-15 cold*
G-DI	23	gasoline	0.9	0.3	1.2	*JAP 10-15 hot*
G-DI	-7	gasoline	0.5	1.8	2.6	*JAP 10-15 cold*
FFV	23	E85	0.5	0.5	1.0	*JAP 10-15 hot*
FFV	-7	E85	2.1	48.0	53.1	*JAP 10-15 cold*
CNG	23	CNG	0.2	0.2	0.4	*JAP 10-15 cold*
CNG	-7	CNG	0.1	0.2	0.3	*JAP 10-15 cold*
LPG	23	LPG, gasoline start	2.7	2.1	4.8	*JAP 10-15 hot*
LPG	-7	LPG, gasoline start	3.1	3.4	9.5	*JAP 10-15 cold*

Results of the C1-C8 hydrocarbons, European test cycle with cars.

Car	Temp °C	Fuel	Methane mg/km	Ethane mg/km	Ethene mg/km	Propane	Propene mg/km	Acetylene mg/km	Isobutene mg/km	1.3-butad. mg/km	Benzene mg/km	Toluene mg/km	Et-benzene mg/km	m,p-xylene mg/km	o-xylene mg/km
MPI	23	gasoline	5.2		2.9	0.0	1.6	1.3	0.8	0.5	1.3	4.5	0.5	1.8	0.0
MPI	5	gasoline	12.1		7.4	0.1	3.6	7.0	2.0	1.3	4.0	18.0	2.7	5.8	1.9
MPI	-7	gasoline	20.9		13.4	0.1	5.6	15.3	3.0	1.9	8.9	40.0	6.1	10.5	4.8
G-DI	23	gasoline	8.8	1.7	6.6	0.0	3.2	2.3	1.6	0.8	3.5	8.6	1.3	2.8	1.0
G-DI	5	gasoline	15.2	2.9	13.4	0.2	7.4	3.2	4.8	1.3	7.8	27.2	4.5	10.4	3.2
G-DI	-7	gasoline	24.0	4.3	23.3	0.3	11.6	6.9	8.1	2.1	15.0	54.1	9.8	21.3	7.1
FFV	23	E85	7.0	1.7	6.6	0.0	3.2	2.3	1.6	0.8	3.5	8.6	1.3	2.8	1.0
FFV	5	E85	24.2	2.9	13.4	0.2	7.4	3.2	4.8	1.3	7.8	27.2	4.5	10.4	3.2
FFV	-7	E85	41.4	4.3	23.3	0.3	11.6	6.9	8.1	2.1	15.0	54.1	9.8	21.3	7.1
CNG	23	CNG	51.5		0.0	0.4	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0
CNG	5	CNG	67.6		0.4	0.5	0.0	0.1	0.0	0.0	0.1	1.1	0.0	0.0	0.0
CNG	-7	CNG	84.4		0.5	0.6	0.0	2.4	0.0	0.0	0.2	1.9	0.0	2.2	0.0
LPG	23	LPG, gasoline st	7.7	1.6	5.1	41.1	1.8	1.1	0.3	0.4	2.0	8.4	2.0	8.6	3.7
LPG	5	LPG, gasoline st	19.1	2.4	18.1	13.8	7.4	6.0	2.1	1.5	14.5	72.8	13.9	44.5	16.4
LPG	-7	LPG, gasoline st	47.7	4.3	47.9	19.1	16.7	12.0	4.4	3.3	41.7	217.1	41.6	134.7	48.7

Results of the C1-C8 hydrocarbons, Japanese test cycle with cars.

