



DETR/SMMT/CONCAWE Particulate Research Programme

SUMMARY REPORT May 2001



DETR/SMMT/CONCAWE Particulate Research Programme 1998-2001

SUMMARY REPORT

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EXECUTIVE SUMMARY:

The DETR/SMMT/CONCAWE Particulate Research Programme has investigated the effect of engine technologies and fuel specifications on regulated particulate matter, particle number, mass and size. A range of light duty vehicles including Diesel, gasoline and bi-fuel plus a range of heavy duty Diesel engines and one heavy duty gas engine were characterised. Engine and vehicle technologies comprised Euro I, Euro II and Euro III status. These engines and vehicles were tested with a range of fuels which they are likely to encounter in normal use. The study also described the application and limitations of current sampling and measurement techniques and makes recommendations regarding instrumentation and sampling methods.

Two Scanning Mobility Particle Sizer (SMPS) instruments were utilised to measure particle number and size within a size range of 7nm to 710nm. Particle mass and size were measured using an impactor (MOUDI) across a size range from <56nm to >10µm. Regulated particulate matter and regulated emissions were also measured. Vehicles and engines were tested over legislated European test cycles and additional steady state conditions.

Two distinct particle types were emitted. These were defined as accumulation mode particles when larger than 50nm, and as nucleation mode particles when smaller than 50nm.

It was determined within this data set that good repeatability was achieved for both nucleation and accumulation mode particles. However, nucleation mode particles were found to be sensitive towards preconditioning of engines/vehicles, sampling conditions and to dilution parameters. Limitations of the particle size and number instrumentation emphasised the difficulties in comparing data derived from different studies. The importance of standardised and representative sampling and measurement methodologies is stressed.

This study has shown that fuel and engine technology both influence particle number emissions. Stricter emissions standards have resulted in reductions in particulate mass and this is generally reflected in reductions of accumulation mode particles. However, no fuel or engine technology tested reduced all nucleation and accumulation mode particles as well as particle mass under all operating conditions.

The largest effect of a single technology on particles was observed with Diesel particulate filters (DPFs) on both light and heavy duty applications, where particle mass and number were reduced by several orders of magnitude. The exception was at high exhaust temperature conditions, where significant numbers of nucleation mode particles were emitted post DPF.

For light duty, highest particle numbers were generally emitted from conventional Diesel vehicles with number emissions from the gasoline direct injection vehicles an order of magnitude lower. Particle number emissions from conventional MPI gasoline vehicles, the LPG vehicle and the Diesel vehicle fitted with a particulate filter system were generally similar but several orders of magnitude lower than those from the conventional Diesel. At high exhaust temperature conditions, it was found that total particle number emissions from all light duty technologies were of a similar level. Particle size distributions were, however, different.

The heavy duty CNG engine emitted significantly lower particle mass and number emissions compared to the heavy duty Diesel engines.

For both light and heavy duty Diesel engine types, Swedish Class I fuel showed a small but significant reduction in particle mass and number compared to the other fuels tested.

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1. INTRODUCTION

There is currently a strong focus on emissions of small particles from both Diesel and gasoline engines. Sampling and measurement effects as well as the influences of fuel and engine parameters on those emissions are being researched in a number of complementary programmes.

Air quality directives implemented by the UK Government and throughout Europe, currently address PM₁₀. However, there is significant interest in PM_{2.5} in the United States and this might be addressed in Europe with the review of legislation in 2003.

This focus on PM_{2.5} reflects the current belief that smaller particles may be significant contributors to adverse health episodes. Individually, small particles contribute very little to mass but can contribute extremely large surface areas for biological interaction. Therefore with mass emissions from combustion sources reducing, particle number measurements may be more appropriate in the future. Indeed, some recent studies have indicated associations between particle number and respiratory effects, although this has not been widely confirmed.

Since measurement methodologies for particle size and number are not yet standardised, it is very difficult to compare results from different studies. This study therefore, was designed to characterise a range of engine technologies and fuel specifications within defined boundaries to enable comparative assessments.

The UK Government Department of the Environment, Transport and the Regions (DETR) (then the Department of Transport, DOT) in partnership with the Society of Motor Manufacturers and Traders (SMMT) commenced a Particle Research Programme in 1995.

For this, the fourth phase of the programme, which commenced in 1998, the Oil Companies European Organisation for Environment, Health and Safety (CONCAWE) joined the partnership and the UK Department of Trade and Industry (DTI) also contributed. Ricardo was commissioned to undertake the testing and analysis in the fourth

phase of the programme. The remit of this study was primarily to investigate the particle production characteristics of in-use and future engines and vehicles. In total six light duty vehicles and four heavy duty engines were tested, each with several fuels selected from a total of thirteen. A brief summary of the results and conclusions is reported here.

2. OBJECTIVES

The objectives of the programme were:

- To characterise a range of light duty cars and a van plus several heavy duty engines in terms of particle number, mass and size emissions when tested over steady state and transient test cycles.
- To evaluate the effect of more stringent emissions legislation on the cars, van and heavy duty engines with respect to technology level.
- To evaluate the effect of fuel specification on particle number, mass and size.
- To evaluate the effects of Diesel particulate filter (DPF) technologies on a light duty vehicle and a heavy duty engine.
- To compare particle character in terms of number, mass and size as well as composition

3. ENGINE / VEHICLES

The engines and vehicles were selected with the intention of covering a wide range of engine and aftertreatment technologies. These engines and vehicles were indicative, but not necessarily representative of, the technology levels stated. The selection encompassed both a cross section of technologies already present on UK roads and examples of future technologies that may be employed to achieve future emissions targets. All engines and vehicles were supplied by SMMT members. These were run in and checked for correct operation via emissions performance prior to testing. Table 1 illustrates the selection of technologies. Detailed descriptions of engine and vehicle technologies are presented in Appendix 1.

TABLE 1 - ENGINE & VEHICLE SELECTION

Emissions Stage	HD Diesel	HD Diesel with DPF	HD CNG	LD Gasoline	LD Gasoline/LPG	LD Diesel	LD Diesel with DPF
Euro I	1	1					
Euro II	1			1(MPI)	1	1	
Euro III	1		1	1(G-DI)		1	1

HD - HeavyDuty MPI - Multi-Point Injection CNG - Compressed Natural Gas G-DI - Gasoline Direct Injection
 LD - Light Duty DPF - Diesel Particulate Filter LPG - Liquefied Petroleum Gas

TABLE 2 - FUELS SELECTION

DIESEL	Engine/ Vehicle	EN590:1996	EN590:1999 (2000)	UK ULS Diesel	Diesel SWCL1
	Euro I	x	x	x	x
	Euro I with DPF			x	x
	Euro II		x	x	x
	Euro III		x	x	x
	Euro III with DPF		x	x	x
GASOLINE	Vehicle	EN228:1996	EN228:1999	ULS Gasoline	
	Euro II	x	x	x	
	Euro II bifuelled		x		
	Euro III		x	x	

EN590 - European standard diesel pump fuel specification
LD - European standard gasoline pump fuel specification

ULS - Ultra low sulphur (<50ppm)
SWCL1 - Swedish class 1

4. FUELS

The engines and vehicles were tested with fuels which they are likely to encounter in normal use. Table 2 (above) shows the selection of fuels, and the engines and vehicles which they were tested in. Detailed descriptions of the fuel specifications are presented in Appendix 1.

The CNG engine was tested with compressed natural gas and also G20 and G25 reference fuels which represent 'high' (100%) and 'low' (85%) methane specification gases respectively. A bi-fuel vehicle was tested on pump LPG as well as on gasoline.

5. INSTRUMENTS AND SET-UP

Within current studies, a wide range of dilution approaches are being employed. Dilution parameters are considered to be the most critical influences when measuring particle number emissions that include the nucleation mode. In the absence of any standards, this study utilises the conventional CVS type dilution according to the procedures for regulated particulate mass. This approach allows the measurement of particle number while maintaining dilution ratios that permit mass measurement as well as enabling comparisons with earlier studies.

In addition to the regulated particulate mass, two Scanning Mobility Particle Sizers (SMPS) were employed to measure particle number concentration and size distribution and a Micro Orifice Uniform Deposit Impactor (MOUDI) was used to measure particle mass and size distribution. The standard diesel procedures for the measurement of regulated particulate matter were

applied to Diesel, gasoline, LPG and CNG technologies.

The MOUDI is a 10 stage cascade impactor which deposits particles according to their size. Particles between 56nm and 10µm are partitioned onto 10 stages while particles smaller than 56nm are collected on an after-filter. The upper 8 stages of the impactor are operated under atmospheric pressure, whilst the lower stages operate at lower pressures.

