measurement of the number and mass weighted size distributions of exhaust particles emitted from european heavy duty engines

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ABSTRACT

This study investigates the measurement of the mass and the number of heavy duty automotive particle emissions and their related size distributions. Limited additional test work has investigated the effect of sampling and measurement conditions on these distributions. Two engines representing Euro 2 and Euro 3 technology were examined, using a selection of diesel fuels representative of European market quality.

KEYWORDS

aerodynamic diameter, automotive exhaust emissions, diesel, heavy duty engine, electrical mobility diameter, particle size, particulate emissions, nanoparticles, nucleation mode.

CONTENTS

SUMMARY

Automotive tailpipe emissions can make a substantial contribution to ambient particulate concentrations, especially within urban areas. Consequently, legislation is in place to measure and control the mass of automotive particulates emitted at the tailpipe (1,2). There is some evidence that adverse health effects are associated with current ambient concentrations, although it is uncertain which feature of the particulate matter, be it chemical or physical, has the most relevance for health. At present there is no proven mechanism whereby low-level ambient PM could cause either early death or morbidity (3). There are no toxicology data to provide a plausible explanation for increased mortality (4).

Recently, attention has concentrated on the number-based size distribution of the ambient particles. Although the EC Air Quality Framework Directive has proposed an air quality standard with respect to PM_{10} (5), the directive also includes the reporting of $PM_{2.5}$, with a review planned in 2003. With this increased focus on particle size, it is important that the different sectors of industry that make significant contributions to ambient particle concentrations develop a good understanding of the size distribution of the particulate emitted. The automotive industry has already developed evidence that some particles emitted from vehicles are extremely small (<15 nm).

To develop a better understanding of the size distribution of automotive particulate emissions from heavy-duty engines, a programme was carried out in two engines representative of Euro 2 and Euro 3 technologies.[1] Tailpipe particle emissions were measured both with respect to their mass and number and the corresponding size distributions. This study complements previous work by CONCAWE on light-duty automotive particle emissions (7) using a similar matrix of fuels.

Extra work was also carried out to investigate the effect that changes in sampling conditions (i.e. dilution ratio, residence time, stabilisation time) could have on measured size distributions. Following completion of the main programme, additional test work was carried out using the Euro 3 engine fitted with a Continuously Regenerating Trap (CRT) and adjusted to a Euro 4 level; this work is reported separately in **Appendix 2**.

The study resulted in the following conclusions:

- measurement of particle size and number has been extended to heavy duty exhaust emissions;
- the use of the Dual Differential Mobility Particle Spectrometer (DDMPS) allows the investigation of particles as small as 3 nm;
- the size distribution of particles emitted from HD engines is bimodal, with peaks below 30 nm (representing nucleation mode particles) and above 30 nm (representing accumulation mode particles);

[1] Engine testing was contracted to AVL, Graz and the particle measurements were conducted by Prof. G Reischl, Vienna University.

- the accumulation mode particles were found to be measurable to a satisfactory level of repeatability and were relatively insensitive to changes in test conditions;
- nucleation mode particles were found to be highly sensitive to changes in sampling conditions;
- nucleation mode particles were found to have the greatest influence on total particle number;
- conclusions about engine technology and fuel effects based on particle number measurements which include the nucleation mode are critically dependent on the sampling conditions.

1. BACKGROUND AND INTRODUCTION

For some time, the possible harmful effects of tailpipe particulate emissions from diesel-engined vehicles have been the subject of debate. The concern is reflected in a requirement for particulate mass measurement in the legislated regulated emissions testing of diesel vehicles (1,2). Views of the relative importance to health of either the physical nature of the particulate itself or its chemical composition (e.g. sulphate which is a potential irritant, adsorbed polycyclic aromatic hydrocarbons which may be potential carcinogens) have varied over time. At present, it is the likelihood of particulate matter of a given size range being retained in the lung that is being highlighted. However, at present there is no proven mechanism whereby low-level ambient PM could cause either early death or morbidity (3) and in terms of plausibility for increased mortality, there are no toxicology data to allow any conclusion (4).

The EC Air Quality Framework Directive is currently addressing limits for an European air quality standard (AQS) with respect to several pollutants including particulate matter. The limit under discussion will apply to PM_{10} (particulate with an aerodynamic diameter less than or equal to 10 µm) but following moves by the US EPA and continued health pressures, it is probable that the next target AQS will be for $PM_{2.5}$, with an EU review planned in 2003.

This debate has focussed attention on whether particle number or particle mass of the particulates in the ambient atmosphere should be of greater concern. Clearly, the appropriate response to this question should be determined on the basis of an assessment of health effects. Clear information on the most critical size ranges and/or particle composition is not available. Recent studies have suggested that very small particles (<15 nm) may be emitted, but there is great uncertainty because small particles can, in some cases, be formed as artefacts in the emission sampling system. Clarification of the extent to which these very small particles are emitted and persist in the atmosphere awaits the results of studies currently under way in USA and Europe.

It should also be recognised that tailpipe emissions are only one source contributing to the ambient aerosol and that agglomeration processes will modify the dimensions of tailpipe-out particulate once it has reached the ambient atmosphere. This is a significant further complication in the extrapolation from vehicle tailpipe particulate emissions to ambient air quality and beyond. This issue has been examined in more depth in a recent SAE paper (5).

CONCAWE maintains contact with the scientific community researching these questions, and to provide basic information to address these uncertainties, CONCAWE has already reported a test programme to investigate the nature of light duty particulate emissions. The measurement technology applied in that work was based on a previous literature survey (6) and the programme itself published both as a CONCAWE report (7) and also as an SAE paper (8). This new report describes further work to extend the investigation to emissions from heavy duty engines.

The light duty test programme provided some key insights into the nature of particle emissions:

- Mass emissions of particles were much lower for gasoline vehicles than for diesel vehicles. The number of particles emitted was also much lower for

gasoline vehicles under most conditions, but high number emissions, equalling those from diesel vehicles, were seen at high vehicle speeds.

- Some differences in number emissions were seen between different vehicle technology levels. No clear fuel effect was seen for gasoline vehicles, and differences in particle number emissions between the diesel fuels were small, even though the mass emissions varied to some extent.
- There is evidence that, whether particulate emissions are judged by mass or number, the highly emitting vehicles will always be detectable. This is of great potential significance in the debate as to how number and mass should be accommodated in future legislative procedures.

Since the completion of the light duty programme and with the benefit of work carried out by other researchers, it became apparent that any work of this type would need to take into account the very small particles (<15 nm) not measured in the previous work. It was also apparent from other work that there were limitations in the use of the standard dilution tunnel when applied to particle number rather than mass measurements. This applies particularly to measurements of these very small particles, which can under some conditions form as artefacts in the sampling system. Nevertheless, in the absence of an alternative sampling system, measurements using the standard dilution tunnel were the only option. The methods and procedures used were repeatable and allow comparison of vehicle and fuel effects, even though some of the absolute levels measured may have some uncertainty at the current level of knowledge.

Interpretation of the light duty work concentrated on values obtained from the regulated test cycles alongside additional information obtained from the investigation of steady-state test conditions. It was agreed that the same approach should be taken for the heavy duty investigation. However, the regulated test cycle for heavy duty engines ECE R49 (2) is a 13-mode steady-state test cycle. Emissions measurements are made at each mode within a specified and limited time period and then combined (taking into account individual weighting factors at each mode) to give a single emission value for each pollutant over the combined cycle. The new test cycle for Euro 3 engines (ESC, (9)) retains the 13-mode steady-state approach but includes a further restriction on the time permitted at each mode. Thus, although it is possible to measure a complete size range distribution at each mode (something not possible with the transient light duty regulated test procedure and the new transient heavy duty cycle (ETC)), it is not possible to carry out repeat scans at individual test conditions. There is also insufficient time to allow the tunnel and sampling system to equilibrate and hence the question of “carry over” or other stabilisation effects as highlighted by others (10) becomes important. The measurement of heavy duty particle emissions is challenging and the selected approach is discussed in more detail under **Section 3**.

2. OBJECTIVES

In order to further expand CONCAWE's understanding in the field of particle emissions, the objectives of this work were defined as follows:

- To extend the measurements of particle size and number to heavy duty engines;
- To extend particle emissions investigations into the range below 15 nm;
- To compare emissions performance between engines, fuels and operating conditions;
- To determine if there is any relationship between mass and number emissions;
- To study the ways in which measurement techniques and sampling conditions affect the measured results.

3. METHODOLOGY AND APPROACH

In the absence of any standard test procedure, protocols or indeed reference measurement equipment, the measurement of automotive particulate emissions with respect to both size and number distributions has generally been conducted using the same system as developed for regulated emissions testing i.e. a dilution tunnel approach. It has however, been shown that the size distribution measured from a dilution tunnel is affected by the conditions used in the tunnel to generate it i.e. extent of dilution, temperature, humidity etc. There is no clear understanding of how the measurements made in the dilution tunnel may relate to the formation of particles in the atmosphere post tail-pipe where conditions may vary enormously. The particles which have the greatest sensitivity to the effect of test conditions have been shown (11) to be the nano-particles - the nucleation particles (those <30 nm) which, because of their minute size have no impact on the mass but can have considerable impact on the total number measured. Thus, total numbers have to be treated with caution as they will often be more closely correlated with the dynamometer conditions than with fuel or vehicle effects. Although the test procedures employed allow comparative results within laboratories to be established, it is essential that the limitations of this approach are understood, especially with respect to any future legislation. Measurements of particles in the accumulation mode (approximately 30-300 nm) seem to be less sensitive to the dilution and sampling conditions. In the presentation of results from this study, distinction will be made between the more reliable accumulation mode data, and measurements of nano-particles, where the uncertainties in the measurements are greater.

Most of the test work in the literature has concentrated on light duty emissions, although there are a few recent references that have addressed heavy duty particulate emissions (12, 13, 14). These references highlight the difficulty in obtaining a stable size distribution within the time specification of the regulated test cycle. There is also a suggestion that “carry-over” effects may be seen, especially with increasing loads where hydrocarbons from the previous mode may have been deposited in the system and desorb and self-nucleate as the temperature increases (15, 16). It would appear that the immediate pre-history of the engine and sampling system may have as much effect in the determination of particle sizes and numbers as the conditions under test.

In order to investigate these effects, it was decided to carry out some extended mode testing, with the modes carefully selected to provide as wide a range of ‘pre-history’ as possible between consecutive modes.[2] This testing would not only give information to assist in the understanding of whether the preceding condition influences the measured size distribution, but also (by repetitive scanning) demonstrate the stabilisation period necessary for the distribution at any one condition. These modes are discussed in more detail in section 5.

[2] As with the light duty programme, the test programme was carried out by contract to a recognised third party test laboratory (AVL) with specialised assistance from the aerosol science field (Prof. G Reischl, University of Vienna).

3.1. SELECTION OF PARTICULATE MEASURING EQUIPMENT

3.1.1. Number & Size Measurement

Measurement of automotive particle number is carried out almost exclusively by electrical mobility techniques. In the first CONCAWE programme, four different types of electric mobility analyser were used. Of these, the SMPS analyser showed advantages in terms of repeatability, and was chosen as the basis of the work on heavy duty engines. However, a single instrument was not able to cover the full extended range of particle sizes desired for this study, since the scan time would be prohibitively long with current instruments. A development of this approach, using similar principles, was therefore employed.

The Dual Differential Mobility Particle Spectrometer (DDMPS) used in this study was specially developed for the purpose of characterising engine emissions. Most of the studies on motor vehicle engine aerosols have been performed with either the SMPS or DMPS (TSI inc.). The lower size limit (typically 10 nm) is controlled by the diffusion losses in the particle sizer and the cut-off diameter of the condensation nucleus counter which is used for particle detection. In the DDMPS particle detection is made using a Faraday Cup Electrometer which avoids the intrinsic properties of the Condensation Nucleus Counter used in the SMPS as the response is not dependent on any particle property. The lower levels of detection are governed by the electronic noise within the system. Due to basic physical laws, the sizing range of a typical Differential Mobility Analyser is limited to approximately two orders of magnitude, consequently two analysers are used in parallel which sample simultaneously and between them cover a wider range in particle size (3 -1000 nm).

The two mobility analysers used in the set-up are both geometrically optimised for their respective size ranges (diffusion losses of ultra-fine particles). The size ranges also overlap so that more information is obtained in the areas where peak particle production is expected. Details of the operation of the DDMPS are given in **Table 1**.

Table 1 Technical specifications of the DDMPS system

CHARGING	1 common ^{241}Am Charger (1.5 mCi, 2 s residence time)
CLASSIFICATION	2 DMAs (3 nm - 150 nm, 10 nm - 1000 nm) simultaneous operation, common data base
SENSOR	2 FCEs ($2*10^{-17}$ A - 10^{-10} A, 10^2 – 10^9 particles/second)
SIZE RESOLUTION	57 logarithmic equidistant steps *
CONC. RESOLUTION	4-10 charged particles/cm^3, up to $5*10^7$ charged particles/cm^3 without calibration (absolute method)
TIME RESOLUTION	76 s / 57 points of a size distribution (limited by the residence time in the DMAs)
FEATURES	Autocalibration, automatic drift correction, real-time data evaluation and real-time data display
LOW CONCENTRATION	Limited by electronic noise ($2*10^{-17}$ A)
HIGH CONCENTRATION	Unlimited

* the equidistant function is lost on the conversion from electrical mobility to particle diameter (see Appendix 1)

3.1.2. Mass Measurement

3.1.2.1. Regulated particulate mass

Regulated particulate mass measurements were made according to legislated procedures from a full flow CVS system. In order to reach the regulated test temperature of 52ºC, a second, very small dilution tunnel was used, to further dilute the exhaust from the main dilution tunnel. Teflon coated glass fibre filters (70 mm) were used for the collection of the particulate matter.

3.1.2.2. Particulate mass distribution

A Berner low pressure impactor was used for this study. This separates particles based on their aerodynamic properties to give a mass size distribution, albeit with lower size and time resolution. The smallest aerodynamic cut off diameter of an LPI is generally about 0.3 µm. In order to extend the range below this limit, smaller orifices or reduced pressure and high jet velocities are needed. The instrument used here is a Berner type 10 LPI where compressible flow is used to achieve smaller cut-off diameters. Details of the LPI are given in **Table 2**.

Table 2 Technical specifications of the LPI

Stage	Dp50 (µm)	Number of jets	Orifice diameter (mm)	Pressure (kPa)
11	16.0	1	15.2	101.32
10	8.0	12	4.2	101.31
9	4.0	24	2.1	101.28
8	2.0	44	1.1	101.15
7	1.0	46	0.7	100.51
6	0.5	25	0.6	97.05
5	0.25	22	0.5	86.87
4	0.125	25	0.4	52.05
3	0.063	116	0.25	34.31
2	0.031	116	0.3	18.72
1	0.016	232	0.3	8.34

In order to quantify the masses on the different stages of the LPI, ring-shaped aluminium foils (thickness 35 µm) were used. Prior to exposure, the foils were equilibrated and weighed in a humidity and temperature controlled environment and, in addition, where chemical analysis was to be carried out, the foils were baked in a nitrogen atmosphere to remove surface hydrocarbons.

4. SELECTION OF ENGINES AND FUELS

4.1. ENGINES

Two engines were selected, representative of Euro 2 and Euro 3 technology. The specifications for these engines are given in **Table 3**. Each engine would be tested over its appropriate legislative cycle. As a range of fuels were being tested, it was agreed to run the engines to constant accelerator pedal position to minimise fuel effects on engine calibration parameters. The engines were calibrated on reference fuel and the subsequent tests carried out without further adjustment to simulate on-road conditions with fuels of differing density. It was accepted that power outputs would vary between fuels.

Table 3 Engine specification data

ENGINE	**EURO 2 (DI/TCI)**	**EURO 3 (DI/TCI)**
Configuration	6 cylinder in-line	6 cylinder in-line
Swept Volume, l	7.3	9.2
Bore x Stroke, mm	107 x 135	118 x 140
Power, kW	230 at 2200 rpm	200 at 2300 rpm
CR	19.5	16
FIE	in-line pump	unit pump injection
EGR	No	Yes

4.2. FUELS

Fuels were selected to cover the range of fuel specifications found throughout Europe and also to provide a link to the study on light duty vehicles. The selected fuels were commercial fuels representing extremes of European Summer/Winter specifications together with Swedish Class I Diesel.

Properties of the test fuels are given in **Table 4**.

Table 4 Fuel specification data

	Test method	Fuel D1	Fuel D2	Fuel D3
DENSITY @ 15°C (kg/m^3)	ISO 3675	857	840	810
CETANE NUMBER	ASTM D 613	50.5	52.2	59.4
IBP (°C)	ASTM D 86	191	163	200
10/30/50/70/95% recovered at (°C)	ASTM D 86	243/273/294/316/367	206/238/263/286/338	214/-/238/-/283
FBP (°C)	ASTM D 86	378	353	293
SULPHUR (mg/kg)	ASTM D 3120	498	418	<1
AROMATICS (%mass)	IP 391/95			
Mono-		21.4	16.2	6.4
Di-		10.6	4.4	0.3
Tri+		1.8	0.4	Not detected
TOTAL		33.8	21.0	6.7
CALORIFIC VALUE (calc.)	ASTM D 4868-90			
NETT / GROSS (MJ/kg)		42.7/45.4	42.9/45.7	43.2/46.1

5. EXPERIMENTAL DESIGN AND PROCEDURES

5.1. PRE-TEST INVESTIGATION

In addition to the basic investigation of particle size distribution emitted over the chosen matrix of fuels and engines and using the legislated cycle, a considerable amount of work was carried out to investigate the extent that changes to the sampling system may have on measured results. A 'pre-test' investigation addressed the stabilisation time necessary for a consistent size distribution to be monitored. Three distinct experiments were carried out; two addressing the sampling system itself and the effect of changing either dilution ratio or residence time on particulate measurements and the third investigating the time needed to develop a stable distribution.

5.2. DAILY TEST PROTOCOL

In order to maintain a strict control of the test programme and to ensure that repeat testing saw exactly the same engine sequence, a fixed daily test schedule (**Table 5**) was used for each engine fuel combination. For each engine, each fuel was tested in duplicate with the baseline fuel re-tested at intervals to provide assurance that the engine was stable throughout the test programme (**Table 6**).

Table 5 Daily test order for one engine/fuel combination

TEST	MEASUREMENT
Regulated cycle (R49 or ESC)	CVS/DDMPS
Regulated cycle (R49 or ESC)	LPI - 10 steps
Extended Mode 1 (EM1)	CVS/DDMPS
Extended Mode 2 (EM2)	CVS/DDMPS
Extended Mode 3 (EM3)	CVS/DDMPS
Extended Mode 4 (EM4)	CVS/DDMPS
Extended Mode 5 (EM5)	CVS/DDMPS
Extended Mode 2 (EM2)	LPI - 10 steps
Extended Mode 5 (EM5)	LPI - 10 steps

Table 6 Fuel test order

DAY	FUEL TESTED
1	D1
2	D1
3	D3
4	D2
5	D1
6	D1
7	D2
8	D3
9	D1

Particulate emissions were measured using a full-flow dilution tunnel with a secondary dilution stage. The samples for both the regulated filter and the DDMPS sampler were taken from the secondary tunnel but the impactor sample was taken from the primary tunnel because of the flow needed through the impactor. Hence, impactor measurements had to be made over separate tests.

The scan time of the DDMPS system allows three consecutive scans to be made at each R49 test condition. These scans are run consecutively during the latter part of the 6 minute sampling time allowed (**Figure 1**, ECE = R49). For the ESC cycle there is insufficient time for more than one scan (except at idle); the sampling protocol for the ESC is shown in **Figure 2**.