Car	Temp °C		Methane mg/km	Ethane mg/km	Ethene mg/km	Propane	Propene mg/km	Acetylene mg/km	Isobutene mg/km	1.3-butad. mg/km	Benzene mg/km	Toluene mg/km	Et-benzene mg/km	m,p-xylene mg/km	o-xylene mg/km
MPI	23	cold-start	3.4		0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.5	0.0	0.0	0.0
MPI	23	hot-start	6.8		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	1.5	0.0
MPI	-7	cold-start	41.0		34.7	0.4	16.0	30.4	9.5	5.2	19.8	91.6	14.1	31.3	10.8
MPI	-7	hot-start	2.8		0.0	0.0	0.0	0.0	0.0	0.0	0.7	5.0	1.4	4.2	1.3
G-DI	23	hot-start	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0
G-DI	-7	cold-start	60.0	11.5	68.9	0.7	37.1	19.2	26.6	6.2	40.4	164.8	30.1	64.5	21.4
FFV/E85	23	hot-start	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.0	0.0	0.0
FFV/E85	-7	cold-start	96.6	10.0	76.0	0.9	12.4	27.5	4.4	1.9	30.8	124.8	26.7	92.1	36.1
CNG	23	cold-start	20.1		0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CNG	-7	cold-start	227.5		1.5	1.8	0.0	0.6	0.0	0.0	0.3	3.7	0.0	3.3	0.0
CNG	-7	hot-start	5.2		0.0	0.0	0.0	0.3	0.0	0.0	0.0	2.1	0.0	2.7	0.0