Two nominally identical SMPS systems were employed. Each SMPS system comprises an impactor (which removes particles above 1µm), a charge neutralizer which reduces the charges on the particles to a defined distribution, an electrostatic classifier responsible for separating particles and a Condensation Particle Counter (CPC) which counts them. Due to the limitations of the system, it can either scan a size distribution and determine the particle number - which takes a finite time (size scan mode), or it can measure the number of particles within a specific size range second-by-second (size filtered mode). Both modes have been employed within this study.

For the steady state tests, both SMPS systems were employed simultaneously in order to measure a wider size range; one measuring 7nm to 320nm, and the other 15nm to 710nm. During transient tests, both SMPS systems were used in parallel to simultaneously measure two different particle sizes.

All particle measurements were taken following dilution within the regulated emissions test procedures. The set-ups for HD engines and LD vehicles are shown in Figures 1 and 2 respectively.

6. TEST METHODOLOGY

Rigorous daily test protocols have been designed to ensure repeatability. In particular a defined preconditioning routine for each of the tests has been found to be critical for repeatable results.

The heavy duty engines were installed on a transient test bed and as a minimum were tested over the legislated European test cycle appropriate to their technology levels, plus five steady state conditions. The steady states were drawn from either the R49 cycle or European Steady State Cycle (ESC) to allow a comparison between particle number, mass and composition for key operating conditions. Where appropriate to the engine technology, the European Transient Cycle (ETC) was employed to give an insight into particle production during dynamic operating conditions. The CNG engine was tested only over this transient cycle.

The test protocols were designed so that test cycles from engines of different technology levels overlapped as shown in Table 3.

The daily test protocol for light duty vehicles included the appropriate legislated cold start European test

cycle, followed by hot start European test cycles and five steady state conditions covering the key speeds within the cycle.

For all tests, regulated emissions including particulate mass were measured. In addition, cumulative MOUDI samples were acquired; either over a single test or, in the case of low emitting technologies, over multiple tests. Both SMPS instruments were employed in parallel. Selected particulate samples were analysed for chemical composition.

During steady state test cycles, the SMPS instruments were employed in size scan mode to measure the particle size distribution and particle number concentration. For transient tests, the SMPS instrument measured in size filtered mode, i.e. transient measurement of a single particle size. Each transient cycle was repeated six times (heavy duty) or three times (light duty) within the daily test protocol with each of the instruments sampling simultaneously a different size range. The range of sizes taken covered 10nm up to 250nm. A composite size distribution was then constructed from the data collected from all the individual sizes. For both steady state conditions and transient tests

TABLE 3 - HEAVY DUTY TEST PROCEDURES

Technology/Cycle	Euro I Diesel	Euro II Diesel	Euro III Diesel	Euro III Diesel
R49	x	x		
ESC			x	
ETC		x	x	x

Figure 1 (right): Heavy Duty Test Schematic

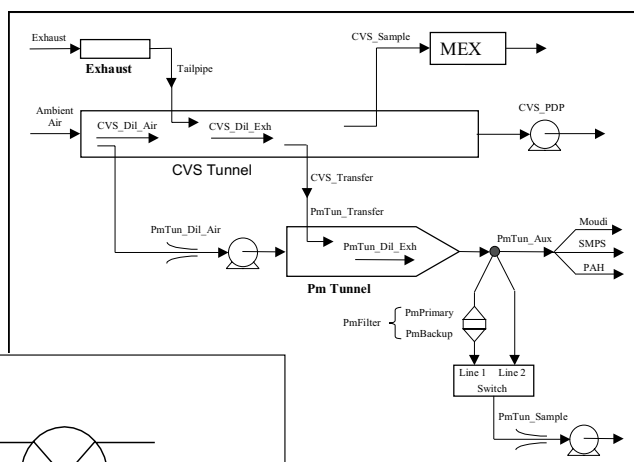
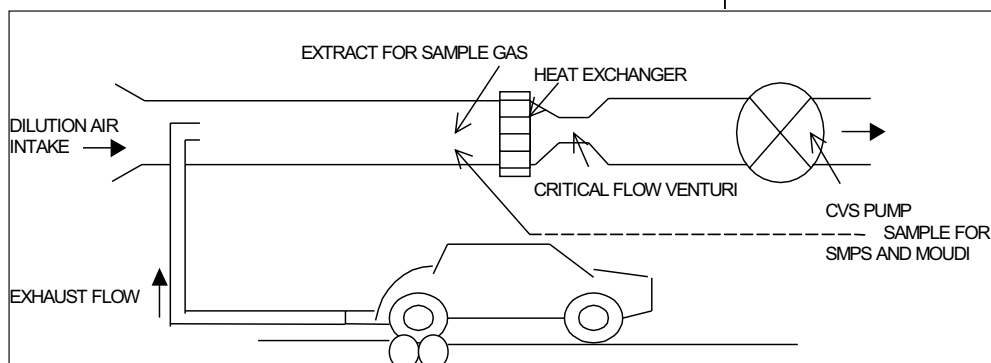


Figure 2 (below): Light Duty Test Schematic



the particle number was reported as the integral of the size distribution.

7. ANALYTICAL METHODOLOGY

Within this study particle mass, number and size were measured. Different measurement methods were employed to measure those parameters as described in Section 5. Two types of particles were emitted – smaller, mainly volatile nucleation mode particles and larger mainly solid accumulation mode particles. Within this study, particles smaller than 50nm (measured by SMPS) and smaller than 56nm (measured by MOUDI) were defined as nucleation mode particles and particles larger than 50nm (measured by SMPS) and 56nm (measured by MOUDI) were defined as accumulation mode particles. This cut-off point was to a certain extent arbitrary, since the smallest solid carbonaceous particles are believed to be within the size range from 30nm to 50nm and in reality the two modes overlap – sharing the 30nm to 60nm region of the size distribution.

The programme's objectives did not include the investigation of particle sampling and measurement methodologies. However, observations of parameters such as measurement methods, test procedures and dilution ratio were deemed necessary and are described in this section.

7.1 SMPS Instrumentation

Two nominally identical SMPS instruments were employed in parallel within this study as described in Section 5. Prior to commencement of the programme, a comparative exercise was carried out to determine the similarity of the two SMPS systems. Figure 3 shows the comparison between the entire SMPS systems and their condensation particle counters (CPCs) operating independently. These instruments have been set-up identically and measured identical diluted exhaust. Both CPC instruments measured very similar values with only 1.5% variance. The SMPS system though, differed by 19% in terms of integrated particle numbers. It is believed that this difference between the concentrations from the matched SMPS systems is the function of imperfectly balanced flows within the electrostatic classifier. These lead to different diffusional and other losses within the system. This variability of the SMPS instrumentation is considerably higher than what would be expected with current regulated emissions measurement instruments.

The next step was to compare the two SMPS systems under the two different set-ups, one measuring ~7nm to ~320nm (SMPS.7) and the other measuring ~15nm to ~710nm (SMPS.15), which were employed within this programme. As an example, Figure 4 shows the normalised size

distributions obtained from these two systems when measuring identical dilute exhaust emitted from a light duty Diesel vehicle at 100kph. Clearly, the two set-ups showed different particle size distributions, with the distribution from the instrument measuring the larger size range shifted to larger sizes relative to the instrument measuring the smaller size range. It was observed that this shift in measured size distribution was linked with the set-up of the instruments, the sample flow, and was not the result of a fault in the instruments themselves. Since the set-up of the instruments is linked to the measured size range of the instrument, this shift in distribution is unavoidable.