Figure 1 DDMPS sampling timing diagram for ECE R49 cycles

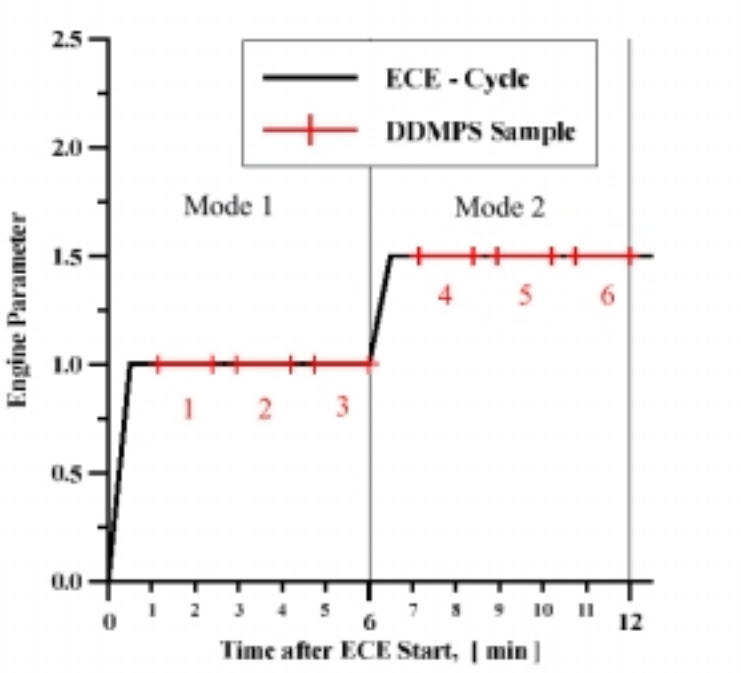
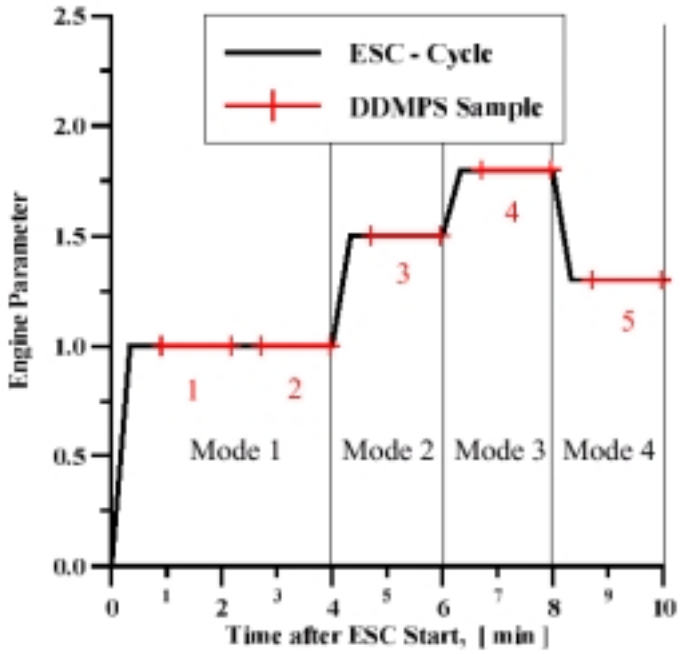


Figure 2 DDMPS sampling timing diagram for ESC cycles



5.3. SELECTION OF TEST MODES

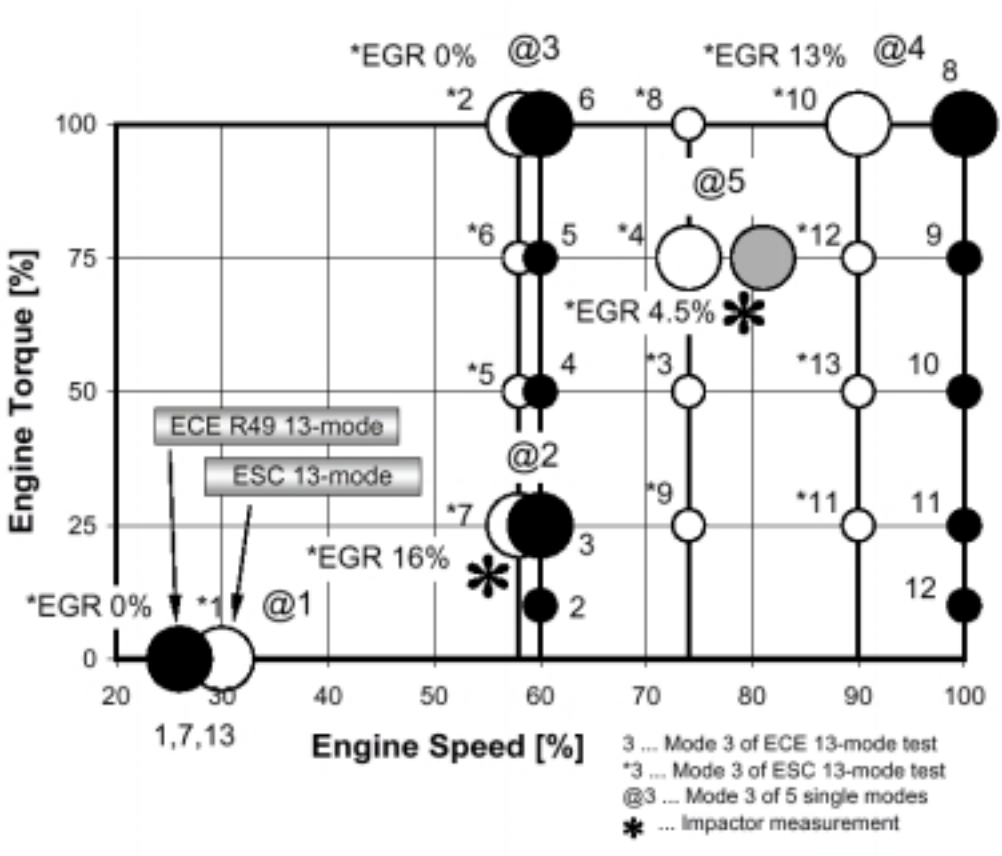
It was agreed that each engine would be tested over its relevant legislative cycle. In addition, five extended modes were chosen to examine the stability, the effect of "carry-over", dilution and residence time. Ideally, all five sets of speed and load conditions would have been run on each engine. However, because the two engines are optimised for different cycles, there was a concern that selection of a steady-state condition outside of the mode steps may give unrepresentative emissions. It was decided that four of the steady-state conditions would be selected to represent modes from the relevant cycles but to be as similar to each other as possible. An additional operating condition was selected to represent road driving and was run on each engine. The modes are shown in **Figure 3** and **Table 7**.

Table 7 Conditions of extended mode testing.

	Euro 2 engine			**Euro 3 engine**		
Extended Mode	R49 mode	% max. speed	% max. load	ESC mode	% max. speed	% max. load
EM1	1, 7,13	idle		1	idle	
EM2	3	60	25	7	58	25
EM3	6	60	100	2	58	100
EM4	8	100	100	10	90	100
EM5*	-	74	75	4	74	75

* simulated road condition

Figure 3 Selection of engine test modes for extended testing



5.4. FURTHER TEST WORK

Additional test work was carried out to investigate the effect of a particulate trap (CRT) on measured particle size distributions. This work is described in **Appendix 2**.

6. VALIDATION OF RESULTS/DATA HANDLING

The experiment was designed with long-term repeat tests on each fuel to allow fuel effects to be compared with the normal day to day variation.

Before analysing the particle number results, the regulated emissions data were examined. Repeatability was found to be good and no outlying data were identified (**Section 7**).

The handling of the size-discriminated particle number and mass data is described in **Appendix 1**.

7. RESULTS AND DISCUSSION

7.1. TEST REPEATABILITY

7.1.1. Regulated Emissions

Before starting the test programme, the compliance of the engines with the legislative emission limits (already in force or proposed) was checked. The Euro 2 engine was tested according to the ECE R49 and the measured emission levels compared to the emission limits applicable for this technology level; the Euro 3 engine was tested according to the ESC cycle and the emission levels compared to the Euro 3 emission limits. These emission tests were carried out using a reference fuel; its main properties are listed in **Table 8**.

Table 8 Specification data for ECE reference fuel (RF 73)

	RF 73
DENSITY @ 15°C (kg/m^3)	**837**
Kinematic Viscosity @ 40°C (cSt)	**3.062**
CETANE NUMBER	**52.1**
IBP (°C)	**184.5**
50/90% recovered at (°C)	**273.5/335**
FBP (°C)	**367.5**
SULPHUR (mg/kg)	**410**
AROMATICS (%mass)	
Mono-	**19.5**
Di-	**3.8**
Tri+	**0.4**
TOTAL	**23.7**
CALORIFIC VALUE (calc)	
NETT (MJ/kg)	**42.94**

Both test engines met the legislative limits as shown in **Table 9**:

Table 9 Engine emissions performance against regulated emissions limits

		HC (g/kWh)	CO (g/kWh)	NOx (g/kWh)	PM (g/kWh)	Fuel Cons. (g/kWh)
ECE R49 Cycle Fuel: RF 73	**Euro 2 Limits**	1.1	4.0	7.0	0.15	
	Euro 2 Engine	0.292	0.707	6.52	0.144	209.3
ESC Cycle Fuel: RF 73	**Euro 3 Limits**	0.66	2.1	5.0	0.10	
	Euro 3 Engine	0.057	0.406	4.42	0.097	206.9

The regulated emissions of the Euro 2 and Euro 3 engines measured with the test fuels are given in **Tables 10** and **11** and shown in **Figures 4** and **5**. Besides the test carried out using the reference fuel to check the compliance of the engines with the emission limits, a minimum of two emission tests was performed for each test fuel; in the case of Fuel D1, seven tests were carried out in all with the Euro 3 engine and six tests with the Euro 2 engine. The repeatability of regulated emission measurements can be assessed from the emission tests performed with Fuel D1. The mean values and the standard deviation of these tests for each pollutant are listed in **Table 12**. As shown in the table, although the test cycle and emission levels were different for the two engines, the repeatability turned out to be good for both.

Table 10 EURO 2 Engine - ECE R49 Test Cycle - Regulated Emissions and Fuel Consumption (g/kWh)

Fuel		HC	NOx	CO	PM	CO_2	Fuel cons.
RF 73		0.292	6.52	0.707	0.144	684.0	209.3
Fuel D1	Mean	0.265	7.20	0.747	0.158	688.9	210.7
Fuel D2	Mean	0.299	7.12	0.683	0.139	678.6	208.4
Fuel D3	Mean	0.339	6.58	0.665	0.110	664.9	205.5

Table 11 EURO 3 Engine - ESC Test Cycle - Regulated Emissions and Fuel Consumption (g/kWh)

Fuel		HC	NOx	CO	PM	CO_2	Fuel cons.
RF 73		0.057	4.42	0.406	0.097	649.4	206.9
Fuel D1	Mean	0.046	4.82	0.370	0.093	662.7	207.7
Fuel D2	Mean	0.072	4.54	0.374	0.088	656.6	206.0
Fuel D3	Mean	0.069	4.11	0.412	0.081	646.9	205.4

Table 12 Engine emissions performance against regulated emissions limits

FUEL D1 – Regulated Emissions and Fuel Consumption							
		HC	**CO**	**NOx**	**PM**	**CO_2**	**Fuel cons.**
EURO 2 Engine (ECE R49 Cycle)	**Average of 6 tests (g/kWh)**	0.265	0.747	7.20	0.158	688.9	210.7
	Standard Deviation	0.004	0.031	0.071	0.003	7.34	0.37
EURO 3 Engine (ESC Cycle)	**Average of 7 tests (g/kWh)**	0.046	0.370	4.82	0.093	662.7	207.7
	Standard Deviation	0.006	0.008	0.063	0.002	3.09	0.58

Figure 4 Euro 2 Engine - Regulated emissions (g/kWh)

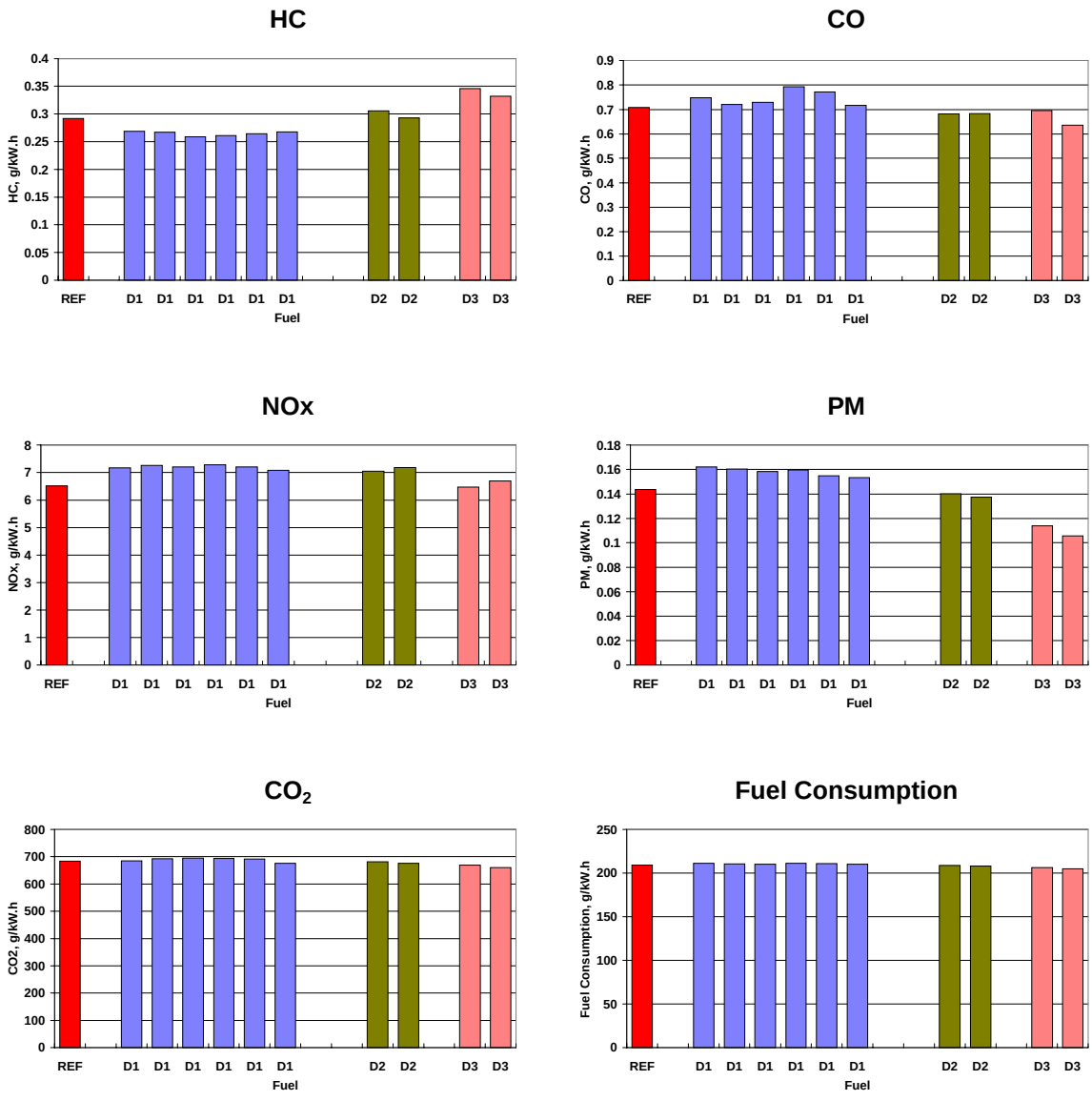
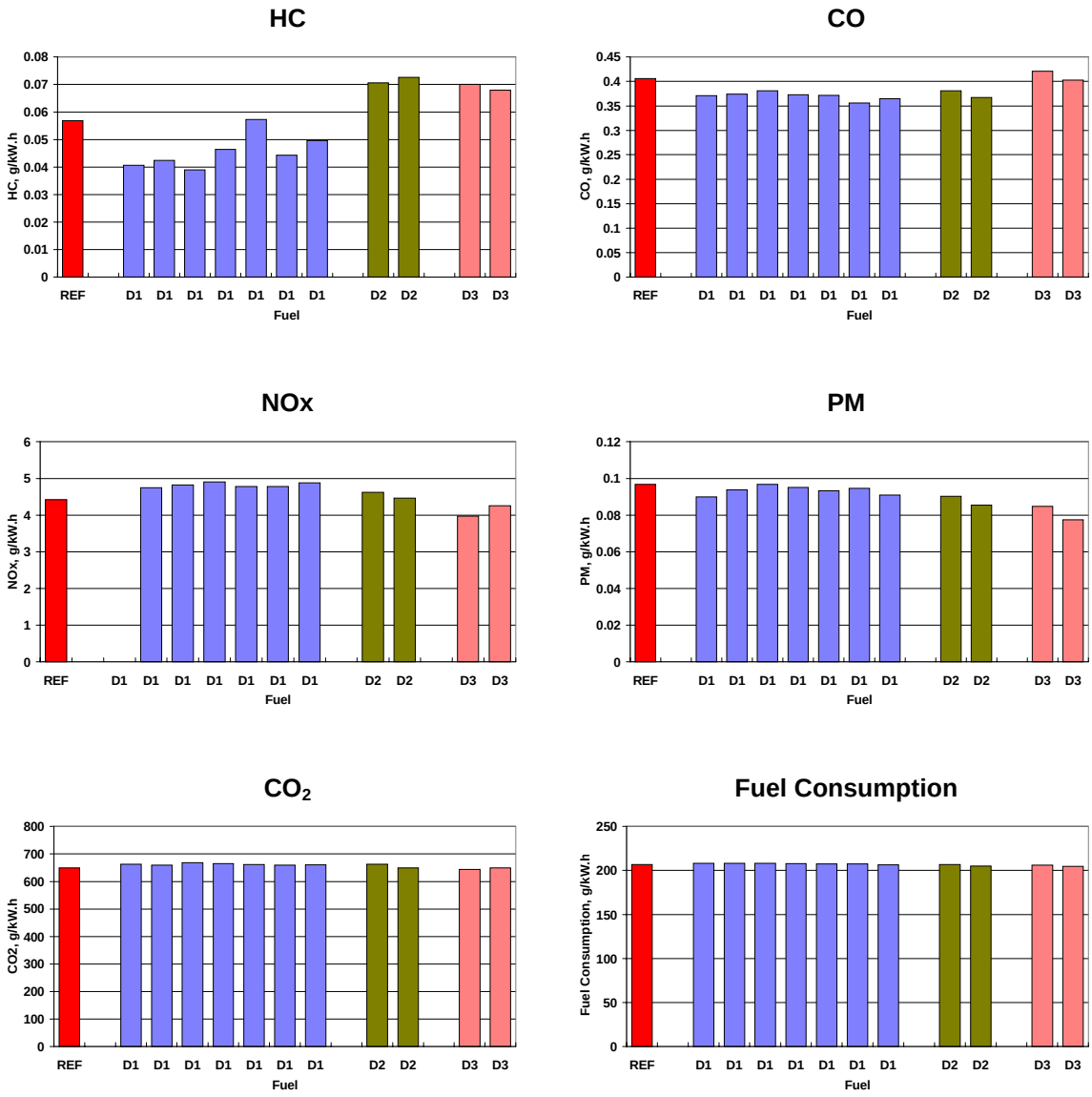


Figure 5 Euro 3 Engine - Regulated emissions (g/kWh)



7.1.2. DDMPS size distributions

The good repeatability obtained for the measurement of the regulated emissions gave a degree of confidence with respect to the size distribution data. For each of the 13 test conditions within the legislated cycles, a size distribution is measured. It is possible to combine these distributions, following application of the relevant weighting factors, to produce a distribution representative of the complete cycle (see **Appendix 1**). **Figures 6** and **7** show these distributions for each fuel run in both engines.

Figure 6 Euro 2 Engine - DDMPS results for fuels D1-D3; ECE weighted averages (individual test runs)

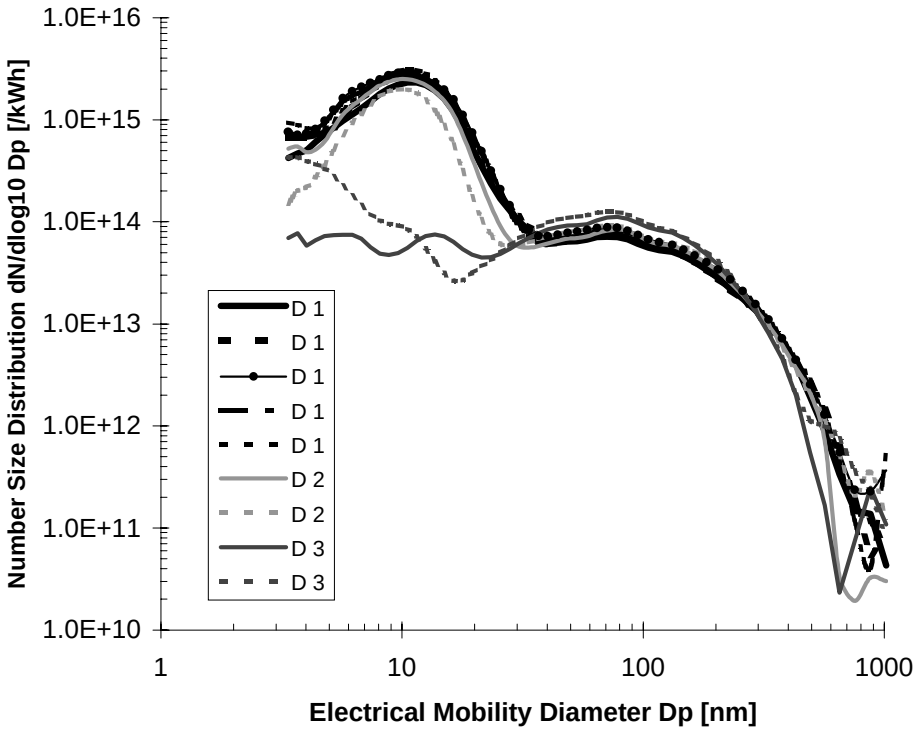
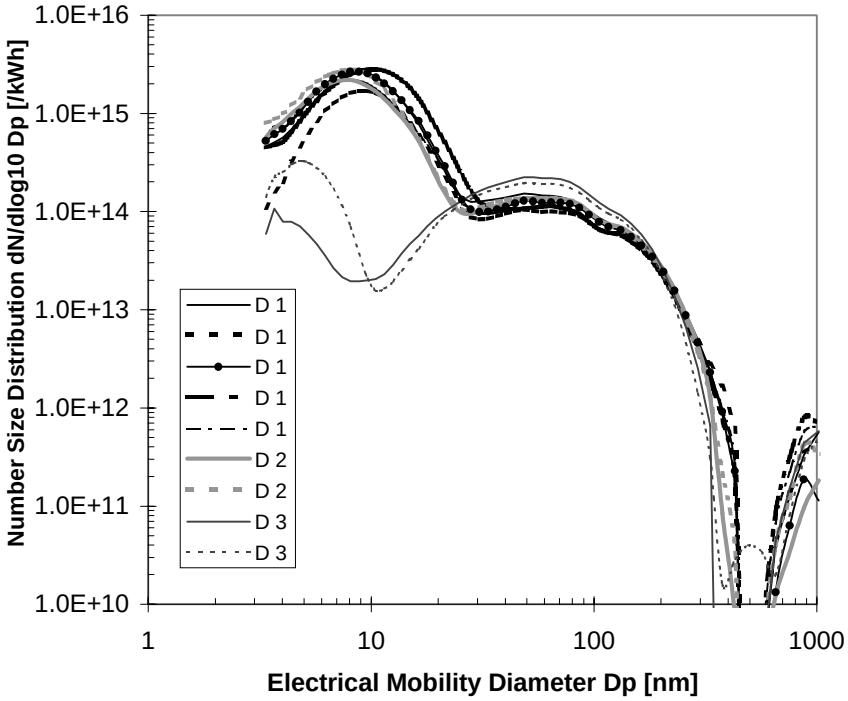


Figure 7 Euro 3 Engine – DDMPS results for fuels D1-D3; ESC weighted averages (individual test runs)



It can be seen that the repeatability of the measurements is very good. The final distribution shows a clear bimodal pattern. In order to assist subsequent discussion, the two areas of this distribution (those particles <30 nm and called nucleation particles and those particles >30 nm and called accumulation particles) will be treated separately and discussed in more detail at a later stage.