LPG	23	hot-start	5.0	0.0	0.0	1.5	0.0	0.1	0.0	0.0	0.2	2.1	1.1	5.3	2.6
LPG	-7	cold-start	104.4	10.7	114.4	27.5	41.0	24.7	11.3	7.2	2.1	494.8	93.6	300.9	108.0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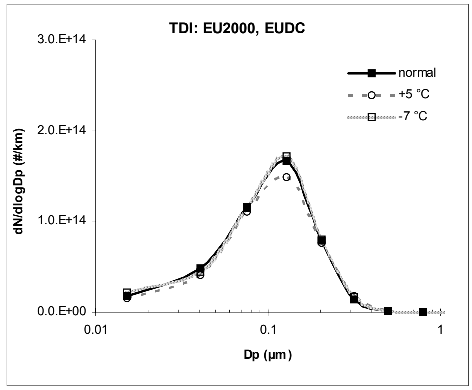
1
Dp (µm)
normal
+5 °C
-7 °C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Dp (µm)
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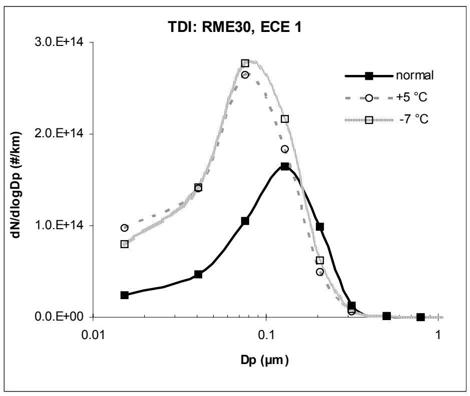
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Dp (µm)
normal
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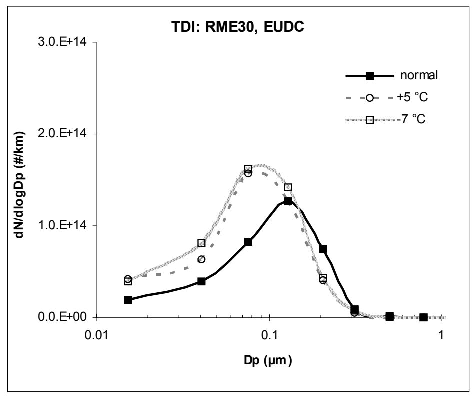
-7 °C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Dp (µm)
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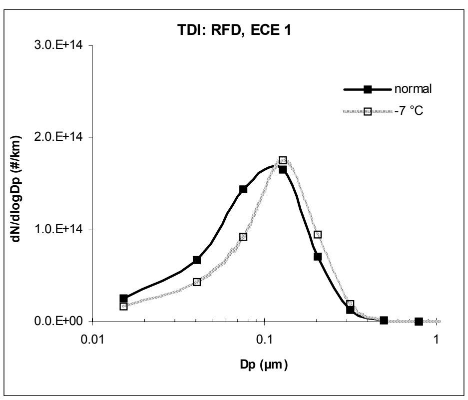
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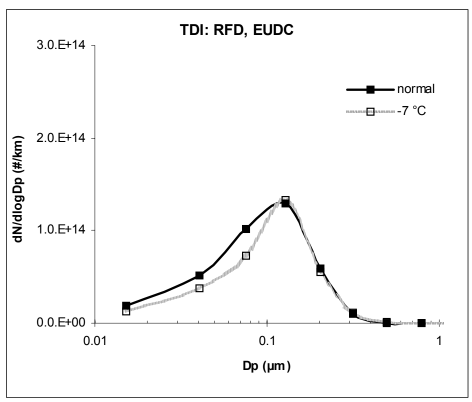
Dp (µm)
normal
-7 °C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Dp (µm)
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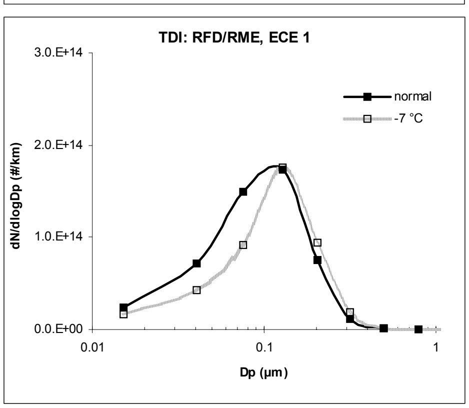
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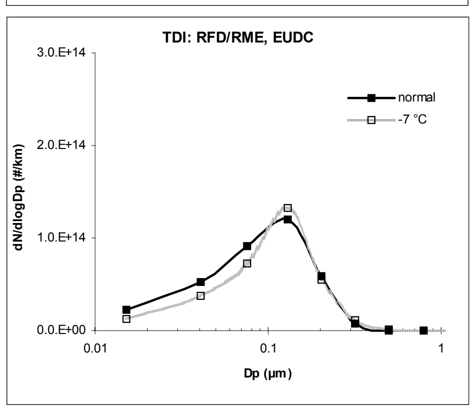