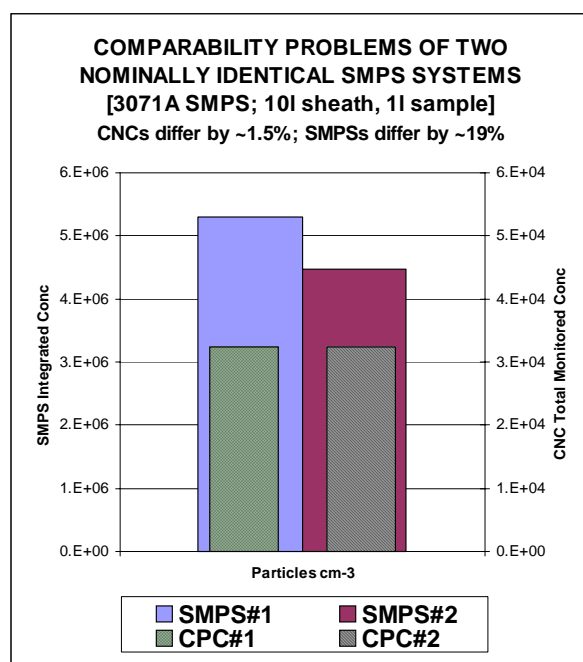


Figure 3 : Methodology : SMPS and CPC Comparisons

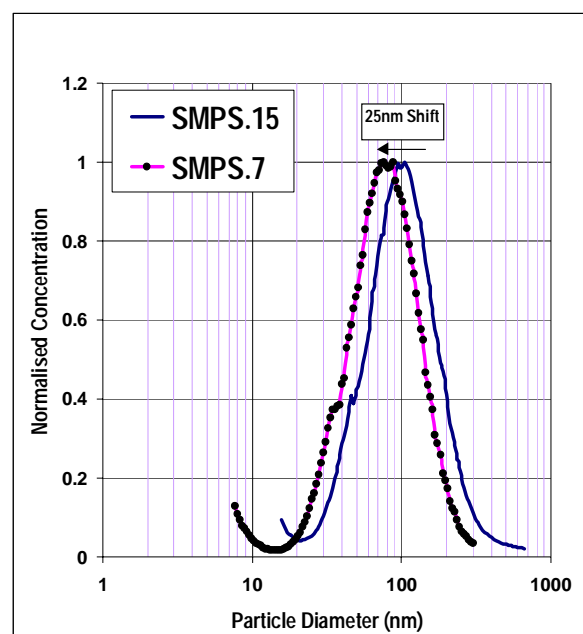


Figure 4 : Methodology : Comparison Of Two SMPS Set-Ups At 100kph

On further investigation it was determined that the shift in the size distribution is not identical for all particle emissions. Figure 5 shows the comparison of the SMPS.7 and SMPS.15 set-ups on diluted exhaust from a light duty Diesel tested at idle. At this condition there are both accumulation and nucleation modes present. For this exhaust aerosol, both set-ups showed nearly identical size distributions for particles smaller than 50nm and only a slight variation for the accumulation mode. These results indicate that the particle composition has an influence on the measured size distribution and any differences can not easily be predicted.

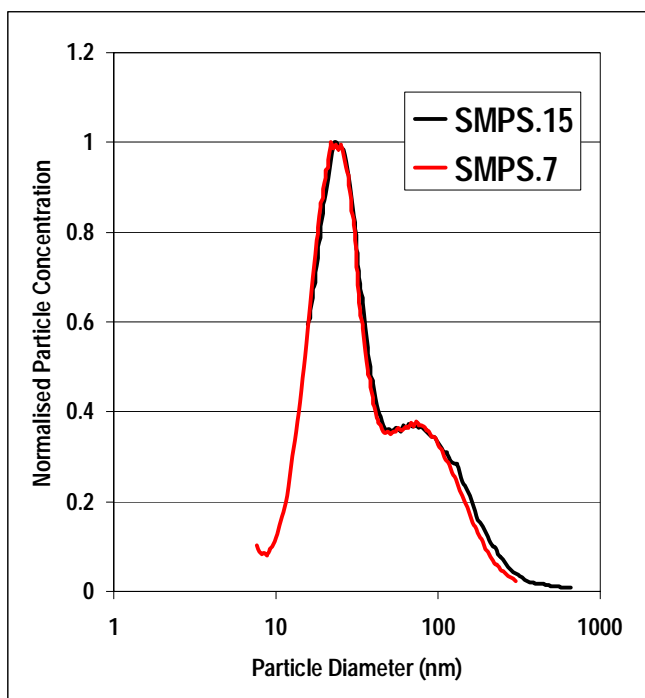


Figure 5 : Methodology : Comparison Of Two SMPS Set-Ups At Idle

These results demonstrate clearly how sensitive particle number and size measurements are to the set-up of the instrumentation. This makes the comparison of data from different studies investigating even the same technologies under the same dilution and sampling conditions very difficult.

To overcome these difficulties, particle number as well as size calibration standards are required so that SMPS systems can be calibrated under any set of operating conditions. These calibration standards would need to cover the nucleation mode as well as the accumulation mode particles and be of suitable chemical composition. Once these standards are available, a standard or a set of standard operating conditions could be defined, but until then consistency and reporting of instrumental configuration is paramount.

At the beginning of the programme it was intended that all steady state particle number and size measurements from both SMPS.7 and SMPS.15

collected in parallel would be combined into one data set. However, following these investigations it has been decided to treat the two data sets as separate entities. It should be noted that the conclusions drawn from each data set are not necessarily identical. However, overall conclusions drawn in this summary report are similar and therefore, only data from SMPS.7 are shown.

7.2 MOUDI Instrumentation

A single MOUDI was employed in order to collect mass distribution data. These data were acquired from a sampling probe intended for regulated mass measurements. Total masses collected by the MOUDI and regulated PM methods showed varying degrees of similarity. The determination of the origin of these differences was not an objective of this programme. However, it was observed that the differences between both particle mass measurements are different for different operating conditions as illustrated in Figure 6. Greatest differences were seen at operating conditions with a high volatile content within the particulate. At these conditions the MOUDI sampled considerably higher masses than the regulated filter. This might be due to the different collection mechanisms between both particulate sampling methods. Within the regulated particulate sampling procedure, the flow rate through a particulate filter is about 100 l/min. The soot loading on the filter has an effect on the retention of volatile material and that of further soot particles. Therefore, there is a link between particle composition and particle mass. For the MOUDI the flow rate is about a third that noted above. The diluted exhaust is not passed through the filter and the collection mechanism relies on impaction rather than filtration. Therefore, the particulate composition might have a lesser effect on the sampled particle mass.

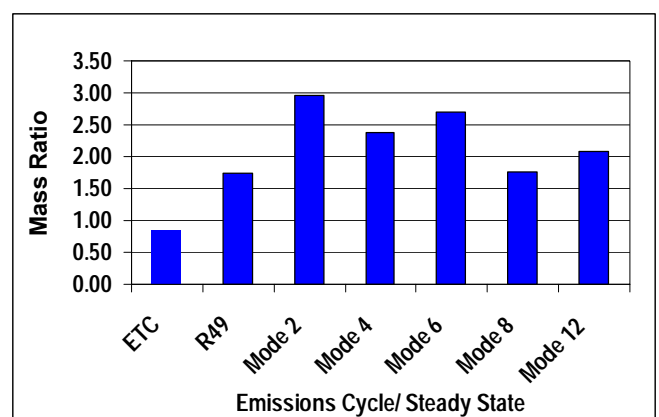


Figure 6 : Methodology : Ratio of MOUDI Particle Mass to Regulated PM

Further research is required to understand these differences. But it should be noted that the results from the MOUDI and regulated particulate filter do not necessarily reflect the same trends.

7.3 System Conditioning

The effects of system conditioning and size distribution stabilisation can be best explained for the R49 cycle. The R49 cycle consists of 13 steady state conditions of equal duration. Initially, the load on the engine is progressively ramped from idle at an intermediate speed up to peak torque. This is then followed by another idle condition. A change to the full load rated power condition is then followed by a progressive ramp down in load to idle. The first mode, the seventh mode following peak torque condition and the thirteenth condition are therefore all at idle. Figure 7 shows particle number and size distributions from these three idle conditions within the R49 cycle. Although the three idle conditions are nominally equivalent, there were clear differences in the three particle size distributions. These differences were similar irrespective of engine type or fuel specification.

The largest and most numerous particles were observed when the prior condition to idle was peak torque. The smallest and lowest number of particles were observed at the thirteenth condition, after the ramp down of load from rated power. This trend in particle size and number also coincides with the trend in exhaust temperature. It has been found in other studies that temperature plays a key role in the production of nucleation mode particles.

In addition to the exhaust and dilution tunnel temperatures, and even though the flow rates through the dilution tunnel are similar for all three idle conditions, the 'conditioning' of the dilution tunnel and transfer pipes is different for each of the three idles. Different particulate and exhaust chemistries in the tunnel will be present prior to each idle, and

these interact with the material present at the tunnel and pipe walls. This constant dynamic process of deposition/re-entrainment and adsorption/desorption may be a key factor in particle formation particularly at low exhaust flow rates.

During the R49 tests on the Euro I engine, an influence of tunnel and system preconditioning was observed following each fuel change although the engine was preconditioned at high load for at least one hour prior to sampling. This affected the repeatability of particle size distributions but could have been eliminated by running a R49 cycle as a preconditioning cycle prior to commencement of measurements. This is recommended for any future programme to eliminate the variable prehistory of the engine, exhaust and dilution system.