The differences observed in the nucleation range with respect to fuel D3 needs to be examined in relation to simultaneous changes in the sampling conditions. This is discussed in more depth later.

Table 11 gives the standard deviation of the different test procedures used in the programme (i.e. number distribution (DDMPS), mass distribution (LPI) and regulated filter measurement) both for total measurement and split into the two areas as described above. It can be seen that for the number distribution there is less variability in the accumulation mode particles than in the nucleation mode. For the LPI there is little difference in the standard deviation for the total mass and those particles >30 nm, but it must be remembered that for the <30 nm mass particles, only the first 1.5 test stages are used for the calculation. (See **Table 2**).

Mass, as measured by the regulated filter procedure, gives the most robust measurement of particulate matter.

Table 13 ESC and ECE cycles - Test-to-test standard deviation for each method.

Method	Measurement	Standard Deviation
DDMPS	Total no. of particles emitted (N/kWh)	0.199 x N
	No. of particles < 30 nm (N/kWh)	0.287 x N
	No. of particles > 30 nm (N/kWh)	0.092 x N
LPI	Total mass of particles emitted (µg/kWh)	0.050 x mass
	Mass of particles < 30 nm (µg/kWh)	0.119 x mass
	Mass of particles > 30 nm (µg/kWh)	0.046 x mass
Regulated emissions	Filter paper mass (g/kWh)	0.032 x mass

7.2. FUEL EFFECTS

As far as the fuel effect on regulated emissions is concerned, **Tables 14** and **15** show the percentage variations of the regulated emission levels when Fuel D2 (winter grade) and Fuel D3 (Swedish class 1) are used, in comparison to the emissions measured with Fuel D1 (summer grade) which is considered as base line. The variations are calculated from the mean values of regulated emissions measured in the tests performed with the different test fuels.

In evaluating the fuel effect on emissions, it should be taken into account that the two engines featured very different technologies and also that the test cycle was different; so, the fuel effect and the technology effect on regulated emissions of the two engines cannot be directly compared because it is not easy to separate the fuel and technology effects from the cycle effect.

Moreover, the test fuels had densities varying in a wide range (min. 810, max. 857 kg/m^3) and the engine management system was not modified in order to compensate for the different densities of the fuel. So, the fuel effects reported in the tables are inclusive of the density effect.

Table 14 Euro 2 Engine – Percentage Variations of Emissions (D2 and D3 vs. Fuel D1 ECE R49 Cycle

	HC	CO	NOx	PM	CO_2	Fuel cons
Fuel D2	13%	-9%	-1%	-12%	-1%	-1%
Fuel D3	28%	-11%	-9%	-31%	-3%	-2%

Table 15 Euro 3 Engine – Percentage Variations of Emissions (D2 and D3 vs. Fuel D1) ESC Cycle

	HC	CO	NOx	PM	CO_2	Fuel cons
Fuel D2	57%	1%	-6%	-6%	-1%	-1%
Fuel D3	51%	11%	-15%	-13%	-2%	-1%

Unburnt hydrocarbons (HC):

For both engines an increase of HC emissions was observed with Fuels D2 and D3 compared to the emissions measured with Fuel D1; the increase was higher for the Euro 3 engine and, in this case, Fuels D2 and D3 showed very similar behaviour. For the Euro 2 engine Fuel D3 caused an increase of HC emissions about twice that of Fuel D2.

Nitrogen Oxides (NOx):

For both engines NOx emissions decreased using Fuels D2 and D3 although, in the case of Euro 2 engine, Fuel D2 had a very small effect. Fuel D3 had a bigger effect than Fuel D2.

Carbon Monoxide (CO):

The fuel effect on CO emissions was very different for the two engines; for the Euro 2 engine the CO emissions decreased with both Fuels D2 and D3 whereas they increased in the case of the Euro 3 engine. Moreover, Fuels D2 and D3 showed a similar effect on the Euro 2 engine emissions whereas only Fuel D3 had a significant effect on CO emissions of the Euro 3 engine. In all cases, CO emissions were well below the regulated limits.

Particulate Matter (PM):

Although particulate emissions, in terms of mass, were reduced by both Fuel D2 and D3 in both engines, the emissions were affected to a quite different extent depending on the engine technology. In fact, the Euro 3 engine (or the Euro 3 cycle?) was less sensitive to fuel quality than the Euro 2 engine, with the reduction in PM mass from the Euro 3 engine only half that measured from the Euro 2 engine.

The regulated emissions for each test fuel were also calculated using the EPEFE equations for HD diesel engines (17) and the values obtained are reported in **Table 16**.

In the case of particulate emissions two values are reported: the first was calculated using the original EPEFE equation, the second one was obtained after correction for the sulphur effect (18). The equations that were used are the following:

g/kWh

CO: 2.24407 – 0.0011 DEN + 0.00007 POLY – 0.0768 CN – 0.00087 T95

HC: 1.61466 – 0.00123 DEN + 0.00133 POLY – 0.00181 CN – 0.00068 T95

NOx: -1.75444 – 0.00906 DEN + 0.0163 POLY – 0.00493 CN + 0.00266 T95

PM: 0.06959 – 0.00006 DEN + 0.00065 POLY – 0.00001 CN

PM*: (0.06959 – 0.00006 DEN + 0.00065 POLY – 0.00001 CN) [1-0.0086 (450 - sulphur)/100)]

* corrected for sulphur effect

Table 16 Predicted emissions from EPEFE equations

Regulated Emissions Calculated from EPEFE Equations – (g/kWh)					
	HC	**NOx**	**CO**	**PM**	**PM***
Fuel D1	**0.24**	**6.94**	**0.59**	**0.129**	**0.130**
Fuel D2	**0.26**	**6.58**	**0.62**	**0.123**	**0.122**
Fuel D3	**0.32**	**6.05**	**0.64**	**0.118**	**0.113**
D2 vs. Fuel D1	**11%**	**-5%**	**5%**	**-5%**	**-6%**
D 3 vs. Fuel D1	**35%**	**-13%**	**10%**	**-8%**	**-13%**

* corrected for sulphur effect

Table 16 also reports the percentage variations of calculated regulated emissions of Fuels D2 and D3 compared to the calculated emissions of Fuel D1.

The EPEFE equations were derived from an experimental programme based on the ECE R49 cycle, therefore the results obtained with the Euro 3 engine tested over the ESC cycle cannot be directly compared with the calculated values.

If the behaviour of the test fuels according to the EPEFE equations is compared to the results obtained with the Euro 2 engine, whilst reasonably good agreement is seen for HC and NOx emissions, it can be seen that the actual effect of fuel quality on CO emission is the opposite of what is estimated by the equations; moreover, the measured effect on PM emissions is higher than the calculated one. Applying such comparisons, it has to be understood that the EPEFE equations are based on a set of engines and that individual engines would differ.

7.3. INVESTIGATION OF SAMPLING EFFECTS

7.3.1. Dilution Ratios

Dilution ratio has been identified in earlier studies as an important factor influencing particle size distributions. In particular, the low dilution ratios applied in the standard dilution tunnel used for regulated PM mass measurement are very different from the real world case of an exhaust mixing into the ambient air. To study the influence of exhaust gas dilution on the resulting aerosol size distributions an AVL Mini dilution tunnel was used, where the dilution ratio can be varied. A series of experiments was performed at selected operating modes of the Euro 2 engine using fuel D1.

For each selected, extended engine operation mode (EM2, EM4 and EM5) three dilution ratios have been investigated. The corresponding temperatures of the diluted exhaust gas are listed in **Table 17**.

Table 17 Sampling parameters at extended mode conditions

	Dilution Ratio	Temperature [°C]
EM 2	5.7	62.5
EM 2	7.8	46.0
EM 2	23.7	30.5
EM 4	10.8	63.5
EM 4	22.8	36.4
EM 4	38.5	30.8
EM 5	8.3	61.2
EM 5	12.7	44.9
EM 5	33.0	31.0

The measured number size distributions for the three selected modes are shown in **Figures 8-10**.

Figure 8 DDMPS – Euro 2 engine – Influence of the dilution ratio – Extended Mode 2

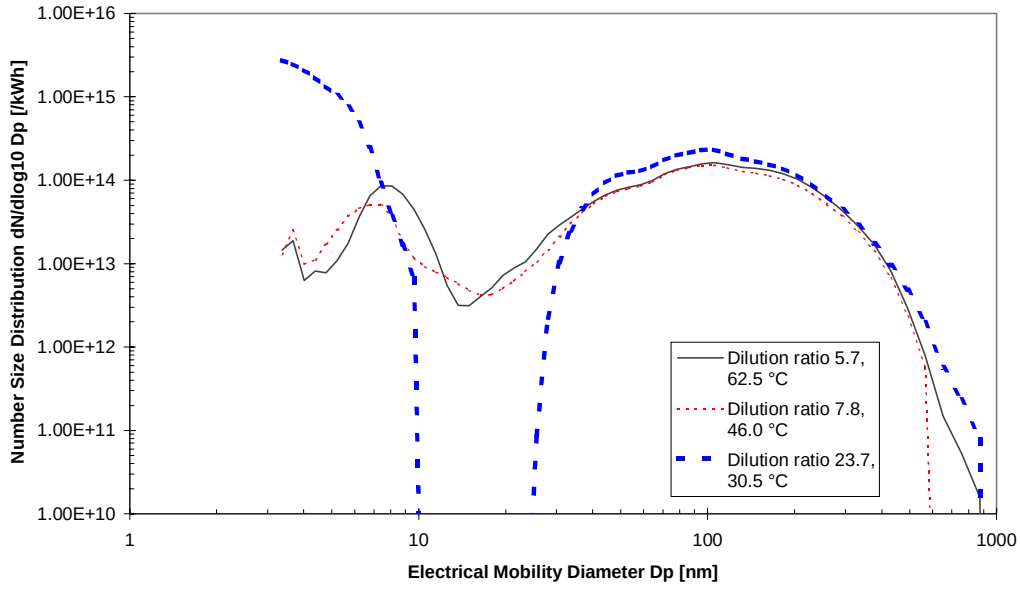


Figure 9 DDMPS - Euro 2 engine - Influence of the dilution ratio - Extended Mode 4

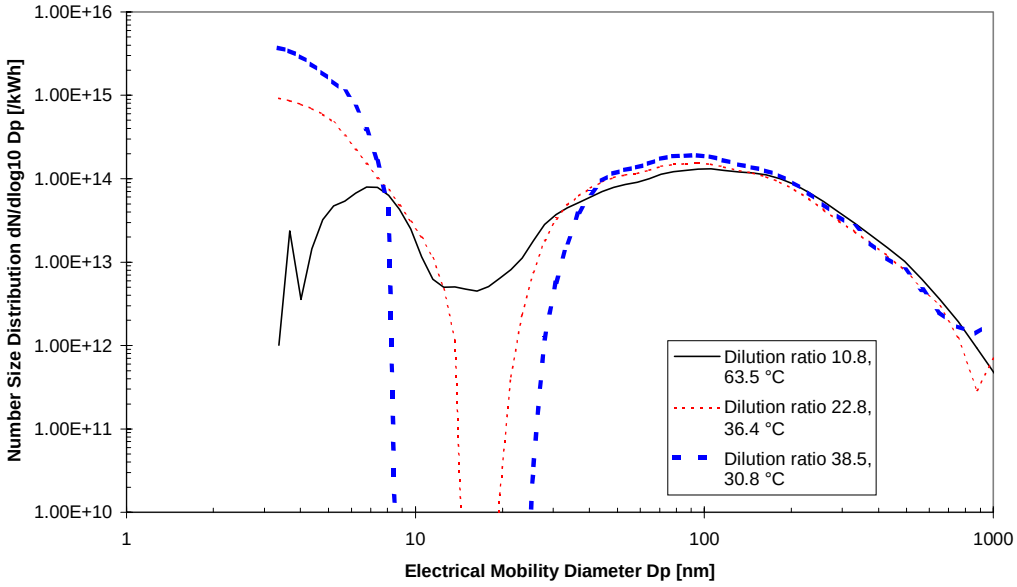
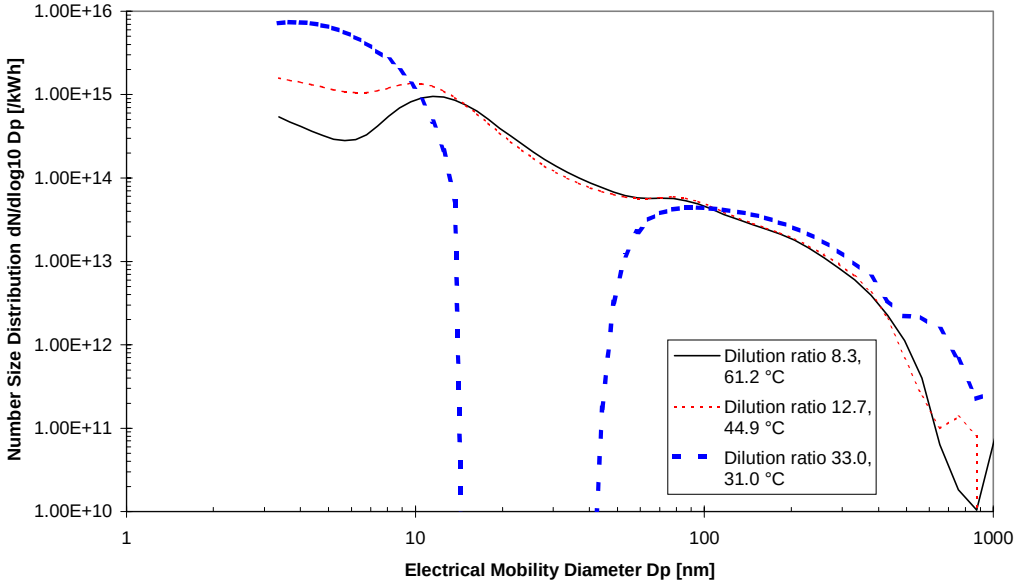


Figure 10 DDMPS – Euro 2 engine - Influence of the dilution ratio - Extended Mode 5



The number/size distributions are normalised to the raw gas concentrations (as has been done throughout this study) to make comparisons easier.

These results show that the accumulation mode particles are relatively insensitive to changes in dilution ratio, whereas the nucleation particles are seen to increase with higher dilution ratios. However, the increasing dilution ratio is associated with a corresponding reduction in temperature. Although this study could not separate these two effects, work by Kittelson (11) has demonstrated that numbers of nucleation particles are increased by a reduction in temperature and decreased by increases in dilution ratio. CONCAWE experts believe that our results are dominated by the temperature effect.

To understand which of these conditions most closely represents the real world situation, measurements under road conditions (19) must become available. However, some insight can be gained by considering the likely mechanisms.

According to Kittelson, the formation of nucleation particles is dependent on the quantity of volatile material present. These volatile components have two alternatives: to adsorb onto existing particles (thereby causing a shift in size but not increasing the number) or to self nucleate (resulting in an increase in the number of small particles).

There are different factors that determine which pathway is taken:

- the saturation ratio of the volatile material
- the available surface area
- the adsorption energy
- time available for adsorption

The saturation ratio is defined as the partial pressure of the individual volatile species divided by the saturation pressure of the same species. If conditions are at the saturation pressure, the vapour is in equilibrium with respect to both evaporation and condensation, but if supersaturated conditions exist, condensation will dominate.

If the saturation ratio is sufficiently high (and especially if there is limited surface area available for condensation) the species may self nucleate.

Kittelson has also demonstrated that the relationship between dilution ratio and saturation ratio gives the highest saturation ratios (i.e. favouring nucleation) at dilution ratios between 5:1 and 50:1 - typical CVS values.

The important considerations for nucleation are the concentrations of the available carbon (for adsorption) and the volatile species. If there is sufficient carbon area, hydrocarbons and sulphate will adsorb, thus preventing the saturation ratio from getting too high. However, in the testing of newer technology engines where optimisation for particulate mass reduction has resulted in much reduced carbon emissions, there is likely to be an increase in saturation ratio and consequently nucleation.

7.3.2. Residence Time

To investigate the influence of the sampling time delay (i.e. the residence time of the aerosol from the engine manifold to the inlet of the measuring device) on the number size distribution, a plenum (installed between the secondary dilution tunnel and the intake of the DDMPS system) was used. With this device the residence time of the aerosol was increased. The dilution tunnel was left unchanged. Measurements were performed for extended modes EM2, EM3 and EM5 with the Euro 2 engine and fuel D1.

The plenum consisted of a cylindrical PTFE-coated polyethylene container with a volume of 90 litres. Aerosol was passed through this plenum with a total flow rate of 24.2 l/min resulting in a mean residence time of 3 min. 43 s. For the standard system, where measurement was made at the secondary dilution tunnel the residence time was only 6 s. With the plenum in place, the aerosol therefore had more than 37 times longer to let dynamic processes alter its size distribution.

While the aerosol is held in the plenum, a number of processes could occur:

- condensation of vapours on nuclei;
- coagulation of small particles on to larger particles.

The results obtained from the experiments with the plenum have been averaged and compared to the results obtained from all the experiments with fuel D1 using standard sampling conditions, as shown in **Figures 11-13**.

Figure 11 DDMPS - Euro 2 Engine - Direct sampling vs. sampling through plenum - Extended Mode 2

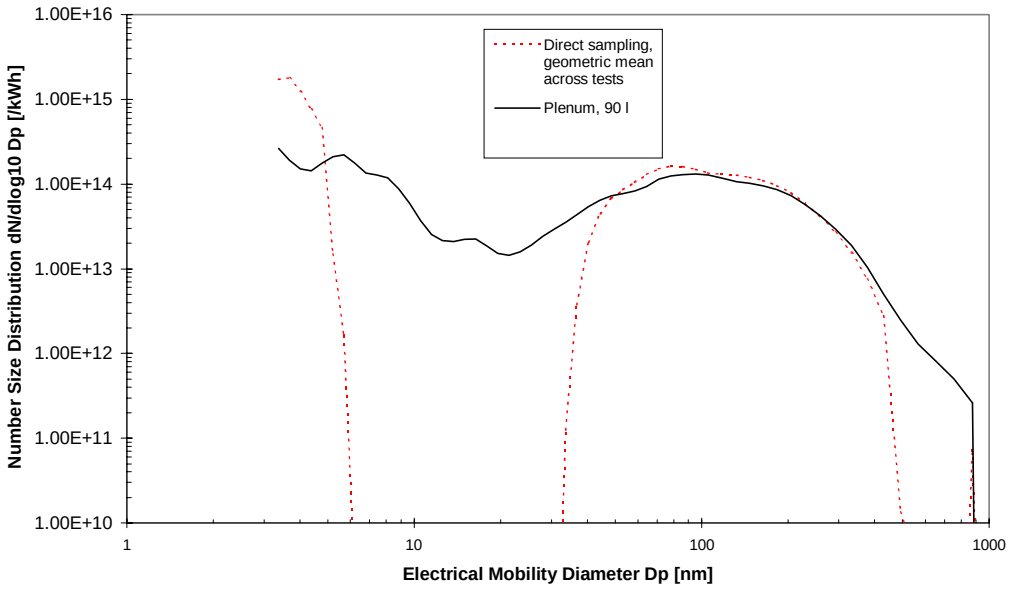


Figure 12 DDMPS - Euro 2 Engine - Direct sampling vs. sampling through plenum - Extended Mode 3

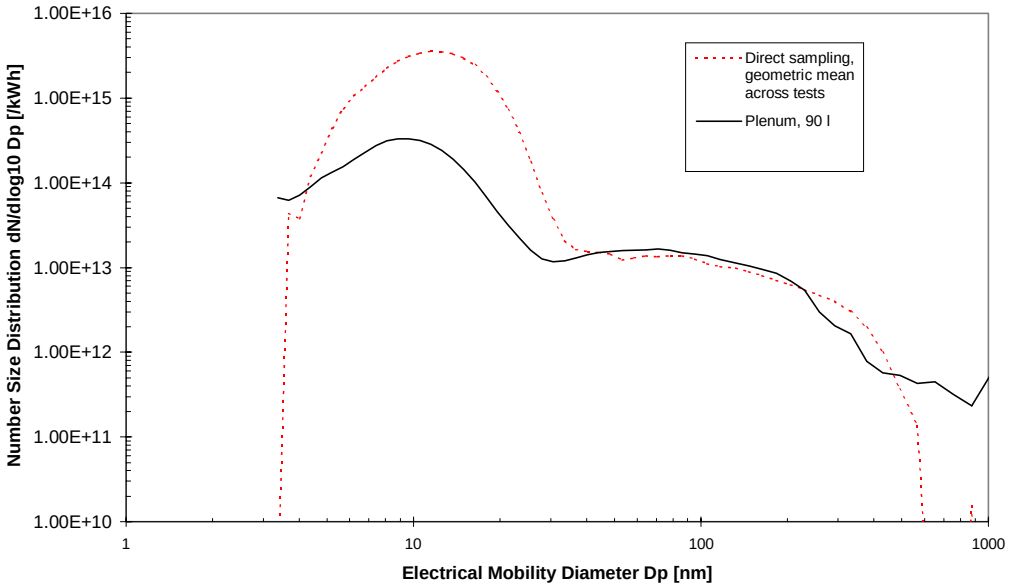
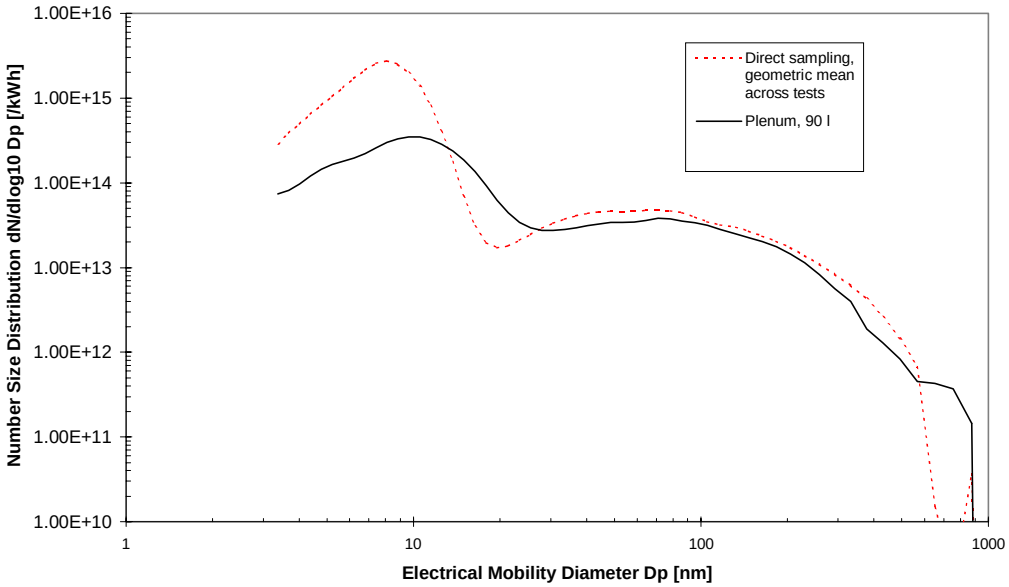


Figure 13 DDMPS - Euro 2 Engine - Direct sampling vs. sampling through plenum - Extended Mode 5



For all three selected modes the long residence time in the plenum resulted in a noticeable decrease of the ultra fine particle mode with a shift towards larger particles. These figures demonstrate that the accumulation mode particles are relatively insensitive to changes either in residence time or engine operating conditions. Again, it is the particles in the nucleation range that show the variability, although not in a consistent manner. These figures imply that nucleation particles are sensitive to engine operating and sampling conditions.