Dp (µm)
normal
-7 °C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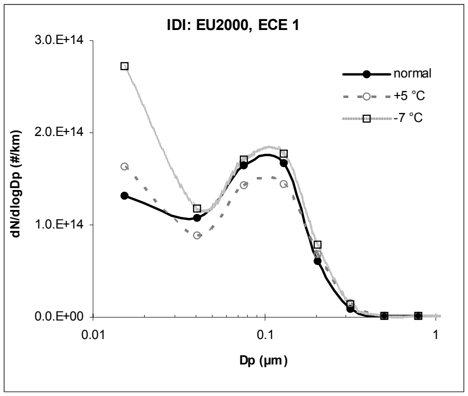
Dp (µm)
normal
-7 °C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Dp (µm)
normal
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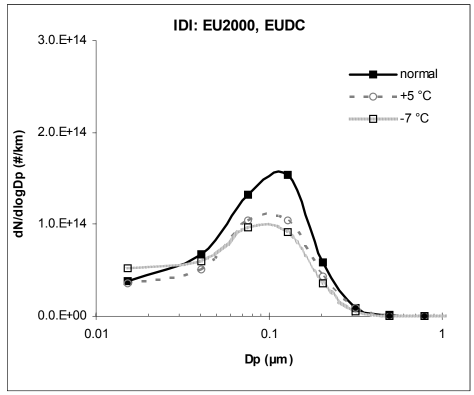
-7 °C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Dp (µm)
normal
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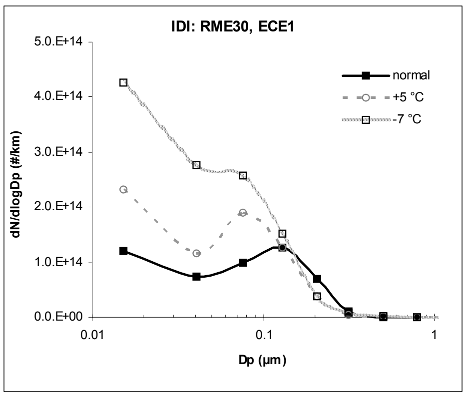
-7 °C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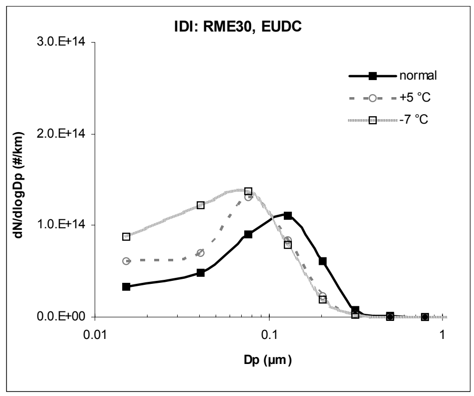
Dp (µm)
normal
+5 °C
-7 °C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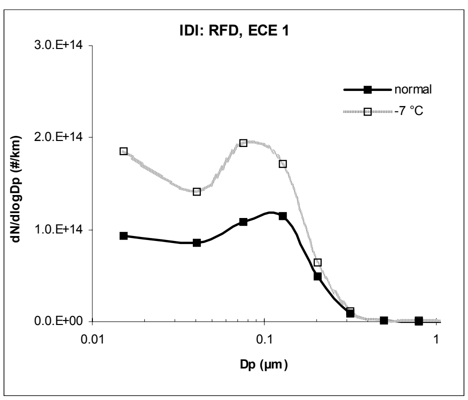
Dp (µm)
normal
+5 °C
-7 °C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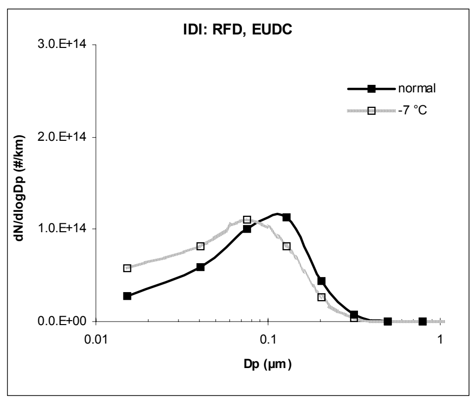
Dp (µm)
normal
-7 °C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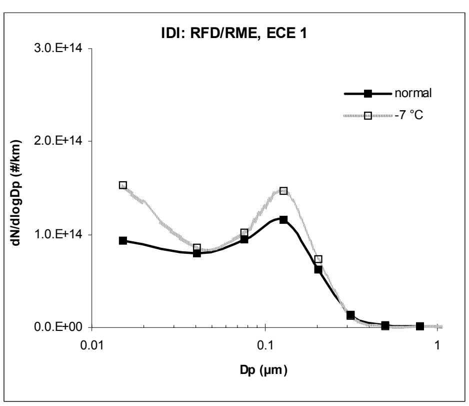
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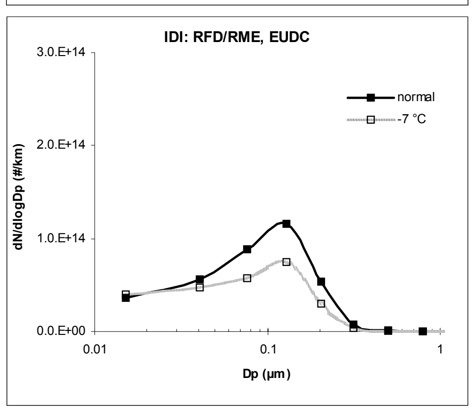
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