7.4 Particle Number and Size Distribution Stabilisation

Particle size distributions collected under steady state conditions rapidly stabilised within the accumulation mode region, but required long periods to reach a stable distribution when the nucleation mode was dominant. This is illustrated in Figure 8, with the particle number and size from the Euro II engine tested at peak torque condition. Particle number and size were sampled over a period of 20 min. During this time the accumulation mode did not change either in location or magnitude. The peak of the nucleation mode however, reduced in both diameter and in magnitude with time, only stabilising at the end of the sampling period. Consequently, during the ESC and R49 steady state test cycles, unstable nucleation mode size distributions and number concentrations but stable

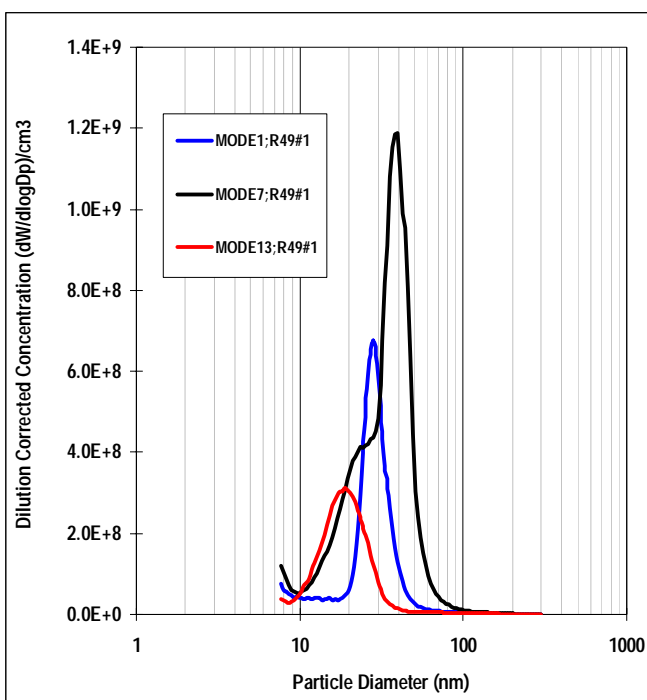


Figure 7 : Methodology : Comparisons of Idle Conditions

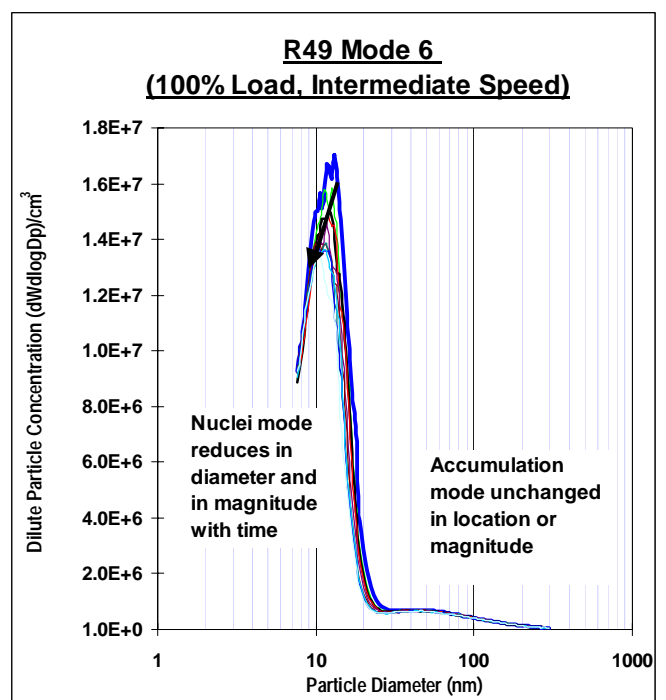


Figure 8 : Methodology : Size Distribution Evolution

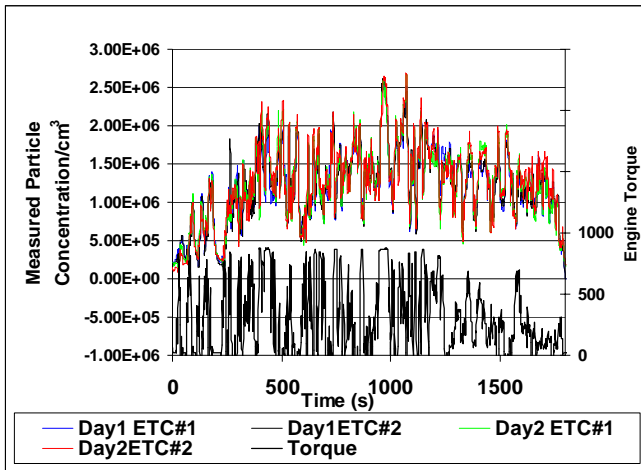


Figure 9 : Methodology : Heavy Duty Transient Production of 10nm Particles

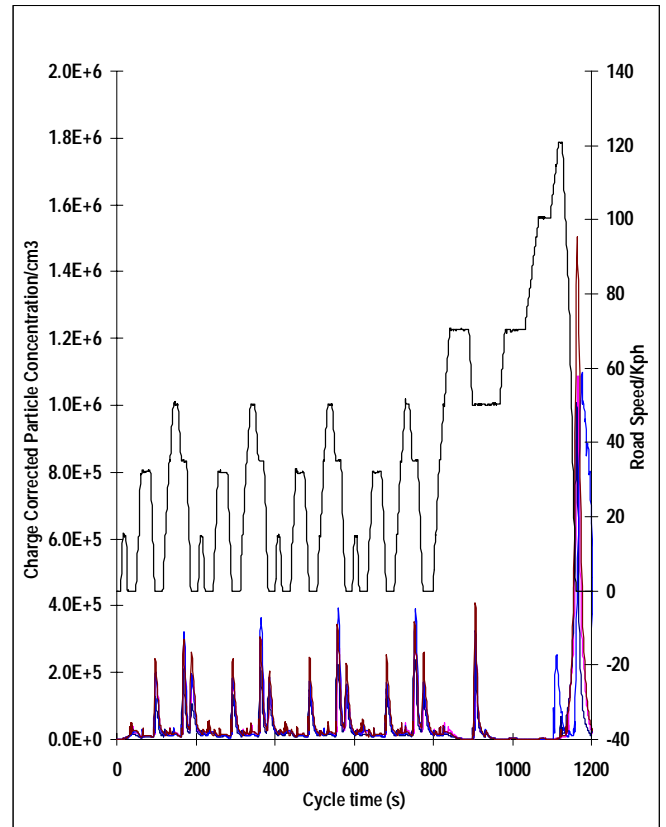


Figure 11 : Methodology : Light Duty Transient Production of 10nm Particles

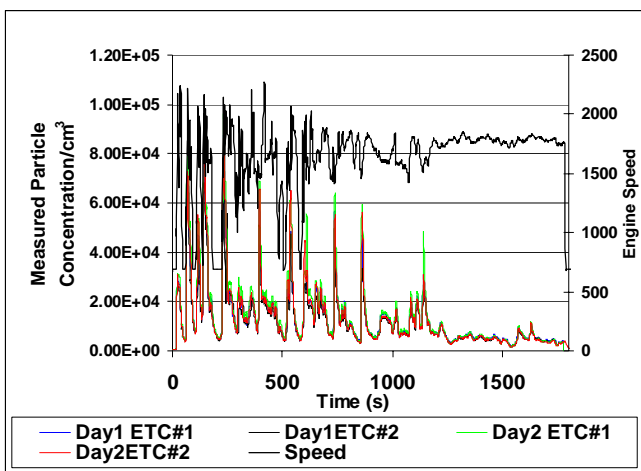


Figure 10 : Methodology : Heavy Duty Transient Production of 150nm Particles

steady state accumulation mode particles were measured during short (6 minutes R49, 2 minutes ESC) steady state intervals. Nevertheless, it should be noted though that although the nucleation particles did not stabilise during the cycle, they were highly repeatable when measured within a strict test protocol.

7.5 Repeatability

Steady state particle size repeatability has been discussed in the previous sections. The standard deviation of the total particle number over the R49 cycle was 20% and 12% for the Euro I engine and the Euro II engines respectively. The standard deviation for the regulated mass and integrated MOUDI mass for this steady state cycle were 10% and 8-20% respectively.

Transient repeatability is demonstrated for the Heavy Duty Engines over the ETC. Figures 9 and 10 show duplicate test cycles tested within a single day, plus two further test cycles tested on the following day for both 10nm particles (representing the nucleation mode) and 150nm particles (representing the accumulation mode) respectively. The 10nm data

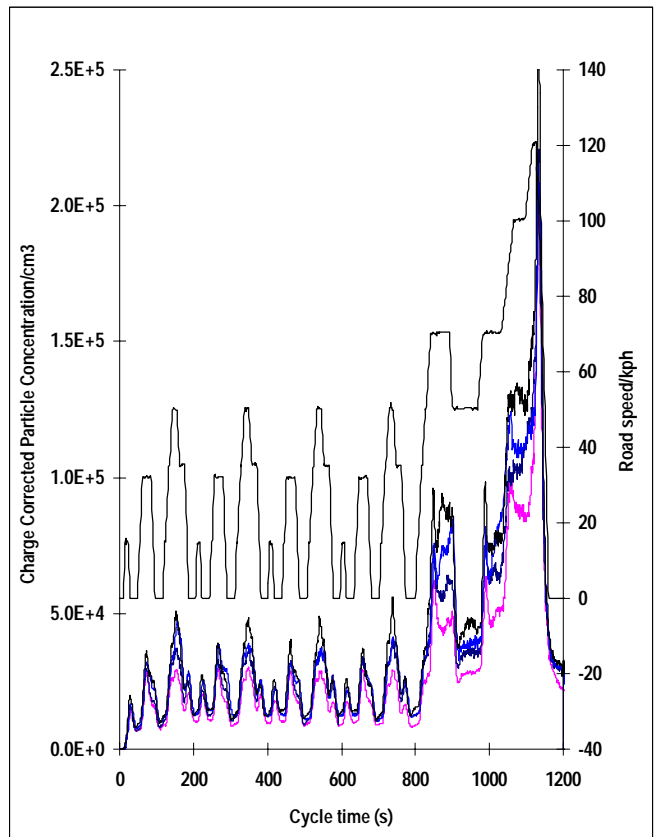


Figure 12 : Methodology : Light Duty Transient Production of 150nm Particles

are plotted together with engine torque and the 150nm data together with engine speed illustrating the relationships between these engine parameters

and particle production. For both particle sizes excellent repeatability has been observed. It should be also noted that the engine control over the ETC cycle was excellent as the speed and torque traces indicate.