Further tests on the effect of residence time were carried out by extending the sample line, where similar results (i.e. reduction in the number of ultrafine particles) was seen.

7.3.3. Summary of sampling effects

The overall conclusions from the studies of dilution ratio, temperature and residence time are:

- The size and number of fine particles (<30 nm) is strongly affected by these parameters. Further study of vehicle and fuel effects on these emissions is strongly dependent on development of an agreed and reliable test methodology.
- Number and size distribution of the accumulation mode particles (essentially >30 nm) is much less sensitive to the dilution and residence time.
- Temperature effects are believed to be the most important in the measurement of small particles.

7.4. INVESTIGATION OF ENGINE TEST EFFECTS

7.4.1. Stabilisation Time

For the extended modes 1-5 of the R49 ECE and ESC cycles consecutive DDMPS measurements were taken for more than 20 minutes at constant engine parameter settings using Fuel D1. Data were evaluated as a function of time after the engine has reached stable conditions. Results from the Euro 2 engine were rather variable, however the Euro 3 engine showed some clear trends and is presented here in **Figures 14-17** for extended modes EM2 to EM5.

Figure 14 Euro 3 engine - DDMPS - Effect of time on Extended Mode 2 (ESC mode 7) results

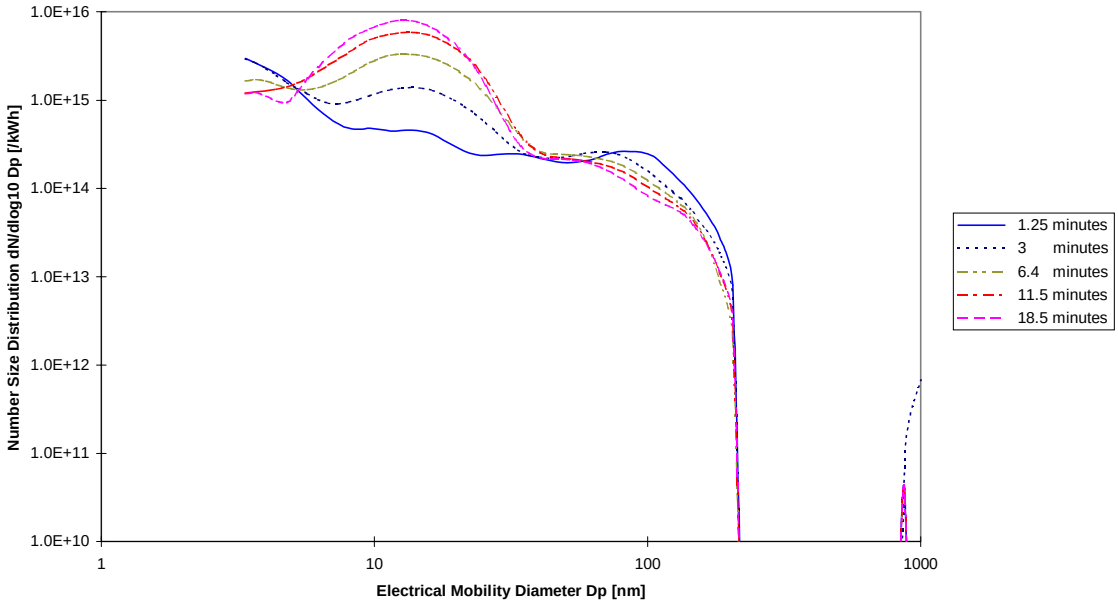


Figure 15 Euro 3 engine - DDMPS - Effect of time on Extended Mode 3 (ESC mode 2) results

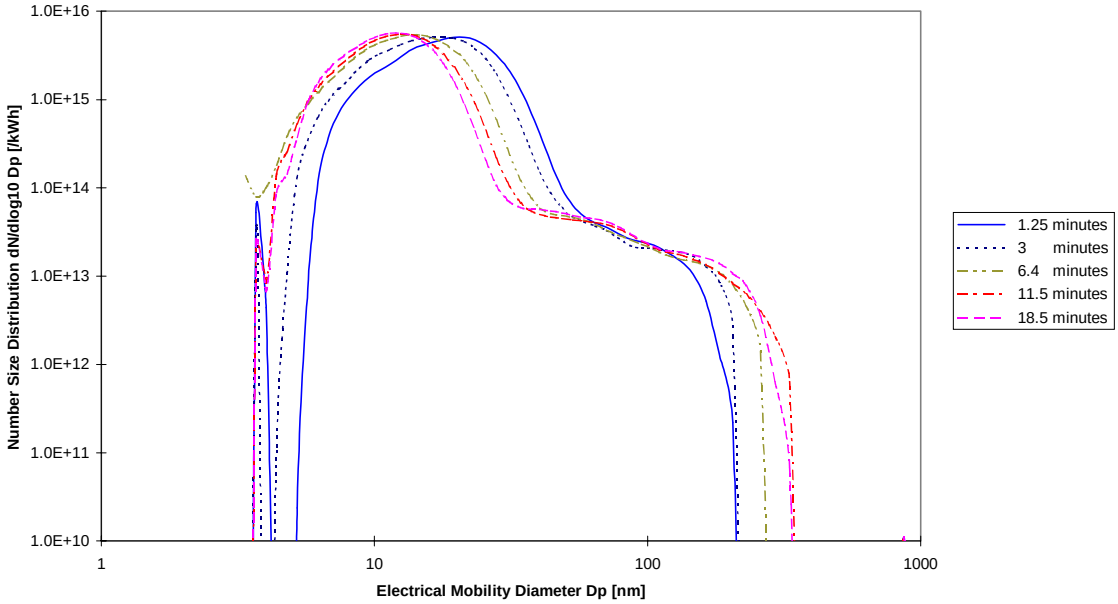


Figure 16 Euro 3 engine - DDMPS - Effect of time on Extended Mode 4 (ESC mode 10) results

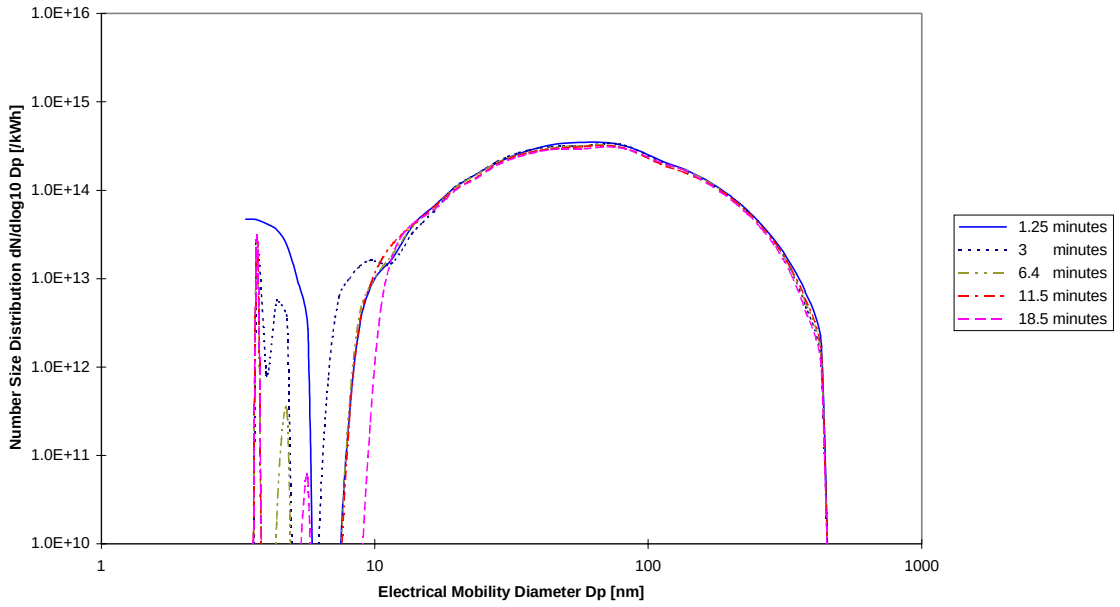
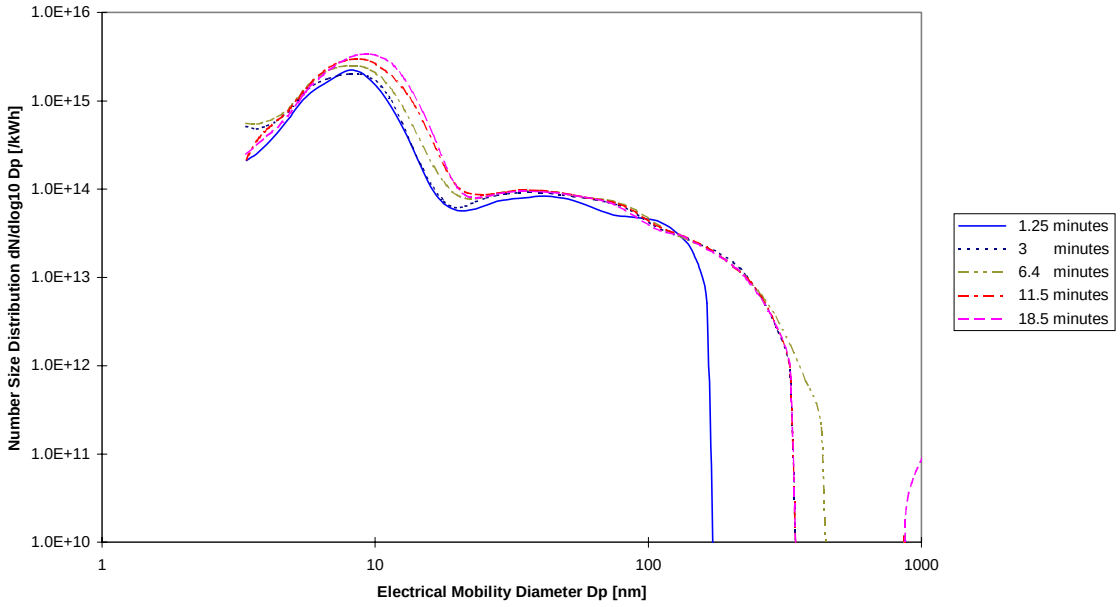


Figure 17 Euro 3 engine - DDMPS - Effect of time on Extended Mode 5 (ESC mode 4) results



Progressive changes in the size distribution can be seen for each of the test conditions - but the trends are not always in the same direction. Two peaks can be seen in each mode, but these do not always split into <30 nm and >30 nm sections; in some cases there is evidence of large numbers of particles at the lower detection limit of the analyser, around 3 nm.

The most stable results were seen for extended mode EM4, which represents a full load condition close to the rated speed of the engine. In this condition, only the accumulation mode was clearly seen, covering a range of 10-400 nm. The total number of particles was much lower for this mode than for EM 1, 2, 3 and 5 due to the fact that there are fewer nucleation particles.

EM 3 and 5, representing medium speed and high to full load, also showed reasonably stable performance, although there were trends with time, different for the two modes.

- EM 3 (full load at 58% speed) showed a trend for decreasing particle size over time, the fine particle peak moving from around 20 nm to 10 nm.
- EM 5 (75% load at 74% speed) showed a small increase in the number and size of fine particles.

EM 1 and 2, both lower load and therefore cooler conditions, showed much larger variations - but again not in the same direction.

- EM 1 (idle, no figure shown) gave a decrease in the size of the very fine particles (around 3 nm), with a corresponding increase in the size of particles in the 10-30 nm range. The number of particles above 30 nm was small. The total number concentration decreased in the same time by a factor of five.
- EM 2 (25% load, 58% speed) showed little change in the size of the fine particles, but a marked increase in their number over time, with a smaller corresponding decrease in the number of accumulation mode particles.

It can be seen that at high load, where the emitted particles are predominantly carbonaceous, the distribution is dominated by accumulation mode particles, the stabilisation is almost instantaneous and the distribution is unaffected by the time series. However at light load, where there is a greater proportion of hydrocarbon and volatile material present in the exhaust, the distribution is dominated by nucleation particles. The distribution shows greater variability and takes much longer to stabilise.

These results illustrate the importance of strict control over engine test conditions to enable repeatable measurements to be obtained. However the pattern of the data is complex, and no clear trends emerge to indicate a best way to carry out the test. In these tests, efforts were made to keep the measurement conditions constant over time, with the intention of studying the stability of the test engine. However, the possibility that the observed variations with time could be related to the sampling and measurement system as well as the engine cannot be ruled out.

Following these investigations, extended mode distribution data were generated as part of the daily protocol following twenty minutes stabilisation.

7.4.2. Comparison of stabilised distribution data with corresponding cycle data

Within the test protocol, selected test conditions (as described in section 5) were investigated in more detail to understand the effect of time on the measured size distribution. The following figures illustrate the size distribution measured once the engine had undergone a 20 minute stabilisation period for extended modes EM2 and EM4 (ESC modes 7 and 10; ECE modes 3 and 8 - representative of a low speed/light load and a high speed/high load condition), plotted alongside the corresponding scan from the legislated cycle test. **Figures 18** and **19** show the results for the Euro 3 engine and **Figures 20** and **21** show the results for the Euro 2 engine.

Figure 18 Euro 3 engine – DDMPS – Comparison of standard mode (ESC mode 7) with extended mode (EM2 at 20 minutes) results

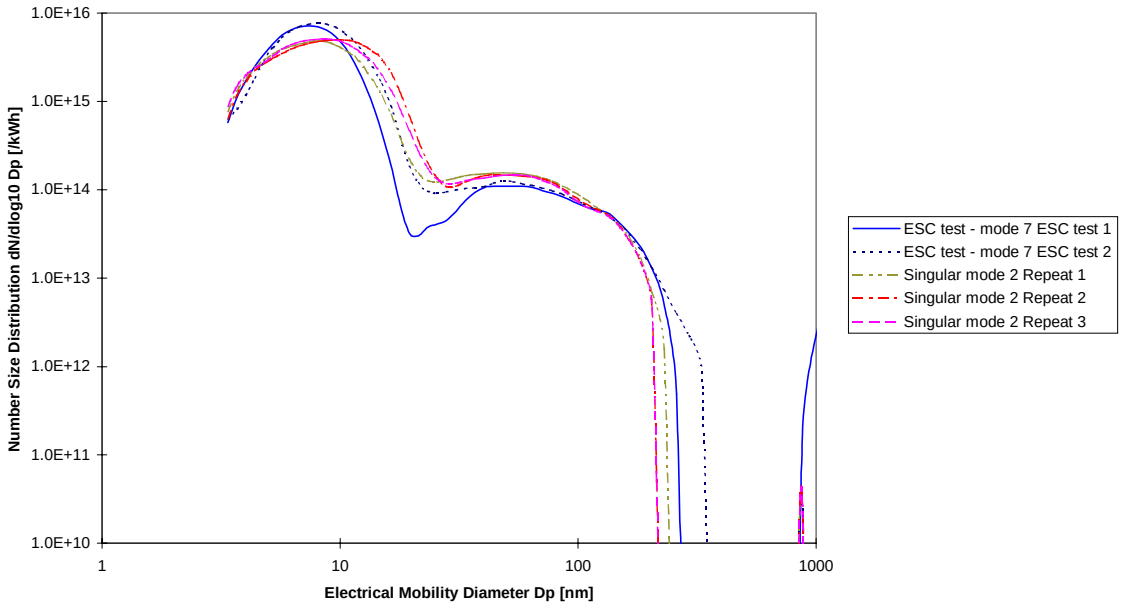


Figure 19 Euro 3 engine – DDMPS – Comparison of standard mode (ESC mode 10) with extended mode (EM4 at 20 minutes) results

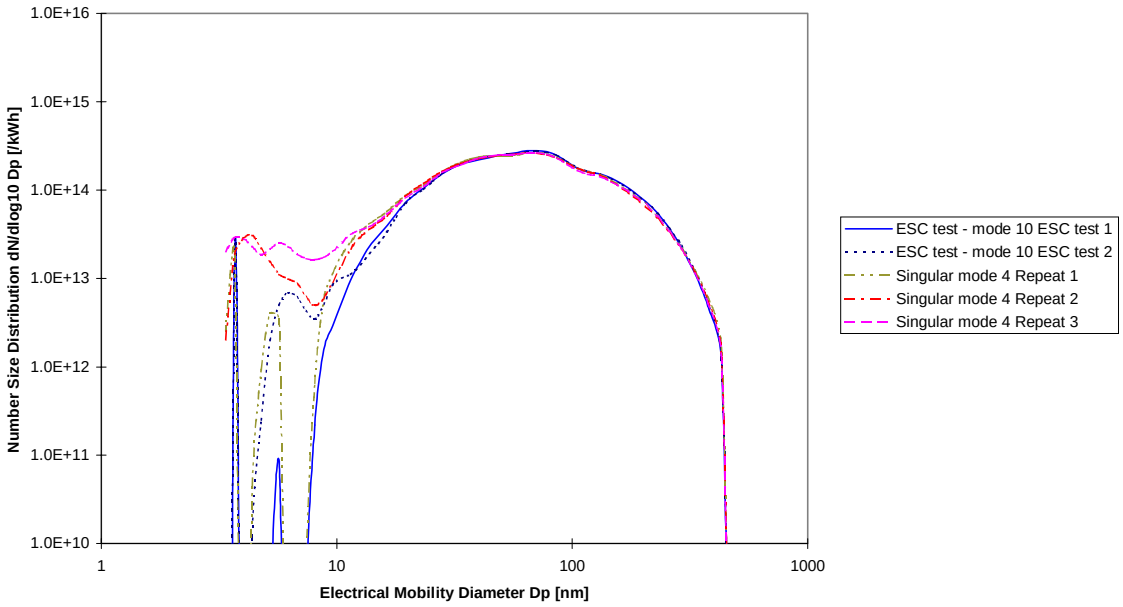


Figure 20 Euro 3 engine – DDMPS – Comparison of standard mode (ESC mode 3) with extended mode (EM2 at 20 minutes) results