For the vehicle tests where repeatability is dependent on the driver, the engine operation was less well controlled and the repeatability was lower. (Figures 11, 12)

In general repeatability was less good from the gasoline vehicles than from the Diesel vehicles. Repeatability from the heavy duty CNG engine was similar to that from the heavy duty Diesel engines.

The high levels of repeatability obtained from the tests conducted on the heavy duty engines within this programme, indicates that close control of the engine eliminates a major source of variability in particle production and measurement.

Overall, the repeatability for particle mass, number and size measurements within this study has been excellent and standard deviations for these unregulated emissions were well within the limits for regulated emissions from studies such as EPEFE.

The conventional dilution systems as employed within this study appear to be appropriate for the determination of accumulation mode particle number and size from both transient and steady state drive cycles. There is a greater uncertainty with the nucleation mode particle size and number and this will require more work in determining test and sampling conditions. However, it has been observed that production of both nucleation as well as accumulation mode particles can be highly repeatable.

8. EFFECTS OF ENGINE AND VEHICLE TECHNOLOGIES AND FUEL SPECIFICATIONS

8.1 Heavy Duty Results

As expected, regulated particulate mass emissions reduced with progressively stricter legislation. This is shown in Figures 13a and 13b. In these and subsequent figures, data that illustrate a scatter +/- one standard deviation of the base fuel mean are indicated on each column by horizontal bars. Effects of engine technology proved larger than those of fuel specification, though Swedish Class 1 fuel emitted significantly less mass than the other Diesel fuels tested.

Additionally, a reduction in mass of about 80% was observed when changing from the Euro III Diesel technology operating on Swedish Class 1 fuel to CNG operation. It should be noted that the CNG engine was operated under stoichiometric

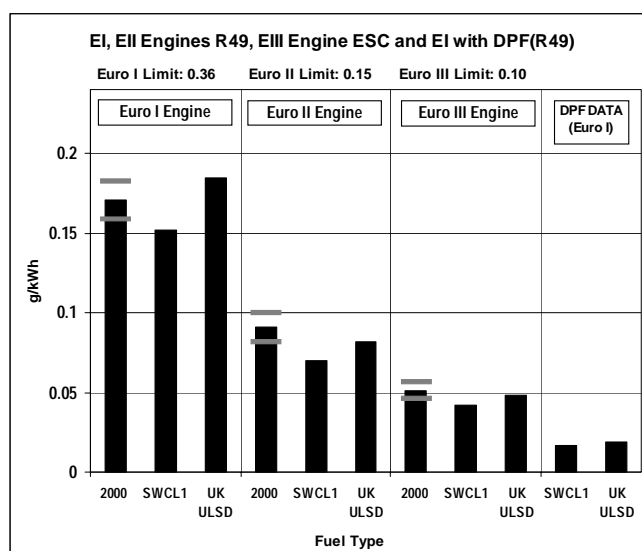


Figure 13a Heavy Duty Engines : Regulated Particulate Mass – R49&ESC

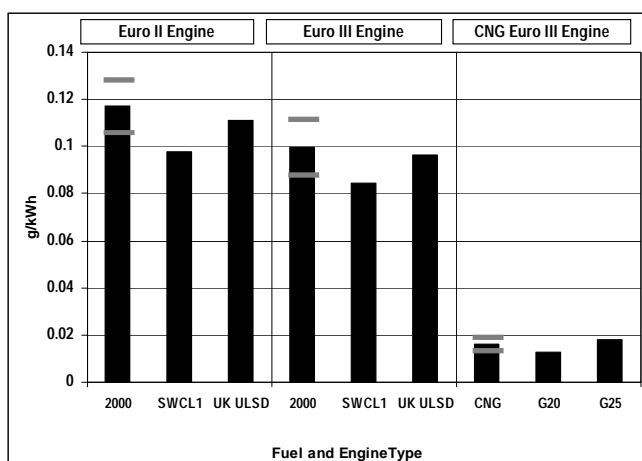


Figure 13b Heavy Duty Engines : Regulated Particulate Mass – ETC

conditions and was fitted with a three way catalyst, and that none of the conventional Diesel engines were fitted with oxidation catalysts (with the exception of the Euro I engine when fitted with the DPF system). The DPF system comprised of a oxidation catalyst and a DPF. Regulated mass emissions over the R49 cycle from the Euro I engine fitted with a DPF system were less than those from the CNG engine over the ETC cycle.

Most of the particle mass was emitted as particles larger than 56nm. As an example, this has been illustrated in Figure 14 for the Euro II and III technologies tested over the ETC. Mass emissions of particles below 56nm were similar between fuels, while masses above 56nm reflected the fuel effects observed with the regulated particulate. As described in Section 7, the collection mechanisms of the MOUDI impactor and the regulated particulate filter measurements are different, and results from each method can lead to a different conclusions. The reduction in the MOUDI mass with the CNG

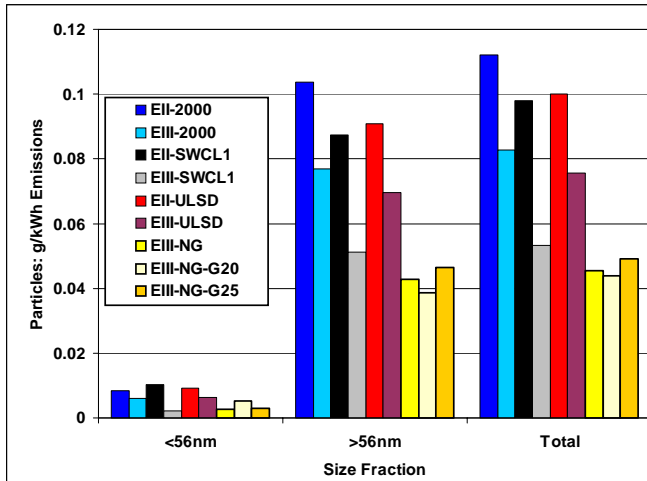


Figure 14 : Heavy Duty Engines : Integrated MOUDI Mass from Diesel and CNG Engines over the ETC

engine was only 10% greater than the reduction from the Euro III Diesel engine when operating on Swedish Class I fuel. However, trends shown here from the integrated MOUDI masses are broadly similar to those from the regulated particulate mass.

In general, particle number measurements showed that more than 50% of the particles are nucleation mode particles, i.e. smaller than 50nm. Figures 15 and 16 show the integrated particle number comparisons of engine technologies and fuel specifications from the ETC and R49 cycles respectively. There were relatively small differences between engines in terms of total particle number emissions, with the Euro II engine showing higher total particle number emissions than the Euro I and Euro III engines.

Over the R49 cycle, the Euro II engine emitted a higher number of nucleation mode particles than the Euro I engine and since these dominated the size distribution, a higher total number of particles. The CNG engine emitted an order of magnitude fewer total particle numbers than the Diesel engines.

For both R49 and ETC cycles, all the Diesel engines emitted the lowest number of nucleation mode particles and therefore, the lowest total integrated number, when operating on Swedish class I fuel. Effects of fuel specification were greatest within the nucleation mode while engine technology effects dominated within the accumulation mode, (particles above 50nm). This is also illustrated in Figure 17.

The highly transient urban (the first 600s of the ETC cycle) and less transient rural and motorway phases (601-1200 and 1201-1800s sections respectively) of the ETC showed similar trends, with a large separation apparent between engine technologies within the accumulation mode. This trend

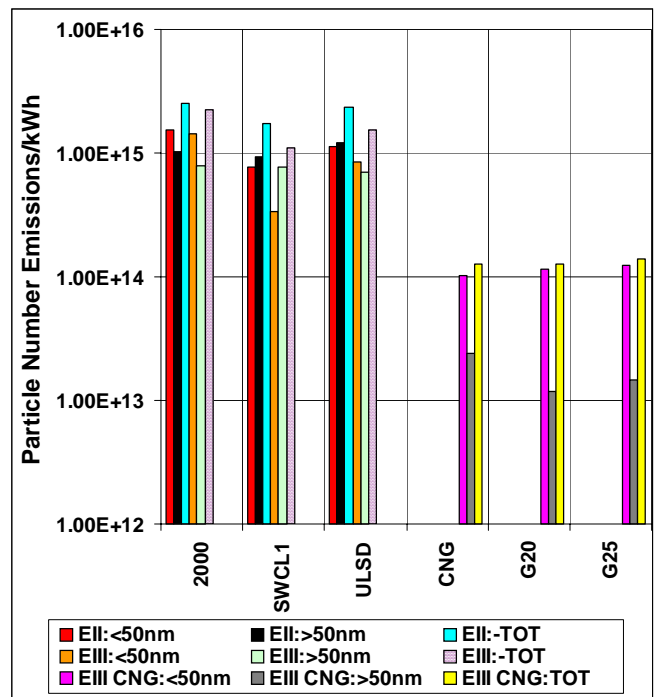


Figure 15 : Heavy Duty Engines : Integrated Particle Number From Diesel And CNG Engines Over The Urban Cycle Of The ETC

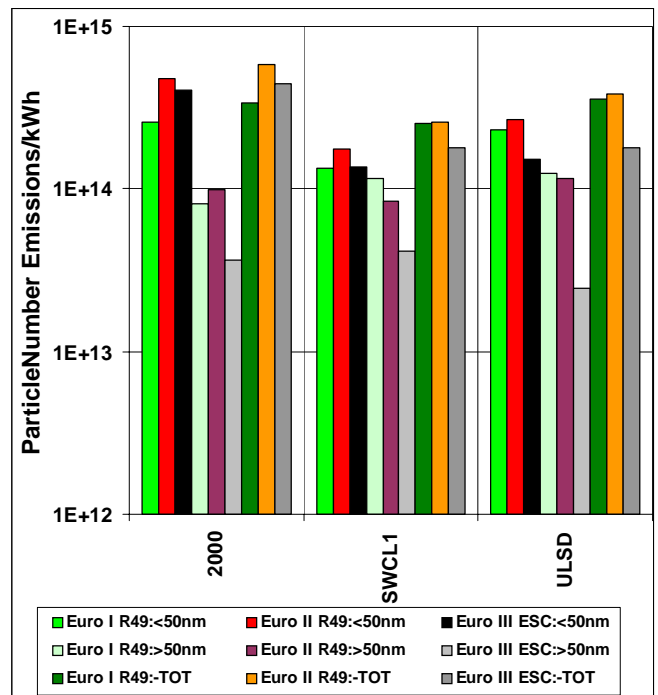


Figure 16 : Heavy Duty Engines : Integrated Particle Number from Diesel engines over the R49 and ESC

corresponds to the reductions in regulated particulate mass and MOUDI particle mass observed between the technologies over the cycle. Differences between fuel specifications within the accumulation mode can only be seen with the largest particle size measured, i.e. 250nm. Although these 250nm particles do not contribute significantly to the particle number they do contribute considerably to the particle mass.

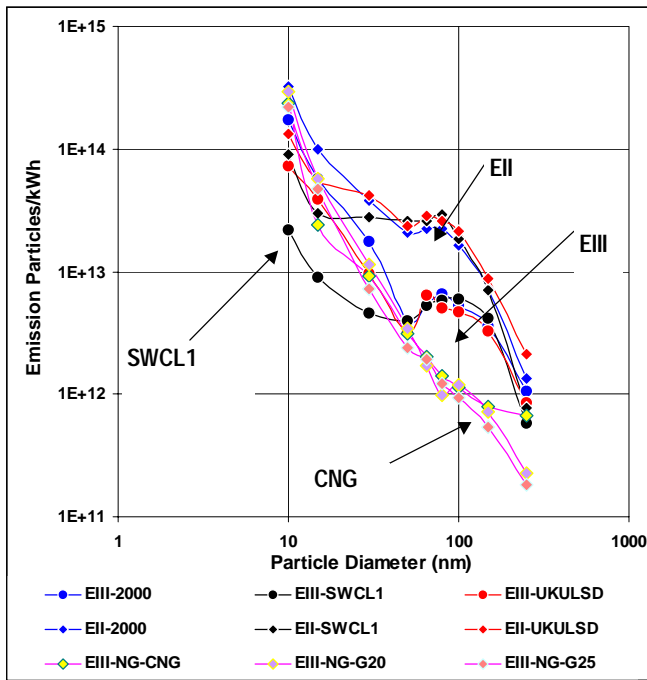


Figure 17 : Heavy Duty Engines : Particle Number and Size from Diesel and CNG over the Urban Cycle of the ETC

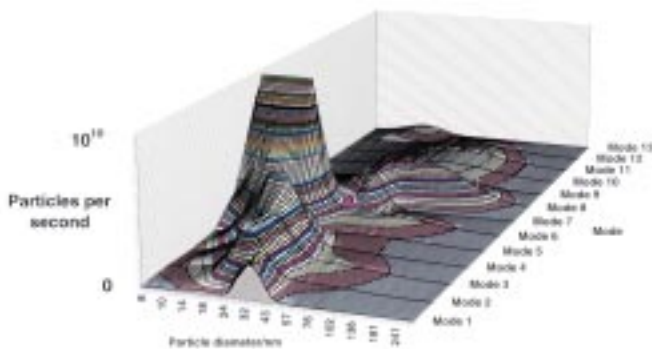


Figure 18: Heavy Duty Engines : 3D R49 Particle Number Distribution, Euro II Engine, EN590:1999 Fuel

The variances between engine technologies within the nucleation mode were smaller; even the CNG engine emitted similar numbers of 10nm particles to the Diesel engines.

These nucleation mode particles consist of volatile materials and the absence of accumulation mode particles (mainly comprising of adsorptive carbonaceous material) allows nucleation mode particles to be formed.

This relationship between particle composition and particle formation can be illustrated within Figure 18, a three dimensional plot of particle emissions from all 13 steady state modes of a regulated R49 cycle.

The first part of the cycle (modes 1-6) represents

a progressive ramp upwards in load from idle to 100% at an intermediate speed. The mode in the middle of the cycle represents idle and conversely, the second half of the R49 (modes 8-13) represents a progressive ramp down from 100% load at high speed, to idle.

Figure 18 shows that nucleation mode particles are concentrated over the first part of the cycle.

At these conditions the particulate consists of greater than 60% of volatile material. However, at rated power (mode 8) the carbon production is high and as a consequence accumulation mode particles are dominant. Because of the carbonaceous nature of these particles they adsorb the majority of the hydrocarbons since the carbon offers a large surface area for heterogeneous nucleation. It might be expected to see a similar effect with the other full load condition, peak torque (mode 6), but this engine has been highly optimised for lowest regulated mass at this condition. The consequent low levels of carbon at mode 6 permit the formation of high levels of nucleation mode particles.

With the absence of significant carbonaceous material, small nuclei, possibly sulphates or metals, are providing the nuclei for hydrocarbons to condense. Also some high molecular weight hydrocarbons might self nucleate and contribute to the nucleation mode. These routes to formation of nucleation mode particles are responsible for the increase in total particle number compared to the Euro I engine, which had not been heavily optimised for low particulate at this peak torque condition.

Over the second part of the cycle the particulate chemistry comprises more than 60% carbonaceous material and as a consequence, the accumulation mode dominates.

This relationship between composition and size has been observed with all technologies and cycles tested. Therefore, the technologies emitting lowest accumulation mode particles can emit significant levels of nucleation mode particles when volatile material is available.

Figures 9 and 10 (Section 7) illustrate the nucleation and accumulation mode particle formation in response to transient engine operation (ETC) respectively. Elevated levels of accumulation mode particles, here represented by 150nm particles, were emitted in response to accelerations, while nucleation mode particles (10nm) were produced in response to accelerations and decelerations. Since the carbonaceous accumulation mode was produced in response to such specific events of short duration, and was quickly cleared from the exhaust and dilution system, the carbon's ability to suppress nucleation was minimised. Therefore, nucleation mode particles were produced in high levels throughout the ETC.

Effects of fuel specification were most obvious within the nucleation mode. Changes in fuel specification are known to affect volatility of exhaust hydrocarbons, exhaust temperature and flow rates. The growth of nucleation mode particles are known to be very sensitive to these parameters. Additionally, this mode is also sensitive to sampling and measuring procedures. Therefore, studies measuring different particle size ranges or employing different dilution methods might suggest very different conclusions from the same engines and fuels.