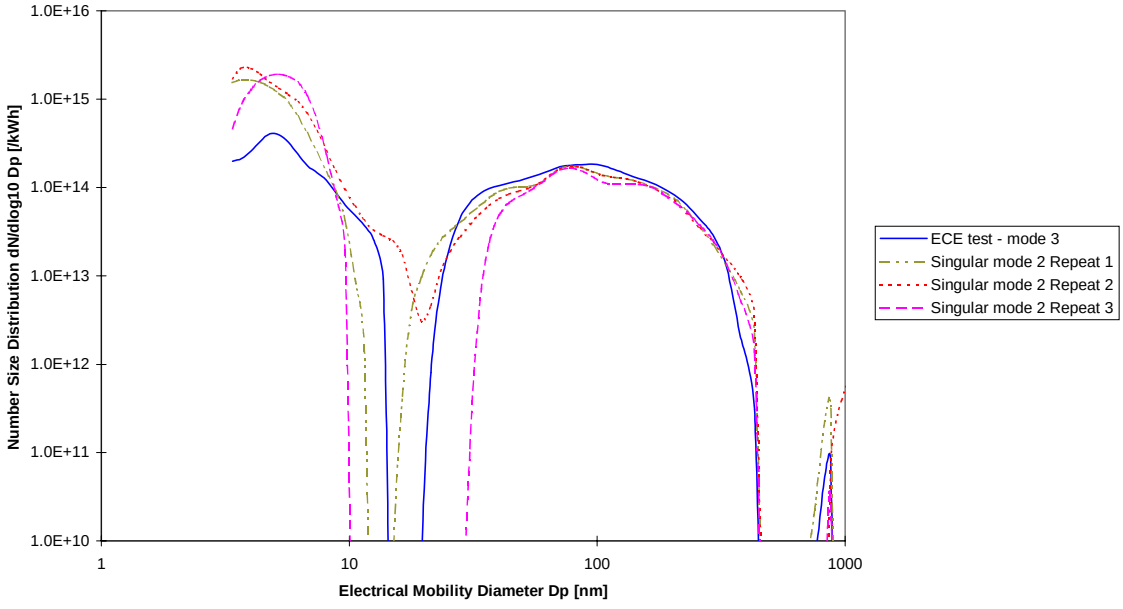
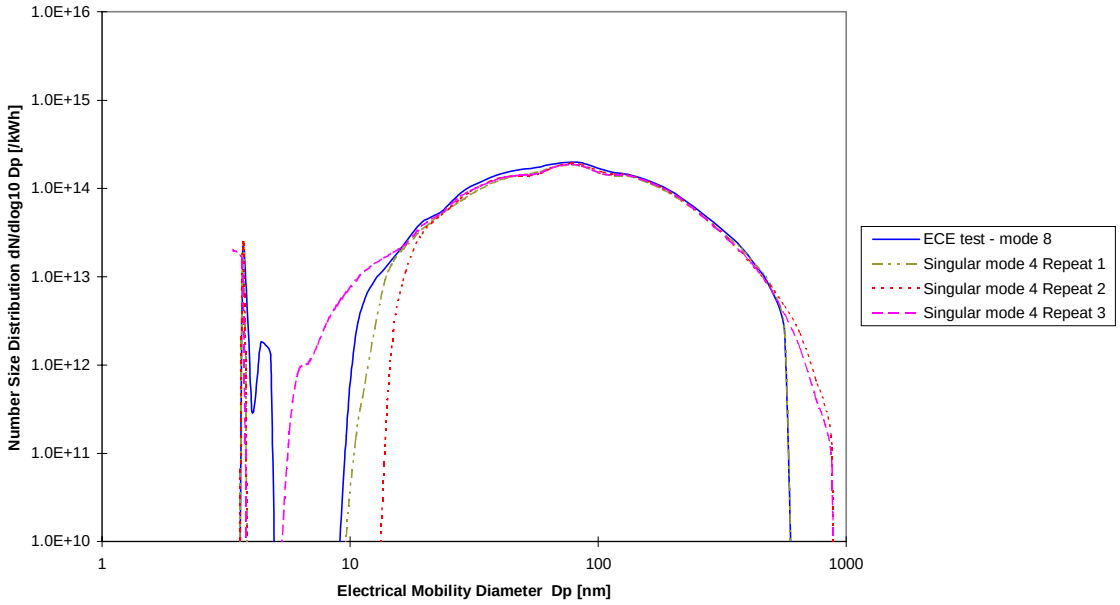


Figure 21 Euro 3 engine – DDMPS – Comparison of standard mode (ESC mode 8) with extended mode (EM4 at 20 minutes) results



It has already been seen that distributions at high load conditions develop and stabilise quickly. Consequently, the distribution measured at the same speed/load condition during the test cycle, where limited test time is available, is very similar to the 20-minutes stabilised distribution. Light load conditions show a pronounced delay in stabilising. However, the scan (**Figure 18**) taken during the test cycle appears comparable to the 20-minutes stabilised distribution, which perhaps may not have been expected considering the limited time available during the cycle for the distribution to develop. It is believed that the engine pre-history has a significant effect on the distribution measured (see **section 7.4.3.1**). It can be concluded that:

- nucleation mode particle distribution is sensitive to the time allowed for stabilisation,
- it is not clear whether fully or partially stabilised conditions are representative of real-world driving.

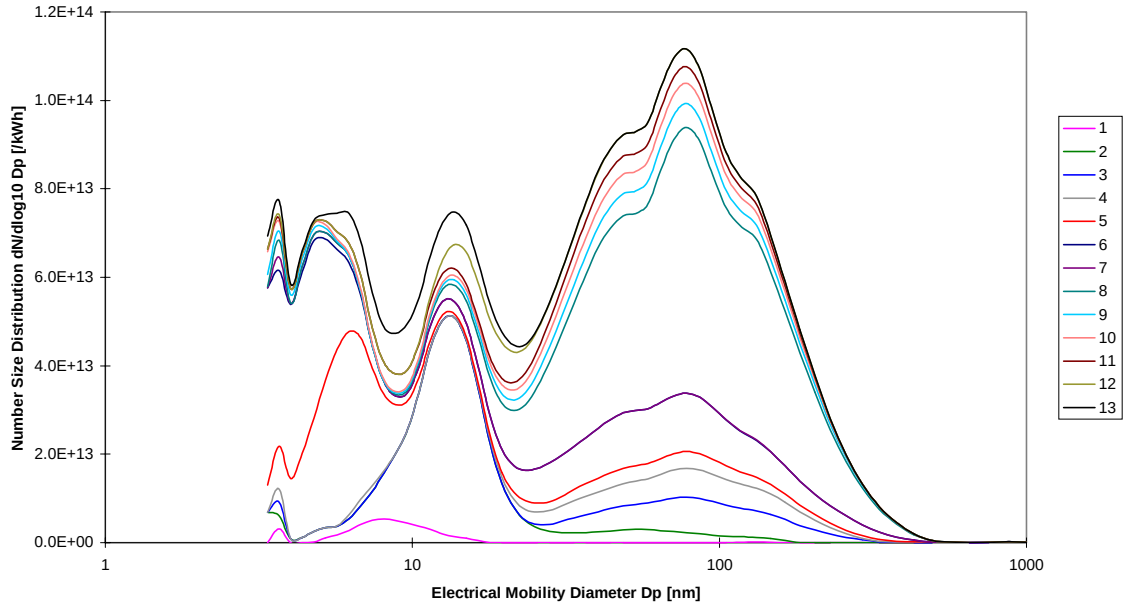
7.4.3. Contribution of individual modes

Figure 22 shows the contribution of each mode to the nucleation and accumulation particles and the cumulative emissions for the complete cycle (for the Euro 2 engine). Again, this shows the greater contribution to the nucleation particles from the low load/low speed conditions (R49 modes 1-6) and the dominating accumulation mode production from the high speed/high load conditions (ECE R49 modes 8-12).

It is apparent that there is a difference in production of these particles in the different size ranges and a summary of the number of particles produced in the two size

selected areas for each engine/fuel combination can be found in **Appendix 3**. In this appendix, the first table represents values as measured i.e. do not take into account weighting factors used within the cycle, whereas the second table summarises the weighted numbers.

Figure 22 Euro 2 engine - ECE cycle - cumulative emissions – DDMPS



7.4.3.1. Effect of previous test condition on particle emissions

This analysis is based on a comparison of the three idle conditions tested during the regulated R49 13-mode test, which were performed on the Euro 2 engine. Examining the distributions from these tests showed a relatively consistent effect, which was dependent on the mode number (i.e. mode 1, 7 or 13). Within a given mode, there was some variation in the measured distribution, however this was smaller than the mode to mode variation. These effects are illustrated for fuel D1 only, since 5 tests were performed on this fuel, compared to the two tests on fuels D2 and D3.

Figures 23-25 show the distributions measured during tests on fuel D1 at modes 1, 7 and 13 respectively. At modes 7 and 13, the distributions are very repeatable. At mode 1, some of the distributions look more like those at mode 7, while other look more like those at mode 13. This apparently greater variation can be explained in two ways:

- Since mode 1 is the first to be tested, some factors leading up to this mode may be less well controlled than during later stages of the tests. This greater variation can also be seen in some of the other measured engine parameters.

- The engine conditions at mode 1 lie between those at mode 7 and mode 13, which results in a distribution that falls between that at mode 7 and that at mode 13. Since the shape of the distribution (particularly the number of particle at about 10 nm) is changing quite dramatically between these conditions, it may be coincidental that mode 1 lies very close to a critical condition in which this shape changes rapidly.

Figure 23 Euro 2 engine - Fuel D1 – ECE mode 1 (idle) - Comparison of all five tests - DDMPS

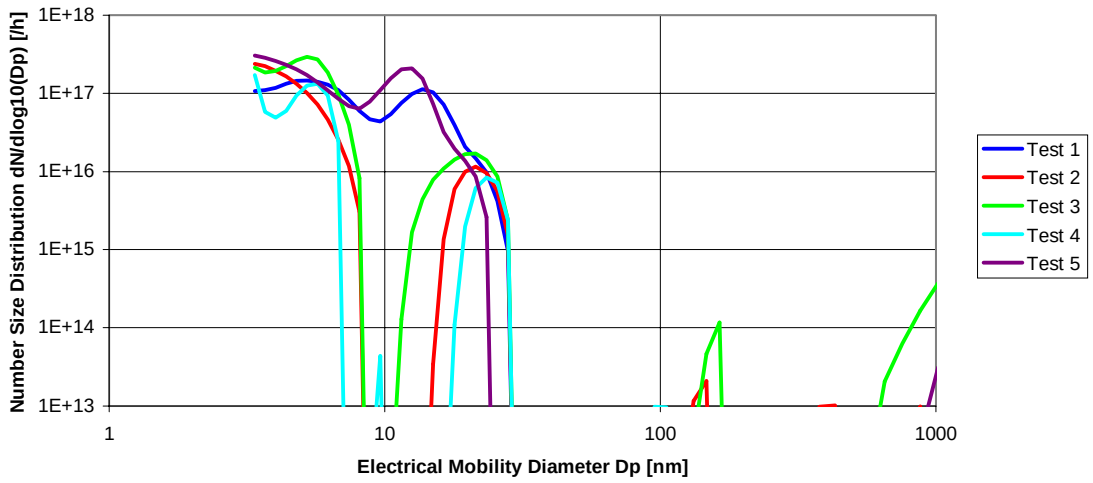


Figure 24 Euro 2 engine - Fuel D1 – ECE mode 7 (idle) - Comparison of all five tests - DDMPS

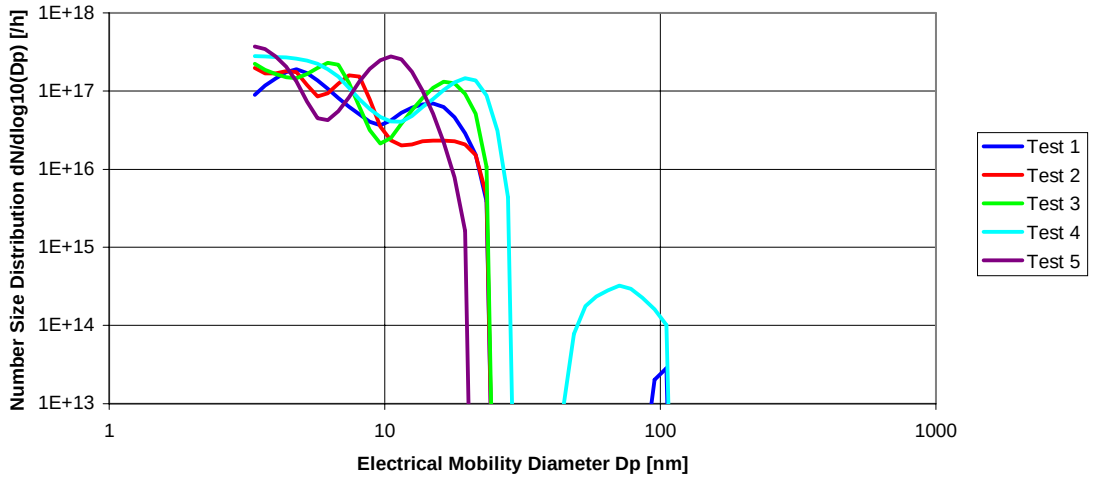
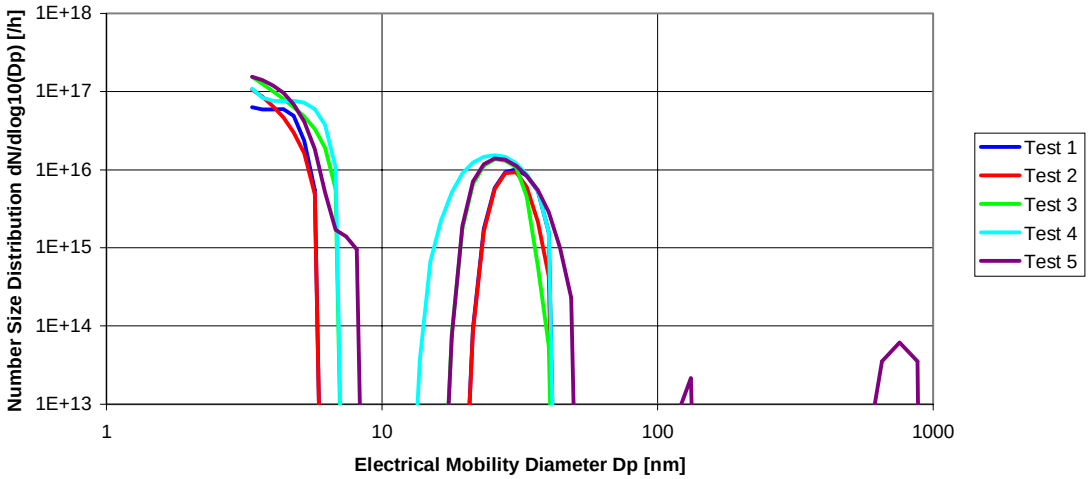


Figure 25 Euro 2 engine - Fuel D1 – ECE mode 13 (idle) - Comparison of all five tests - DDMPS



Other work (13) has suggested a relationship between exhaust gas temperature and the shape of the distribution. This relationship, and also the possible influence of exhaust hydrocarbon content, was briefly investigated here. Again, exhaust gas temperature appears to correlate with the change in idle distribution shape, more so than the exhaust HC composition. **Figures 26** and **27** show the mean exhaust gas temperatures and exhaust HC concentrations, respectively, during each of the idle tests. **Figure 26** shows a clear trend, with mode 7 having the highest exhaust temperature and mode 13 having the lowest temperature. These temperatures are clearly dependent on the previous mode operated by the engine, with mode 6 being 100% load while mode 12 is 10% load. There is no such clear trend with the HC emissions.

The mean and standard deviations for these data are given in **Table 18** for exhaust gas temperature and HC emissions. The exhaust gas temperature shows much greater variation in mode 1 than in the other two idle modes.

Figure 26 Euro 2 engine - ECE idle modes (modes 1, 7 and 13) - Exhaust Gas Temperature

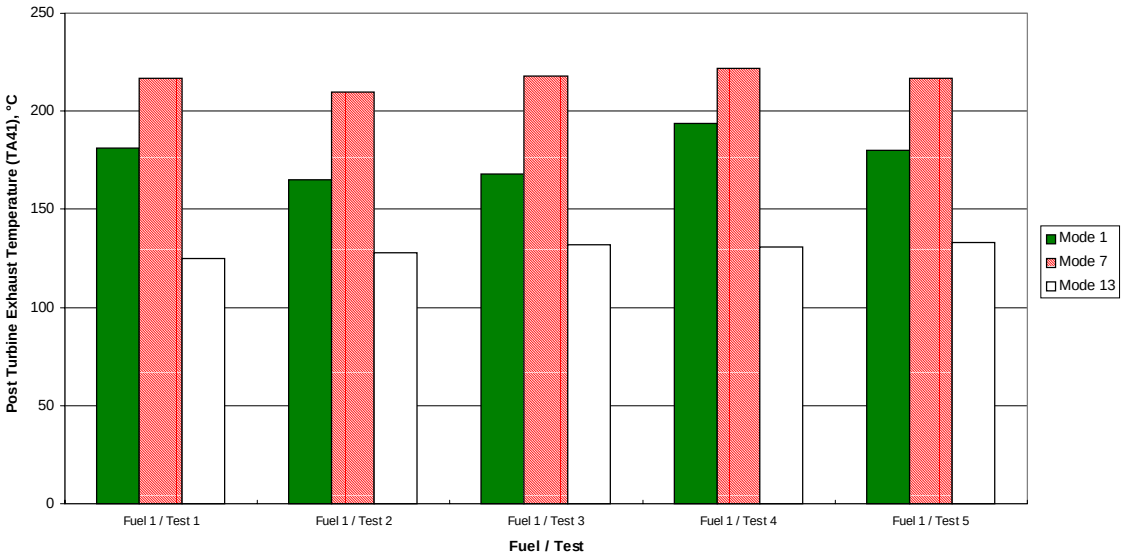


Figure 27 Euro 2 engine – ECE idle modes (modes 1, 7 and 13) - Exhaust HC Emissions

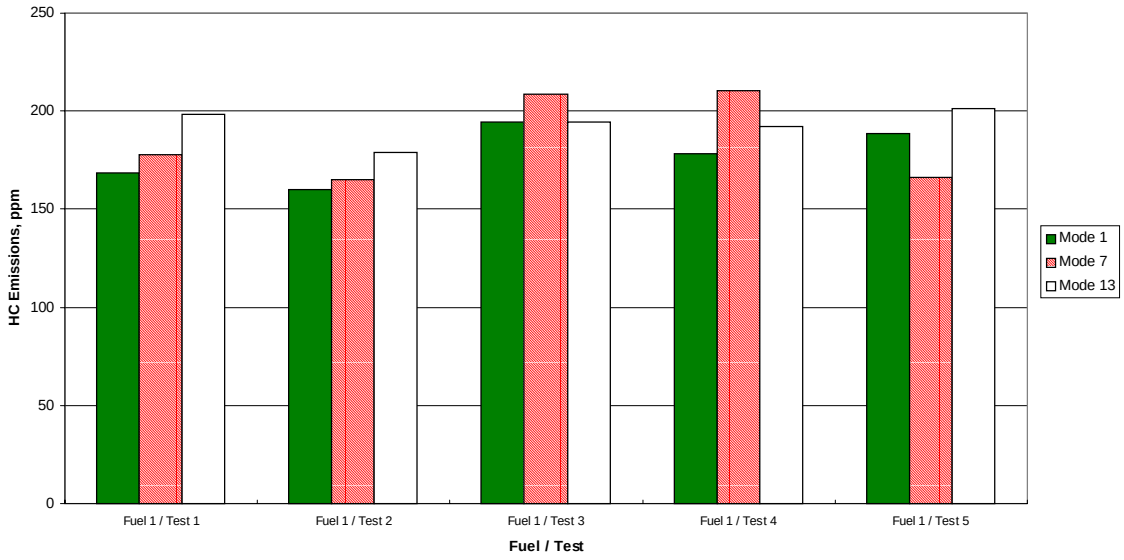


Table 18 Euro 2 engine - Mean and Standard Deviation of Exhaust Gas Temperature and Exhaust HC Emissions

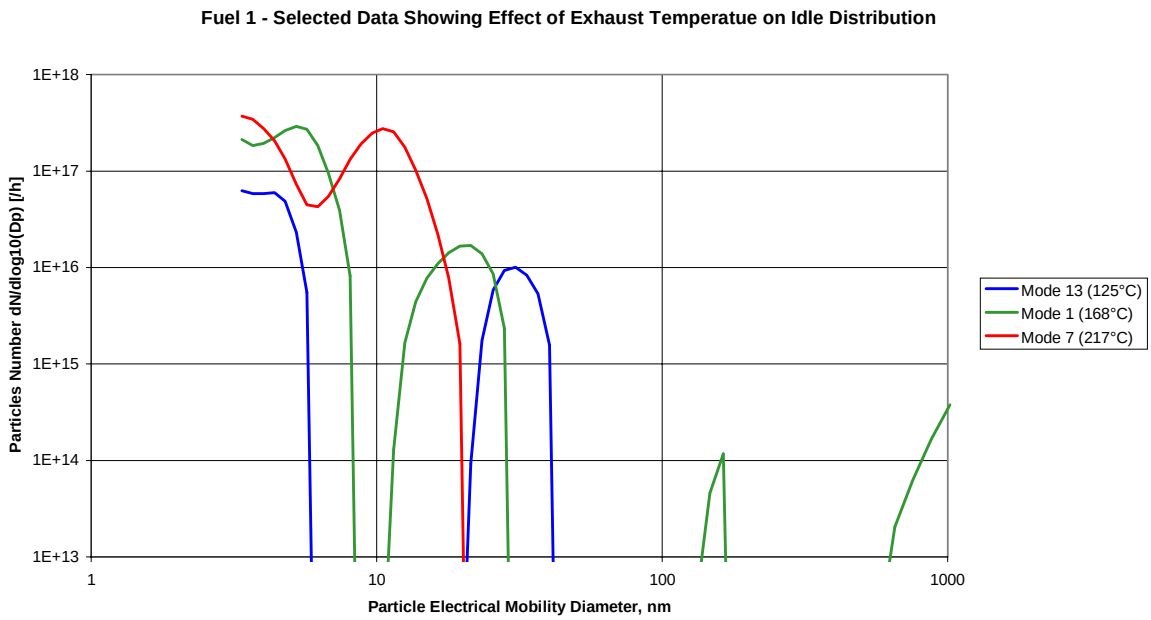
Fuel D1

	Post Turbine Exhaust Gas Temperature, °C		Exhaust HC Emissions, ppm C	
	Av.	S.D.	Av.	S.D.
Mode 1	177	10.7	179	13.2
Mode 7	217	3.9	185	20.0
Mode 13	130	2.9	195	9.1

Figure 28 shows a typical size distribution which is representative of the results seen at different exhaust gas temperatures. It is evident that these come from the three different modes within the test, the lowest temperature result coming from mode 13 and the highest temperature result coming from mode 7. Describing the change in size distribution is difficult, but broadly appears to be:

- The peak at about 10 nm, seen at the highest exhaust gas temperature (mode 7), appears to grow in size as the exhaust gas temperature is reduced. Thus with a 50°C reduction in temperature (to mode 1) this peak moves to about 20 nm, and with a further 40°C reduction (to mode 7) it moves to about 30 nm. At the same time, there is a significant drop in the magnitude of the peak, which could be approximated by a cubic relationship suggesting simple agglomeration as the mechanism.
- Below 10 nm, the trend is less clear. At the highest exhaust temperature, the smaller size distribution (which appears to peak at 3 nm (or below), merges in to the larger size distribution discussed above. At the lower temperatures, there is a distinct smaller size distribution. However the position of the peak of this distribution, and its magnitude does not follow any simple trend. Although changing from an exhaust gas temperature of 217°C to 168°C appears to show a growth in particle size - with the peak moving from about 3 nm to about 5 nm, but the magnitude remaining the same - a further reduction to 125°C shows both a reduction in the distribution size and magnitude.

Figure 28 Euro 2 engine - R49 idle modes (modes 1, 7 and 13) - Typical Size Distributions



Summary

The particle number distributions measured at the three idle conditions during the R49 tests are distinctly different. The differences appear to correlate with the differences in the exhaust gas temperature, as suggested by other workers. Comparing the three idle modes in the Euro 2 engine, there can be almost 100°C difference in exhaust gas temperature (post-turbine) between the modes, with mode 7 giving the highest temperatures (mean 217°C) and mode 13 the lowest temperature (mean 130°C). It is evident that this difference in temperature is caused by the previous operating mode, although the engine is considered to have stabilised sufficiently for regulated emissions measurement. There is evidence that this reduction in temperature allows the growth (probably through agglomeration) of particles of typically 10 nm diameter to particles of typically 30 nm diameter.

7.5. VEHICLE/FUEL EFFECTS - WEIGHTED CYCLE DATA

7.5.1. Particle number distribution

From **Figures 29** and **30** it can be seen that any effects of fuel changes are more apparent in the nucleation mode. From the pre-test work and the investigation of sampling effects, it has been seen that there is a substantially greater variability in the nucleation rather than the accumulation mode.

Figure 29 Euro 2 Engine - DDMPS results for fuels D1-D3; ECE weighted averages (geometric means of individual test runs)

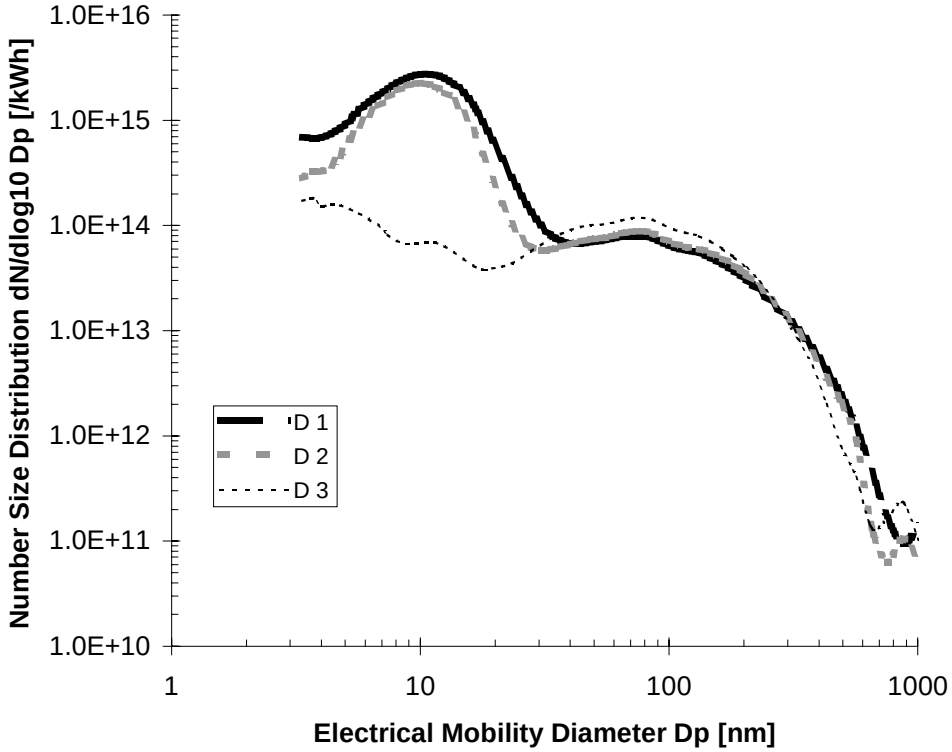
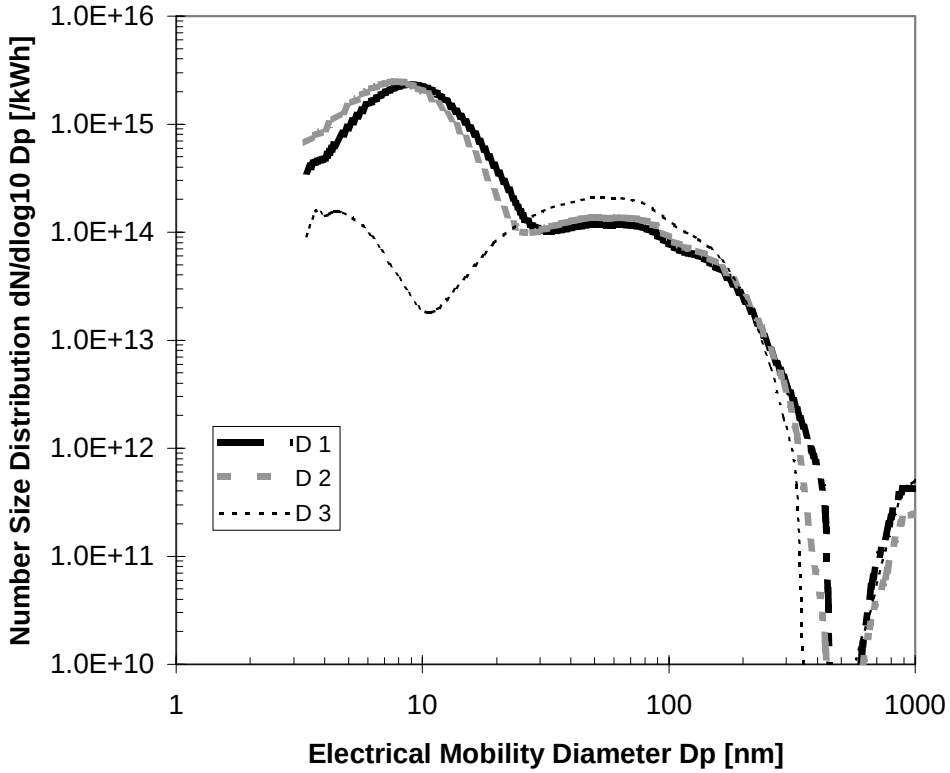


Figure 30 Euro 3 Engine – DDMPS results for fuels D1-D3; ESC weighted averages (geometric means of individual test runs)



This variability is illustrated in **Figures 31**-**33** which summarise the total number of particles produced on either side of the 30 nm cut off for each fuel for firstly the Euro 3 and secondly the Euro 2 engine. **Figure 33** shows a different grouping of the size cut particles to show how they are affected by fuel type and engine technology. It can be seen that the number of particles >30 nm are less affected by either changes in fuel or engine, whilst the previously mentioned variation is clearly apparent for those particles <30 nm.

Figure 31 Euro 3 engine - ESC - Total number of particles <30 nm and >30 nm (geometric means across tests)

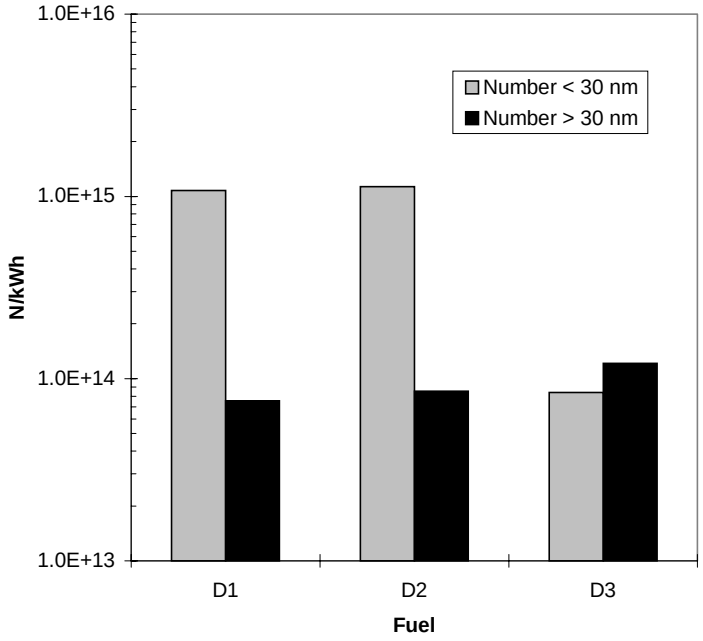


Figure 32 Euro 2 engine - ECE - Total number of particles <30 nm and >30 nm (geometric means across tests)

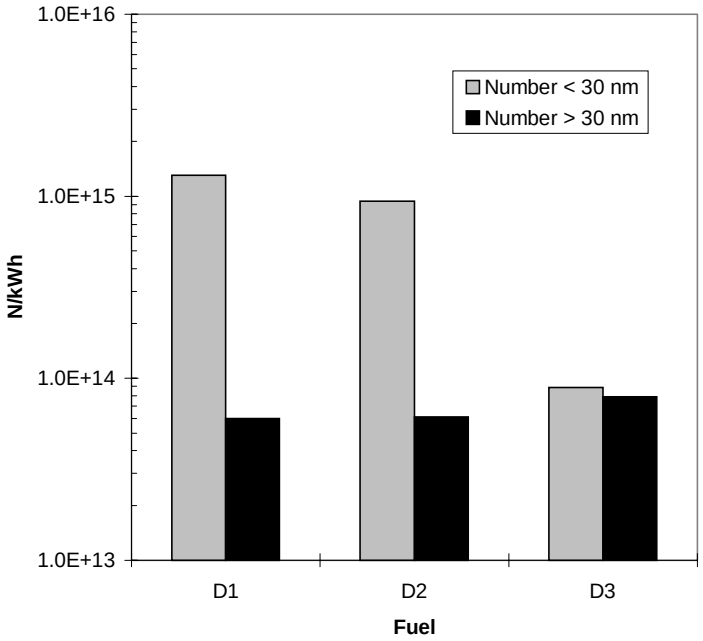
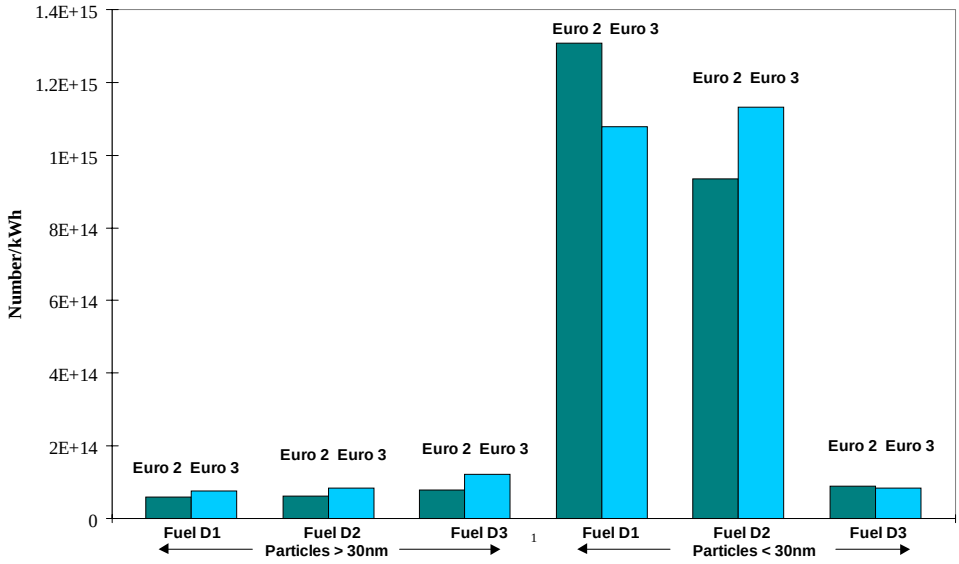


Figure 33 Comparison of total particles <30 nm & >30 nm across each fuel with changing engine technology



As with the distribution data, it can be seen with total integrated numbers that the accumulation mode again shows greater repeatability and lower sensitivity to external changes. These figures show that both with respect to the total numbers measured and the impact of either fuel quality or vehicle technology changes, the major effect is seen only in the nucleation particle range.

- fuel/engine effects on the accumulation mode are small
- fuel D3 gives less nanoparticles - understanding nanoparticle formation is important.

7.5.2. Regulated mass emissions

Details on regulated particulate mass emissions are given in **Section 7.1.1**.

7.5.3. Particulate mass distribution

Figures 34 and **35** show the particulate mass distribution measured by the low pressure impactor (LPI) during the cycles.

Figure 34 Euro 3 engine - ESC cumulative mass size distribution - LPI (arithmetic mean distribution over tests)

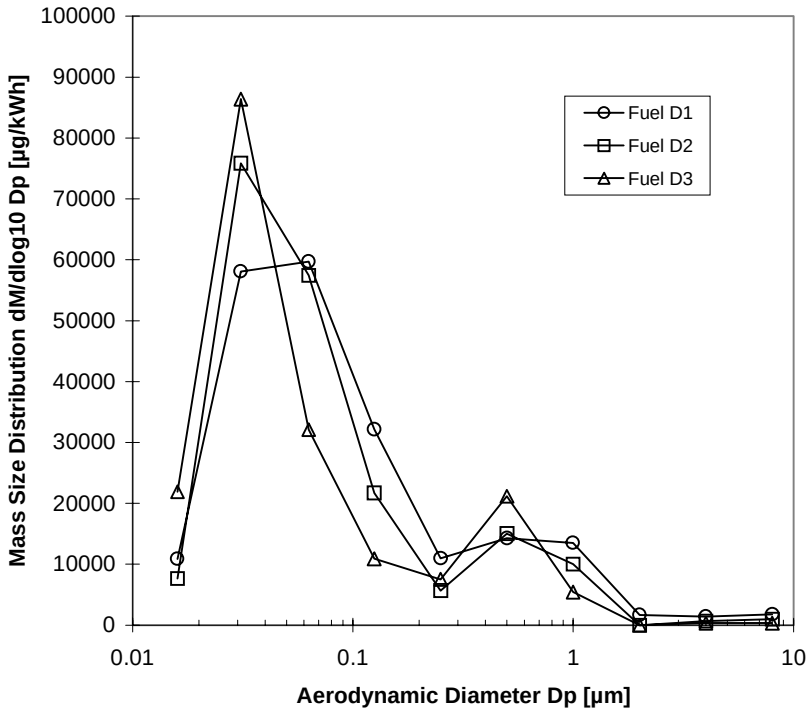
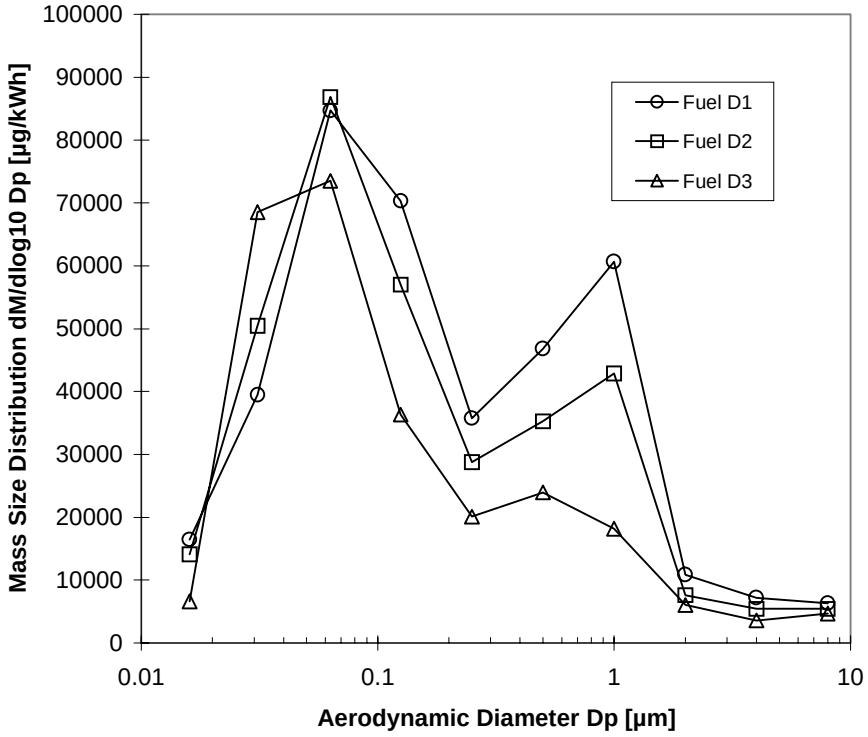


Figure 35 Euro 2 engine - ECE cumulative mass size distribution - LPI (arithmetic mean distribution over tests)



7.5.4. Comparison of impactor mass and regulated filter measurements

Figures 36 and **37** illustrate the relationship between the regulated filter paper mass, the total mass as measured by the impactor and the total number count for each fuel/engine combination for those particles >30 nm. It must be remembered that measurements of mass and number are based on very different physical procedures. A better correlation is obtained with the impactor mass than with number. This is not surprising as for these accumulation particles, mass will dominate over number. Particles <30 nm, although having a significant contribution to the total number, will only have a minimal contribution to the measured mass.

A direct comparison between total particulate mass, as collected by the LPI, and that from the regulated particulate filter has to be undertaken with caution. The fate of the volatile component is affected differently in both because of the mechanism of collection. For regulated filters, the particulate is collected via a flow-through mechanism on a single filter and thus the collected mass may be stripped of some volatile material by the continued passage of exhaust. For the LPI the collection is different – by impaction on a number of different surfaces. Thus, only the surface (not the bulk) of the collected material is continually exposed to passing exhaust, but the low pressure aspect of the collection facilitates the removal of volatile material. This effect is probably greatest in the nucleation region.

Figure 36 Euro 3 engine - Comparison of number and mass of particles > 30 nm with filter paper mass

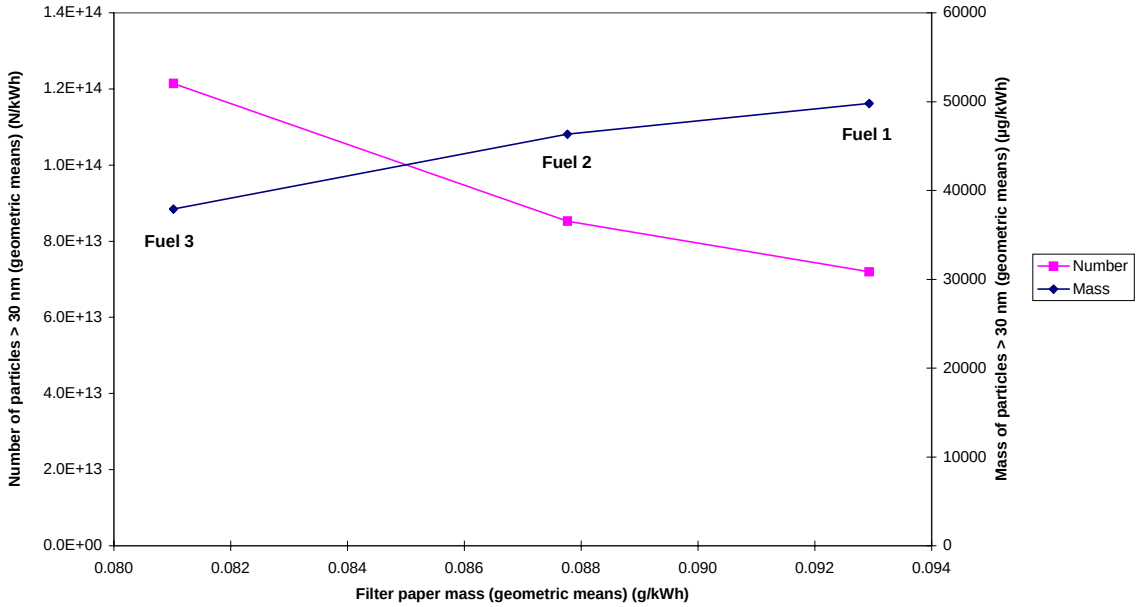
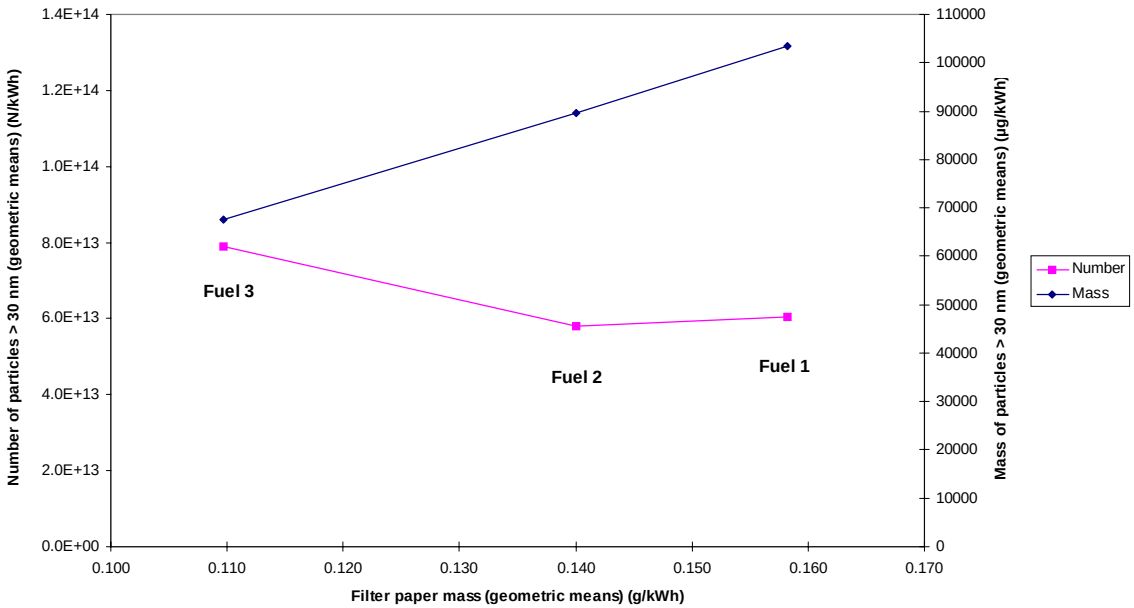


Figure 37 Euro 2 engine - Comparison of number and mass of particles > 30 nm with filter paper mass



7.5.5. Chemical analysis of particulate matter

Particulate filters from both regulated cycles and extended mode testing were analysed for soluble (hydrocarbon) and insoluble (sulphate and carbon) fractions. Results from these analyses are given in **Appendix 4**.