8.2 Euro I HD Engine : Effects of a Diesel Particulate Filter (DPF) System

The Euro I engine was tested with and without a DPF system fitted. The system comprised an oxidation catalyst followed by a DPF. In a comparison between non-DPF equipped and post-DPF emissions, regulated particulate mass (PM) and integrated MOUDI mass emissions were reduced by about 90% and 75% respectively over the R49 cycle with both Swedish Class 1 and UK ULSD fuels. This is illustrated in Figure 19.

The chemical composition of the regulated particulate changes with the utilisation of a DPF system, as shown in Figure 20. The particulate collected without a DPF system fitted consists mainly of carbonaceous material, the particulate downstream of a DPF system comprises mainly volatile material. These volatile materials consist

mainly of sulphates and were emitted at the high load conditions. The UK ULSD fuel emitted approximately 3 times higher levels of sulphates than the Swedish Class I fuel.

The following two figures illustrate the effect of the DPF system on particle number when tested over the R49 cycle. Figures 21 and 22 show particle number emissions from Swedish Class 1 tested with and without the DPF system respectively.

Under all operating conditions the accumulation mode was almost totally eliminated when the DPF system was fitted. This was reflected in the absence of carbonaceous material and reduced particulate mass. Under full load conditions, sulphate emissions were formed over the oxidation catalyst. In the presence of those sulphates and in the absence of carbonaceous material, coupled with the thermal desorption of low volatility hydrocarbons from the exhaust system, nucleation mode particles were formed. These particles formed a mode located between about 10nm and 30nm. Within the R49 cycle, the full load conditions dominate the composite result.

Under low load conditions, no sulphate emissions were observed and volatile hydrocarbons were probably either oxidised over the catalyst or were stored upon the carbon within the filter. Therefore, particle precursors were effectively removed and total particle numbers were reduced by several orders of magnitude.

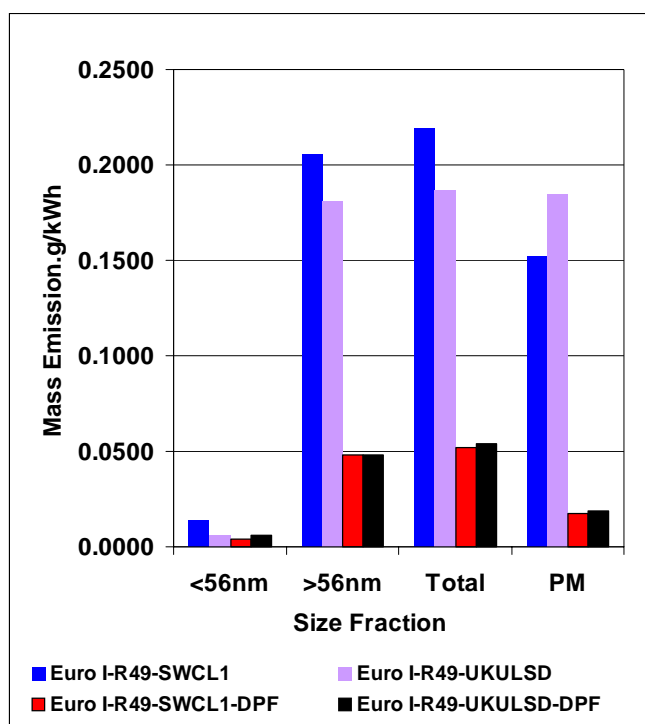


Figure 19 : Heavy Duty Diesel Euro I Engine, R49 : Effect of Diesel Particulate Trap System on Regulated Particulate Mass and Integrated MOUDI Mass Emissions

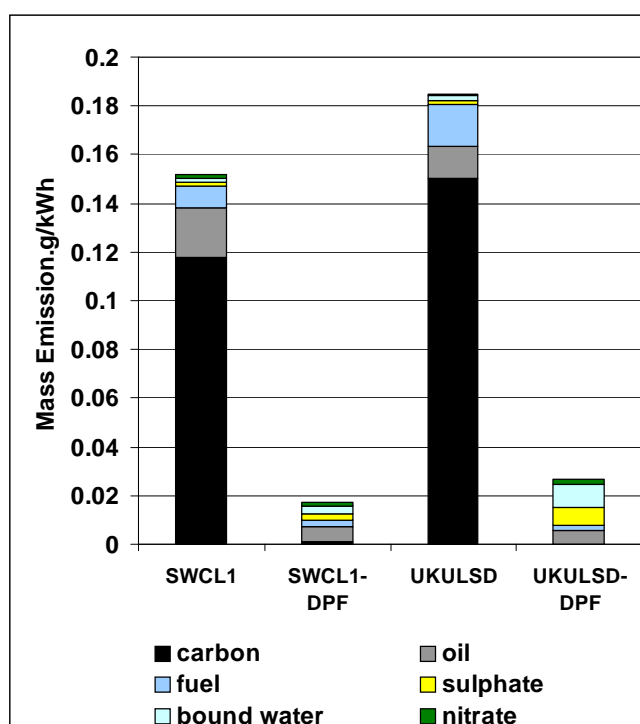


Figure 20 : Heavy Duty Diesel Euro I Engine R49 : Effect of Diesel Particulate Trap System on Particulate Composition

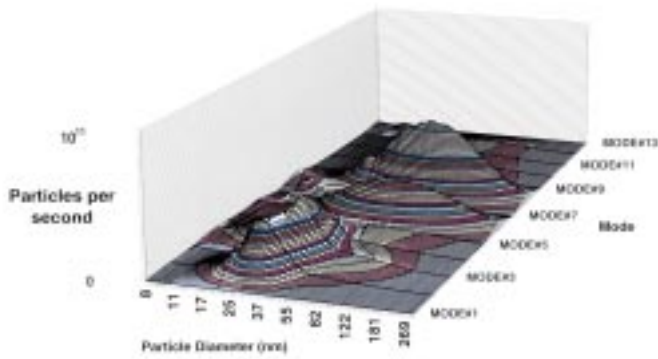


Figure 21 : Heavy Duty Diesel Euro I Engine R49 Particle Size Distribution, SWCL1 without a DPF System

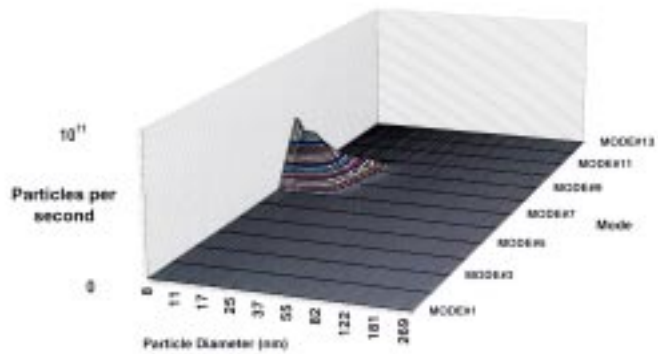


Figure 22 : Heavy Duty Diesel Euro I Engine R49 Particle Size Distribution, SWCL1 with a DPF System

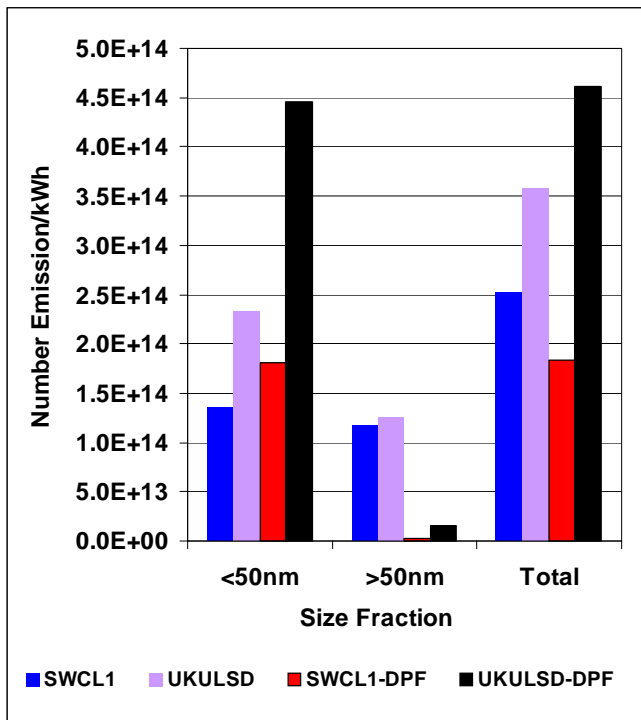


Figure 23 : Heavy Duty Diesel Euro I Engine R49 : Effect of Diesel Particulate Trap System on Particulate Number

As shown in Figure 23 with UK ULSD, total particle number when the DPF system is fitted can be similar to or exceed levels observed in tests without the DPF system.

With the UK ULSD fuel, particle emissions were 3 times higher than those with the Swedish Class I fuel. This reflected the increase of sulphate emissions and the greater range of volatility with the UK ULSD fuel.