8. CONCLUSIONS

- Measurement of particle size and number has been successfully extended to heavy duty exhaust emissions.
- The use of the Duel Differential Mobility Particle Spectrometer (DDMPS) has allowed the investigation of particles as small as 3 nm.
- The number distribution of particles emitted from HD engines is bimodal, with peaks below 30 nm (representing nucleation particles) and above 30 nm (representing accumulation particles).
- The accumulation mode particles were found to be measurable to a satisfactory level of repeatability and were relatively insensitive to changes in test conditions.
- Nucleation mode particles, with the greatest influence on total number, were found to be sensitive to changes in sampling conditions.
- Conclusions about engine technology and fuel effects based on particle number measurements are critically dependent on the sampling conditions.
- Although the repeatability for the measurement of the accumulation mode is good, it is still three times worse than the repeatability for the mass measurement on particulate filters.

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10. GLOSSARY

AQS	Air Quality Standard
CONCAWE	Conservation of Clean Air and Water in Europe (the oil companies' European organisation for environment, health and safety)
CP(N)C	Condensation Particle (Nucleus) Counter
CR	Compression Ratio
CRT	Continuously Regenerative Trap
CVS	Constant Volume Sampling System
DI	Direct Injection
DMA	Differential Mobility Analyser
DDMPS	Dual Differential Mobility Particulate Spectrometer
DMPS	Differential Mobility Particle Sizer
ECE	ECE R49 Heavy Duty Engine Test Cycle
EGR	Exhaust Gas Recycle
EM	Extended Mode
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
ESC	European Stationary Cycle
FCE	Faraday Cup Electrometer
FIE	Fuel Injection Equipment
HD	Heavy Duty
IDI	Indirect Injection
LPI	Low Pressure Impactor
$PM_{[x]}$	particles with an aerodynamic diameter less or equal to [x] micron
SMPS	Scanning Mobility Particle Sizer
TCI	Turbo Charger Intercooler
US EPA	United States Environmental Protection Agency

11. ACKNOWLEDGEMENTS

CONCAWE's Automotive Emissions Special Task Force AE/STF-10 wishes to place on record the contribution of staff from AVL List GmbH, Graz, Austria and of Professor G. Reischl, Institute for Experimental Physics, Vienna University, Austria.

APPENDIX 1 HANDLING OF PARTICULATE DATA

Particulate number distributions were measured by a DDMPS (dual differential mobility particle spectrometer) system. This measures particle number as a function of particle electrical mobility Z_p which is monotonically related to particle diameter D_p. The measurement range was divided into 57 contiguous electrical mobility intervals of equal width on a log Z_p scale. The electrical mobility distributions were then converted into particle size distributions. The mid-points D_p ranged from 3.4 to 1019 nm but were not equally spaced on the converted log D_p scale. Thus the frequencies needed to be normalised before they could be plotted as a distribution curve against log D_p.

In particle sizing studies, it is usual to normalise emission measurements to what they would have been had the measurement interval been 1 unit in width on a $\log_{10}$ (or ln) scale. This allows comparisons to be made between the number and/or mass of particles measured by different analysers. By convention, the notation $dN / d\log_{10} D_p$ [3] (or $d\,mass / d\log_{10} D_p$) is used to describe the units of such measurements (where *N* or *mass* means the number or mass of particles emitted per unit of time, power output or volume). In this particular study, the numbers of particles of different sizes differed by several orders of magnitude and so the values of $dN / d\log_{10} D_p$ are plotted on a log scale (vertical axis).

The DDMPS allowed particle size distributions to be measured for each of the 13 modes in the ESC and ECE cycles. For each mode, only the number measurements taken in the last two minutes, when the engine had reached stable conditions, were used in the analysis. In addition to the ESC and ECE cycles, particle size distributions were also measured over an extended period for 5 singular modes, i.e. 5 chosen engine torque and speed combinations. For each non-idle mode, the data was converted from number per m^3 of raw exhaust at 20°C and 1013 mbar to number per kWh using the measured exhaust gas flow rate and power output values. It is not appropriate to express idle mode emissions in number per kWh as the power output is zero. However, it is possible to calculate the contribution of the idle modes to the sampling-time weighted average emissions per kWh over the complete 13-mode ESC or ECE cycle using the weighted-average power output as a common denominator. It is thus possible to plot how emissions accumulate over the 13 modes but this is only meaningful if a natural scale is used for the vertical axis.

[3] The notation is mathematically correct only if *N* is regarded as the number of particles *smaller than or equal to* D_p in diameter emitted per chosen unit.

The weights, i.e. the relative amount of time spent in each mode, were as follows:

ESC mode	Weighting	ECE mode	Weighting
1	0.15	1	0.0833
2	0.08	2	0.08
3	0.10	3	0.08
4	0.10	4	0.08
5	0.05	5	0.08
6	0.05	6	0.25
7	0.05	7	0.0833
8	0.09	8	0.1
9	0.10	9	0.02
10	0.08	10	0.02
11	0.05	11	0.02
12	0.05	12	0.02
13	0.05	13	0.0833

Particle mass distributions were measured by a LPI (low pressure cascade impactor). The measurement range for the LPI was divided into 10 contiguous size intervals with successive mid-points on a particle diameter D_p scale differing by a factor 2 (falling from 8000 to 15.6 nm). The bins were thus of equal width on a log D_p scale.

The LPI was unable to measure the particle mass distribution on a mode-by-mode basis within the ESC and ECE cycles, only the accumulated distribution over the 13 modes. The LPI thus recorded the overall mass of particles emitted per m^3 of exhaust for each of the 10 intervals. The data was then converted to mass per kWh using the sampling-time weighted averages of the measured exhaust flow rate and measured power output figures for each mode. Finally the data was normalised to $d\ mass / d\log_{10} D_p$. Values of $d\ mass / d\log_{10} D_p$ are plotted on a linear scale (vertical axis) in this report.

The LPI was able to measure particle mass distributions for individual modes when these were run in isolation in the extended modes. Mass distributions are thus available for at least 2 of the 5 previously chosen singular modes for each engine × fuel combination.

Numerical integration formulae were used to calculate the total number and total mass of particles emitted taking due account of the unequal spacing of the mid-points on the log D_p scale for the DDMPS. Most of the observed number and mass distributions showed two peaks corresponding to the particle nucleation and particle accumulation processes (see Section 7.1.2). Therefore the number and mass of particles in each mode was also computed. A visual inspection of the data suggested that 30 nm was a good dividing line. To fully utilise the limited amount of information on the mass of small particles, the two extreme intervals were allowed to make full rather than half contributions to the mass integration. This gave extended ranges of integration from the lower limit of the first bin to the upper limit of the last (11.0 to 30 to 11310 nm) instead of from their mid-points (15.6 to 30 to 8000 nm).

The variability in most emission measurement processes increases as the actual level of emissions increases. It is natural therefore to use geometric (logarithmic) means instead of simple arithmetic means when averaging particulate emission measurements. Thus geometric means were used when averaging the total number or the total mass of particles emitted (units N/kWh or µg/kWh) in different tests. Geometric means were also used when averaging particle

number distributions (units $dN / d\log_{10} D_p$) across tests[4]. However, to maintain additivity, arithmetic means had to be used when calculating the average contributions of individual modes to overall ESC/ECE cycle emissions. Arithmetic means also had to be used when averaging mass distributions (units $d\ mass / d\log_{10} D_p$) as the LPI recorded zero mass in one or more size intervals in many tests.

[4] Arithmetic means were used to average the three repeat particle size distributions acquired within each DDMPS extended mode test.

APPENDIX 2 TESTS ON EURO 3 ENGINE WITH A PARTICULATE TRAP

As additional testing to the designed test programme it was possible to test the Euro 3 engine both according to its design specification and also configured with a particulate trap (Continuously Regenerating Trap (CRT)) to conform to Euro 4 specifications. This necessitated changes to the engine with respect to readjustment of the injection timing and an increase in the rate of cooled EGR.

The effect of the trap configuration on both regulated emissions and particulate number distribution was assessed both over regulated ESC cycles (duplicate tests) and extended mode testing as described in Section 5.3 of the main report. The fuel used for this part of the test work was an Austrian City Diesel (D4), which was very similar in properties to fuel D3 used in the main programme. This fuel was used to assess the performance of the engine in both configurations. Properties of the fuel are as shown below:

Table A2.1 Austrian City Diesel data

	Test method	**Fuel D4**
DENSITY @ 15°C (kg/m^3)	ISO 3675	821
CETANE NUMBER	ASTM D 613	51.3
IBP (°C)	ASTM D 86	186
10/30/50/70/95% recovered at (°C)	ASTM D 86	210/228/243/260/-
FBP (°C)	ASTM D 86	302
SULPHUR (mg/kg)	ASTM D 3120	<10
AROMATICS (%mass)	IP 391/95	
Mono-		13.9
Di-		7.3
Tri+		0.3
TOTAL		21.5
CALORIFIC VALUE (calc.)	ASTM D 4868-90	
NETT (MJ/kg)		43.2

The regulated emissions from the engine, whilst running in both configurations and on Fuel D4 are shown in **Table A2.2.**

Table A2.2 ESC cycle emissions data, g/kWh

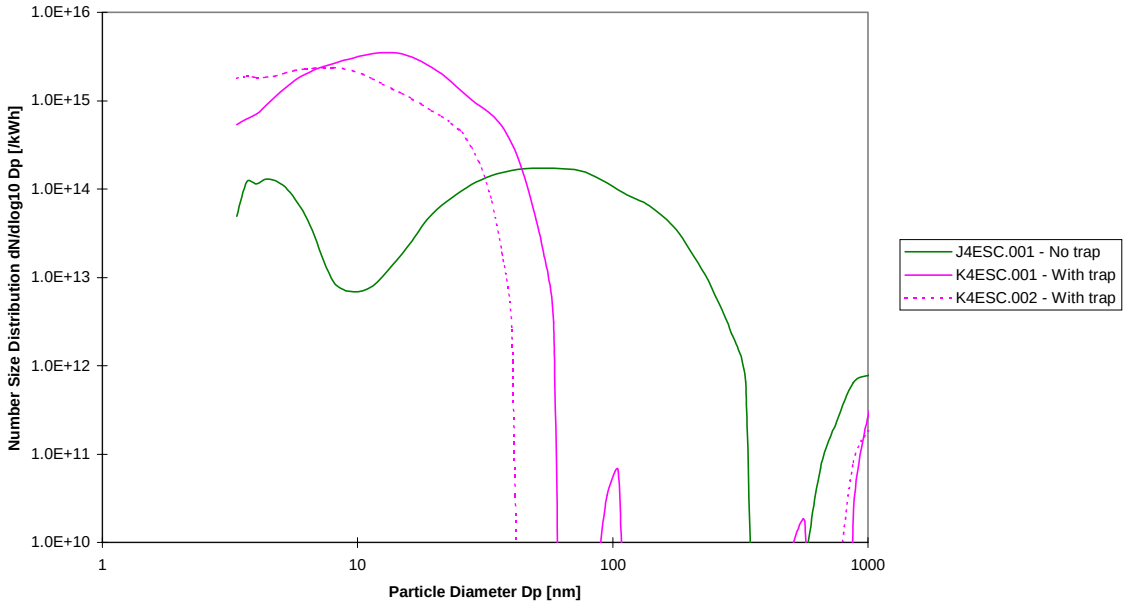
	HC	**NOx**	**CO**	**PM**	**CO_2**	**FC**
Euro 3 build (w/o trap)	0.055	4.338	0.378	0.071	642	205
Euro 4 build (with trap)	ND	2.64	ND	0.022	674	212
Euro 4 limits	0.46	3.5	1.5	0.02		

Average of two runs of ESC cycle

PARTICLE SIZE DISTRIBUTION

The particle size distribution was determined according to the protocol employed in the main programme. Distribution data collected at individual modes of the ESC cycle were combined (as described in Appendix 1) to provide distribution curves representative of the entire cycle. These curves for the cycles run with the trap (Euro 4 build) and compared to that measured without (Euro 3 build) are shown in **Figure A.2.1.**

Figure A.2.1 Influence of particle trap (Euro 3 base engine) – DDMPS – ESC - Fuel D4

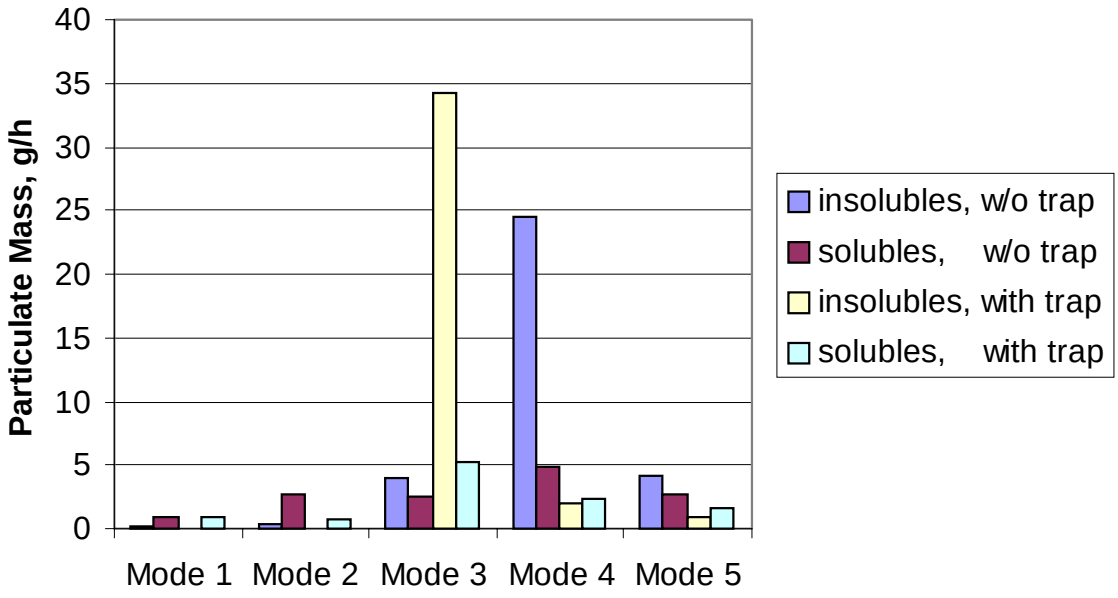


These curves show that, although there is a substantial reduction in accumulation mode particles, there is a considerable increase in the number of nucleation mode particles when the trap is in place. Examination of the extended mode showed that, where that mode had a tendency to produce nucleation particles, this tendency was increased, whereas if the mode produced predominantly accumulation mode particles, these were substantially reduced.

This increase of nucleation particles would be assumed to derive from sulphate particles that are forming following the oxidative nature of the trap. This is happening even at 10 ppm fuel sulphur level. There is possibly also an element of sulphate storage contributing to the release of these particles at higher operating speeds.

This formation is illustrated from the chemical analysis of the particles collected from the extended mode testing (see **Figure A2.2**), where it can be seen that at mode EM3, where significant nucleation particles are produced (see **Figure 15** of main report), the presence of the trap causes a substantial increase in the insoluble fraction (i.e. in this case, sulphate).

Figure A2.2 Insoluble and soluble particulate mass emissions (g/h)
Extended modes EM1 to EM5 – ESC – Fuel D4



CONCLUSIONS

This work demonstrates the effectiveness of a particulate trap in reducing the mass of particles emitted, by way of reducing the accumulation mode particles produced by the engine. However, whilst mass is reduced, the potential exists for a large increase in particle number as a result of increased sulphate conversion over the catalysed section of the trap.

This increase in number needs to be taken into account whilst assessing the environmental benefit of the trap. It also needs to be remembered that nucleation particle formation and measurement is still poorly understood and that the observation made here may not be true for all testing and sampling conditions.

APPENDIX 3 THE EFFECT OF DIFFERENT FUEL SPECIFICATIONS ON THE EXHAUST PARTICLE SIZE DISTRIBUTION FROM TWO HD DIESEL ENGINES

a) Integrated particle emissions (Number/kW.h/10^{12}) for all modes and fuels (arithmetic means). Figures are calculated by dividing the number of particles by the power for each individual test mode.

Euro 2 engine

		ECE R49 Test Mode Number (also showing Speed % and Load % for each condition)												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Particle		30%	60%	60%	60%	60%	60%	30%	100%	100%	100%	100%	100%	30%
Size Range	**Fuel**	0%	10%	25%	50%	75%	100%	0%	100%	75%	50%	25%	10%	0%
3-1000 nm	**1**	.	7215	327	2375	2016	1379	.	156	277	557	1296	2661	.
	2	.	4054	194	1613	1721	1180	.	165	184	293	718	1736	.
	3	.	1048	163	118	216	94	.	205	143	188	414	1183	.
3-30 nm	**1**	.	6958	212	2340	2002	1366	.	21	204	463	1108	1967	.
	2	.	3979	68	1573	1705	1165	.	20	105	175	511	1172	.
	3	.	939	7	51	192	73	.	21	32	48	185	605	.
30-1000 nm	**1**	.	257	115	34	14	13	.	135	72	94	188	693	.
	2	.	75	126	40	16	15	.	145	80	118	208	564	.
	3	.	109	156	67	24	21	.	184	111	140	229	578	.

Euro 3 engine

		ESC Test Mode Number (also showing Speed % and Load % for each condition)												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Particle		26%	58%	74%	74%	58%	58%	58%	74%	74%	90%	90%	90%	90%
Size Range	**Fuel**	0%	100%	50%	75%	50%	75%	25%	100%	25%	100%	25%	75%	50%
3-1000 nm	**1**	.	1124	1330	1187	2621	2004	4084	1229	2842	199	814	190	275
	2	.	1180	1328	1027	2855	2237	4573	1332	3078	220	753	206	243
	3	.	60	125	107	82	66	181	359	293	281	486	267	306
	4	.	36	92	89	37	32	73	215	229	229	450	231	257
3-30 nm	**1**	.	1104	1286	1152	2601	1987	4030	1207	2708	30	502	53	112
	2	.	1161	1285	987	2833	2219	4528	1302	2936	33	423	39	50
	3	.	11	39	36	27	24	69	322	69	39	114	52	60
	4	.	3	19	27	2	3	7	180	40	27	93	51	46
30-1000 nm	**1**	.	19	44	36	20	17	53	22	134	168	312	137	163
	2	.	18	43	40	22	18	45	30	142	187	330	166	193
	3	.	49	85	71	55	42	112	36	224	242	372	216	246
	4	.	34	72	62	34	29	66	34	188	202	357	180	211

b) Contribution of each mode to the total weighted cycle particle emissions (Number/kW.h/10^{11}, arithmetic means). Results for each mode are cycle weighted and normalised by the weighted cycle power.

Euro 2 engine

		ECE R49 Test Mode Number (also showing Speed %, Load % and Weighting % for each condition)													
		1	2	3	4	5	6	7	8	9	10	11	12	13	
		30%	60%	60%	60%	60%	60%	30%	100%	100%	100%	100%	100%	30%	
Particle		0%	10%	25%	50%	75%	100%	0%	100%	75%	50%	25%	10%	0%	Total
Size Range	Fuel	8.3%	8%	8%	8%	8%	25%	8.3%	10%	2%	2%	2%	2%	8.3%	Cycle
3-1000 nm	1	529	1027	120	1742	2217	6342	757	362	95	127	149	121	159	13747
	2	90	579	71	1187	1884	5441	122	381	63	66	83	83	80	10130
	3	35	167	61	87	241	432	16	466	49	44	49	56	55	1759
3-30 nm	1	529	991	77	1716	2201	6282	757	48	70	106	128	90	152	13147
	2	90	569	25	1158	1866	5373	122	47	36	40	59	56	79	9519
	3	35	150	3	38	214	337	16	48	11	11	22	29	55	968
30-1000 nm	1	0	37	42	25	16	60	0	314	25	22	22	31	7	600
	2	0	11	46	29	18	67	0	334	27	27	24	27	1	612
	3	1	17	58	49	27	96	0	418	38	33	27	28	0	791

Euro 3 engine

		ESC Test Mode Number (also showing Speed %, Load % and Weighting % for each condition)													
		1	2	3	4	5	6	7	8	9	10	11	12	13	
		26%	58%	74%	74%	58%	58%	58%	74%	74%	90%	90%	90%	90%	
Particle		0%	100%	50%	75%	50%	75%	25%	100%	25%	100%	25%	75%	50%	Total
Size Range	Fuel	15%	8%	10%	10%	5%	5%	5%	9%	10%	8%	5%	5%	5%	Cycle
3-1000 nm	1	180	1378	1279	1706	999	1147	785	2139	1368	308	197	137	133	11756
	2	157	1445	1284	1483	1098	1288	882	2320	1497	339	181	148	117	12239
	3	4	73	121	156	32	38	35	630	143	432	116	189	145	2114
	4	3	45	88	128	14	18	14	381	110	356	105	162	120	1544
3-30 nm	1	179	1354	1237	1654	992	1138	775	2102	1304	47	122	38	54	10995
	2	156	1423	1242	1425	1089	1278	873	2267	1428	51	102	28	24	11386
	3	3	14	38	52	10	14	13	567	34	60	27	37	28	897
	4	2	3	19	39	1	1	1	320	19	42	22	35	22	526
30-1000 nm	1	0	24	42	51	8	10	10	38	64	261	75	99	78	761
	2	0	23	42	58	9	11	9	53	69	289	80	119	93	853
	3	1	59	83	103	21	24	22	64	109	372	89	152	117	1217
	4	1	42	69	89	13	17	13	61	91	315	83	126	98	1018

APPENDIX 4 CHEMICAL ANALYSIS

Regulated filters

All regulated filters collected over the legislated test cycles from each engine/fuel combination were subjected to chemical analysis to give the breakdown between soluble and insoluble fractions of total particulate.

Figure A.4.1 shows this breakdown for the Euro 3 engine and **Figure A.4.2** for the Euro 2. Both figures also include the analysis of the particle mass collected during the engine set-up phase, using ECE reference fuel and the Euro 3 engine. **Figure A.4.1** includes the additional fuel used for the testing of the particulate filter.

Figure A.4.1 Particle composition from regulated filters generated over the ESC cycle from the Euro 3 engine.

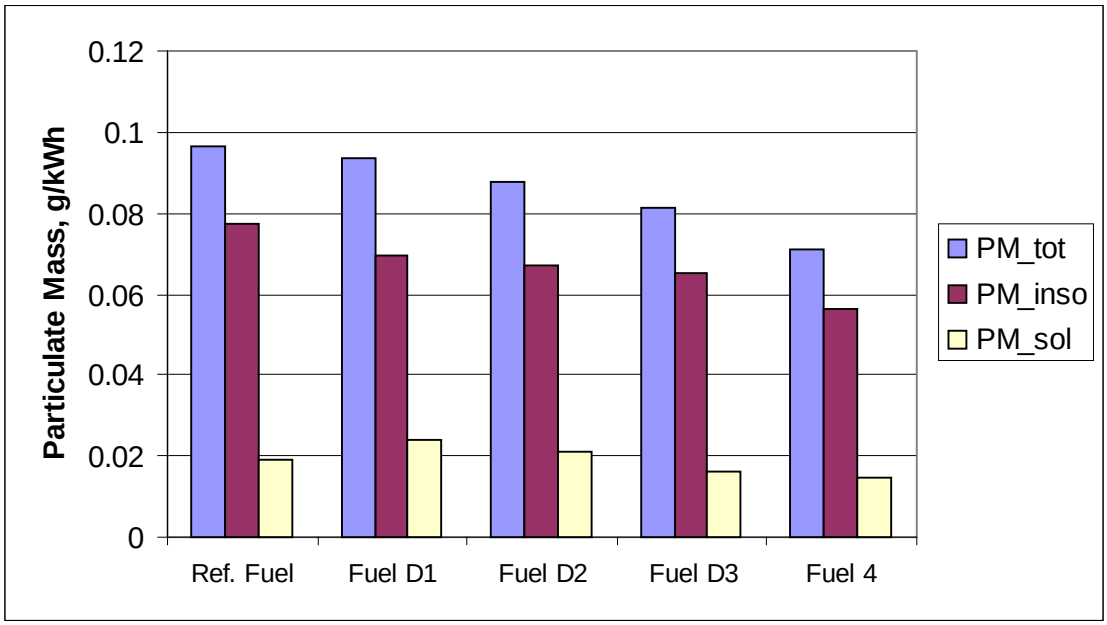
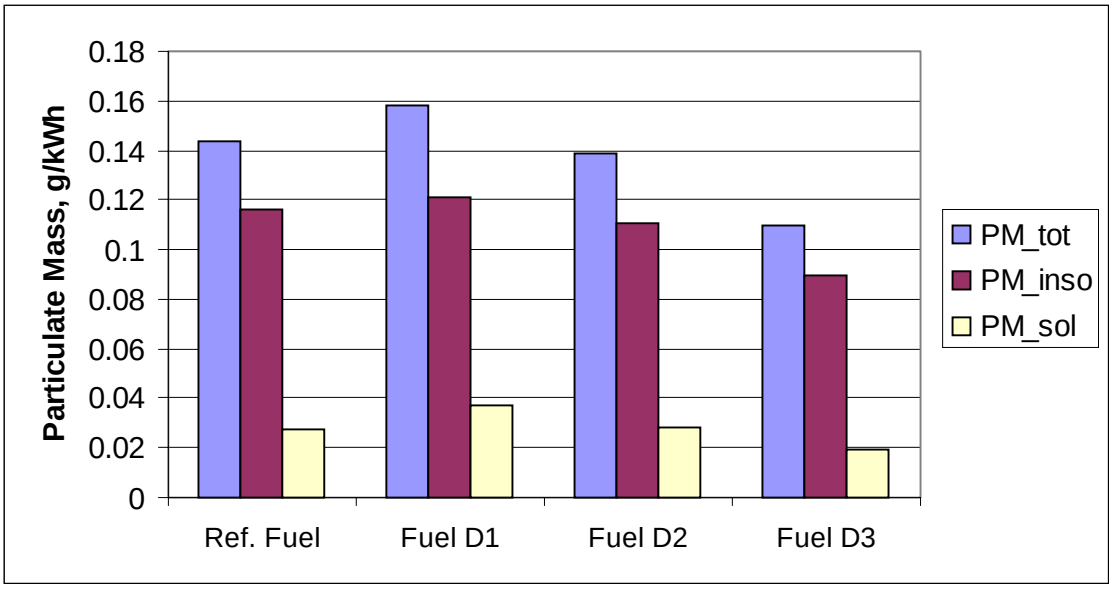


Figure A.4.2 Particle composition from regulated filters generated over the ECE cycle from the Euro 2 engines.



From these figures it can be seen that the reduction observed in total particulate mass when moving from the Euro 2 to Euro 3 engine is caused almost exclusively by a reduction in the insoluble (carbonaceous/sulphate) components. The organic contribution to the total mass is fairly consistent between the two engines.

Fuel effects on total particulate mass show the same trends although the magnitude is greater for the Euro 2 engine.

Individual modes

In addition to regulated filters, particulate analysis was carried out on filters generated over the extended mode testing for the five additional modes detailed in the main report.

For the Euro 3 engine, **Figures A.4.3-A.4.5** show the total, insoluble and soluble particulate respectively for modes EM1-EM5, whilst **Figures A.4.6**-**A.4.8** show the same breakdown for the Euro 2 engine.

Figure A.4.3 Total particulate emissions (g/h) from the Euro 3 extended mode testing

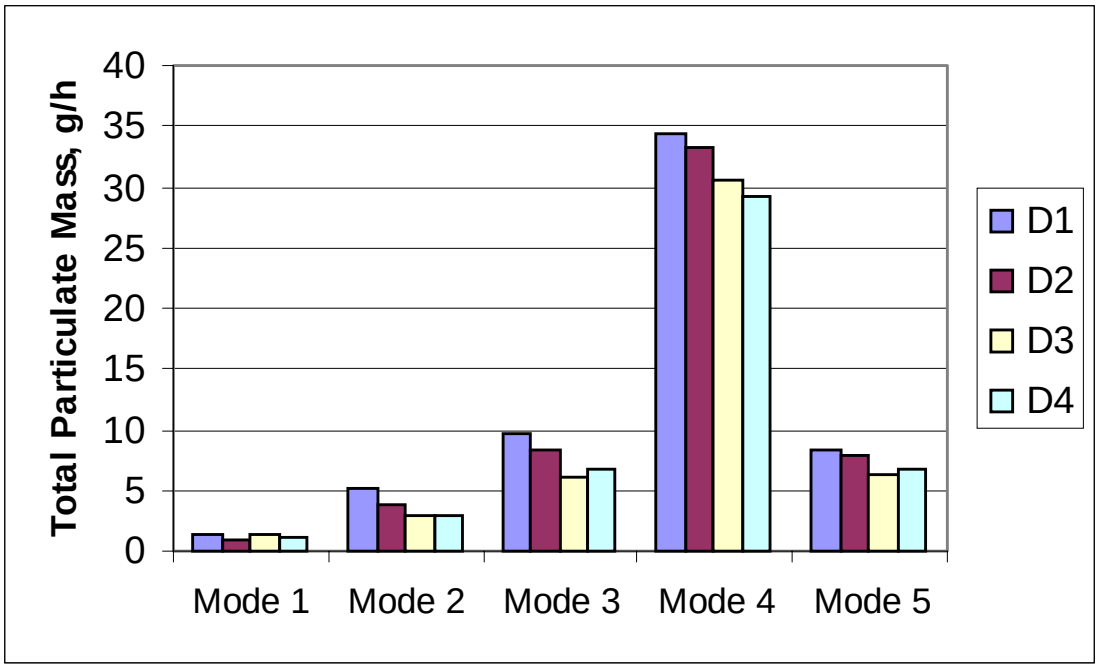


Figure A.4.4 Insoluble fraction of particulate (g/h) from the Euro 3 extended mode testing

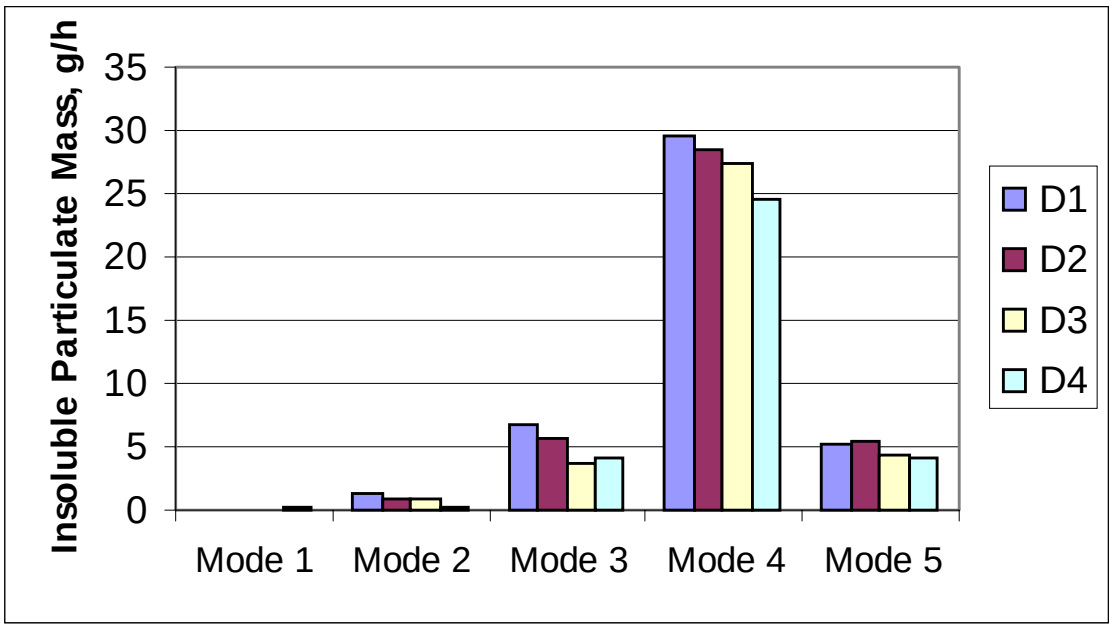


Figure A.4.5 Soluble fraction of particulate (g/h) from the Euro 3 extended mode testing

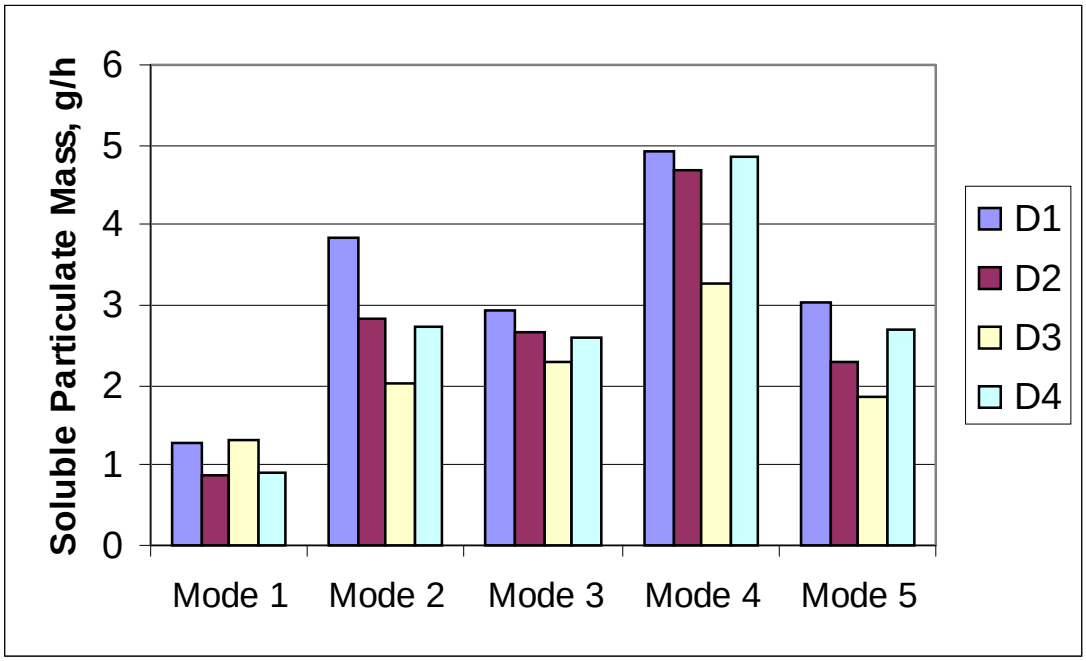


Figure A.4.6 Total particulate emissions (g/h) from the Euro 2 extended mode testing

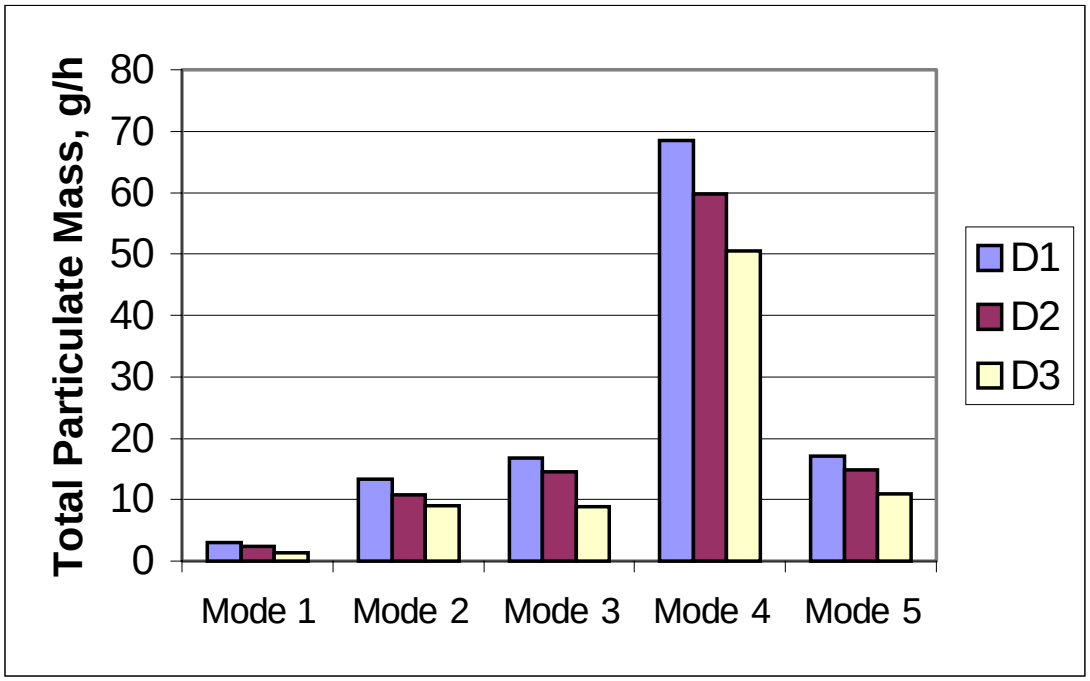


Figure A.4.7 Insoluble fraction of particulate (g/h) from the Euro 2 extended mode testing

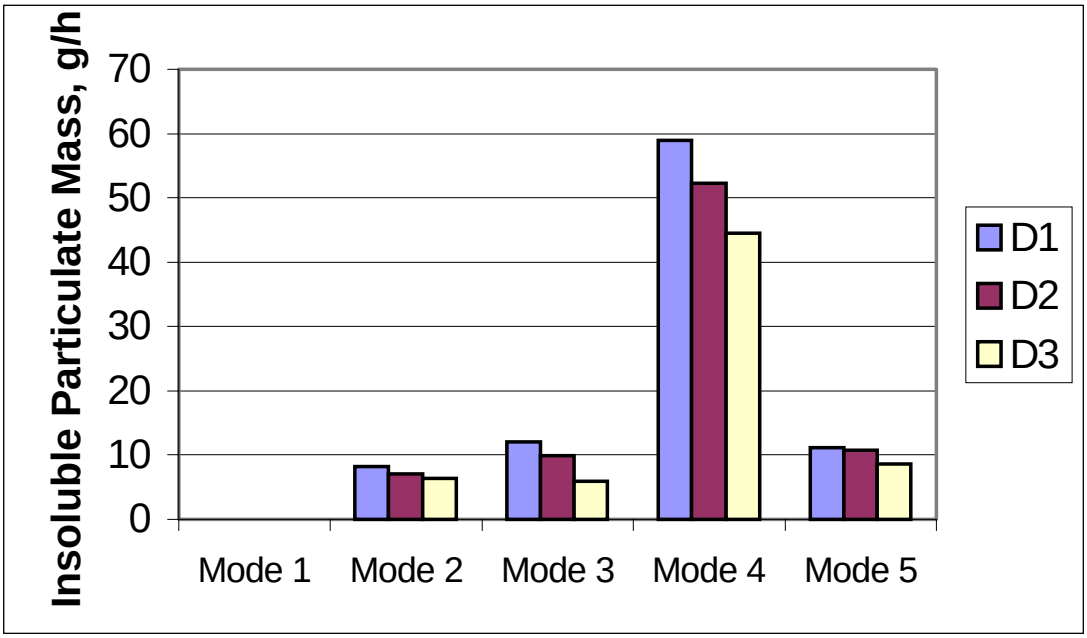
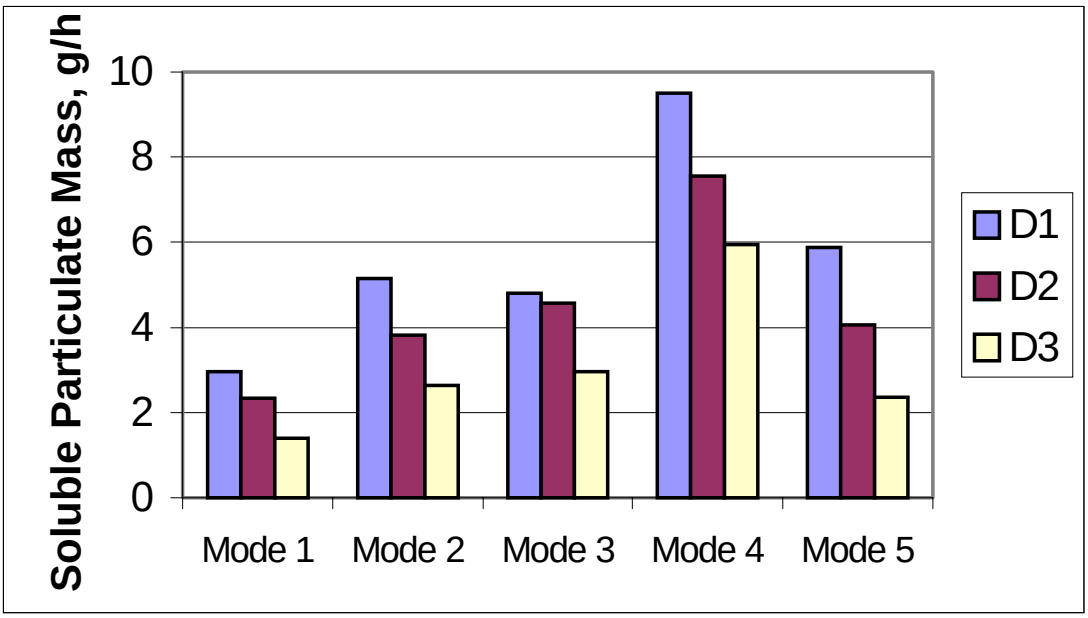


Figure A.4.8 Soluble fraction of particulate (g/h) from the Euro 2 extended mode testing



Results from the analysis of the individual modes is in line with expectations i.e. where the engine is operating at high speed/high load conditions, the particulate is mainly carbonaceous - shown clearly by comparing the mode EM4 results for the total and insoluble fractions for both engines. At low speed/low load conditions, where there is a higher amount of unburned fuel in the exhaust, there is a correspondingly greater proportion of organic material on the particulate. This is demonstrated most clearly for modes EM1 and EM2.