Table 4 (below) describes type and specification of the six light duty vehicles tested. Further details can be found in Appendix 1; Table A1.1.

TABLE 4 - IDENTIFICATION OF VEHICLES

Vehicle Identifier	Fuel/Emissions Specification	Injection and Vehicle Types
DV1	Diesel, Euro III	DI; Passenger Car (PC)
DV2	Diesel, Euro II	DI; Light Commercial Vehicle
GV3	Gasoline, Euro II	MPI; PC
BV4	Gasoline/LPG, Euro II	MPI; PC
GV5	Gasoline, Euro III type	G-DI; PC
DV6	Diesel, Euro III	DI; PC (has DPF)

As seen with the heavy duty engines, stricter legislation has led to reductions in regulated particulate mass for light duty Diesel vehicles (as shown in Figure 24) when tested over the cold start European drive cycle. The Euro III vehicle fitted with a DPF system emitted an order of magnitude less regulated particulate mass than the conventional Euro III Diesel vehicle. With respect to fuel, the conventional Diesel vehicles emitted significantly lower levels when tested with Swedish Class I fuel than from the other fuels. However, although very low, regulated mass emissions from the Diesel vehicle fitted with a DPF system were similar from both Swedish Class 1 and UK ULSD fuels.

The regulated particulate mass from the conventional Diesel vehicles comprised 80% carbon and 20% volatiles, while that from the Diesel vehicle with the DPF system comprised close to 100% volatiles (with approximately 40% of those being sulphates). This is illustrated in Figure 25 for the UK ULSD fuel.

Figure 26 shows particle mass emissions from all gasoline vehicles when tested over the regulated cold start European drive cycle. Particulate matter is not currently regulated for gasoline vehicles, so to enable these measurements, the legislated procedures for Diesel particulate were employed. Particulate mass emissions from the gasoline direct-injection vehicle were ~12 times of those from

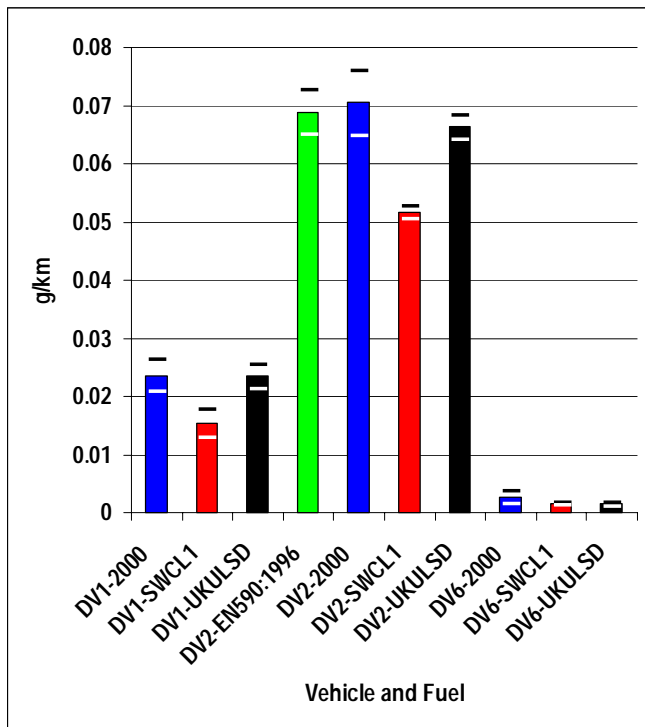


Figure 24 : Light Duty Diesel Vehicles : Regulated Particulate Mass Emissions over the European Drive Cycle

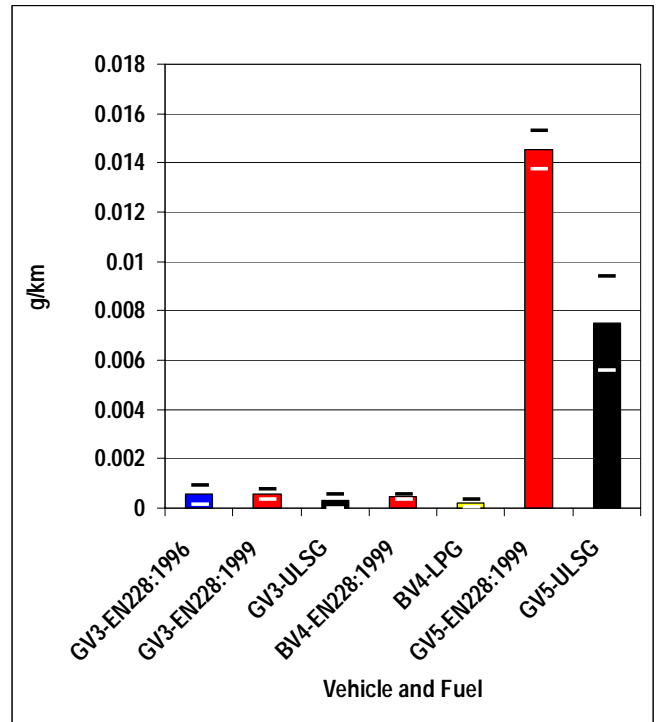


Figure 26 : Light Duty Gasoline Vehicles : Particulate Mass Emissions over the European Drive Cycle

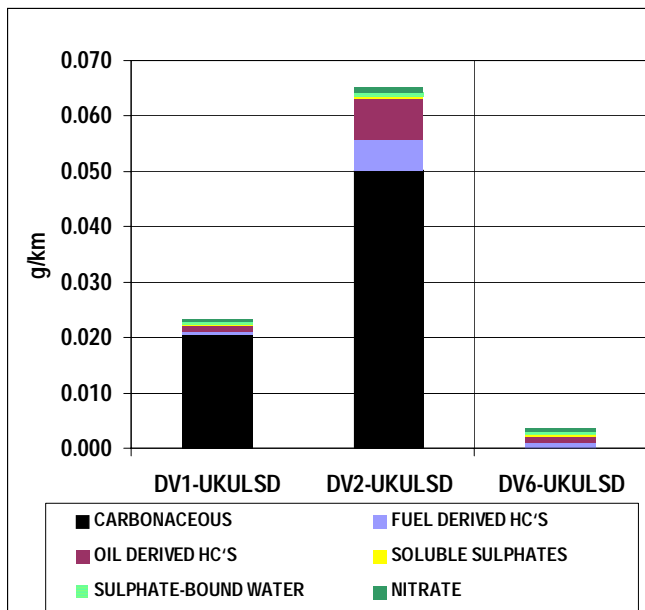


Figure 25 : Light Duty Diesel Vehicles : Particulate Composition - UK ULSD Fuel

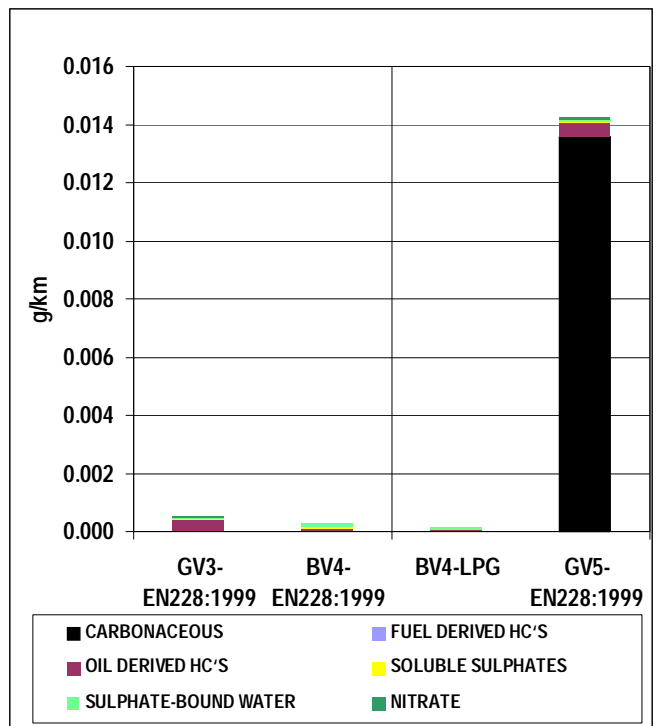


Figure 27 : Light Duty Gasoline Vehicles : Particulate Composition for LPG and EN228:1999 Fuel

the port-injected vehicles. The particulate composition from the gasoline direct injection and MPI technologies is shown in Figure 27.

Effects of fuel specification were observed with the gasoline direct-injected vehicle, where masses were ~50% lower from the ULS fuel compared with the EN228:1999 fuel.

The particulate material emitted from the gasoline direct injection vehicle appeared to be of similar composition to that from the conventional Diesel vehicles, predominantly consisting of carbonaceous material. However, it should be noted that the contribution of volatile material to the particulate mass will not be the same between gasoline and Diesel fuels because of fundamental differences in volatility.

The particulate emitted from port-injected vehicles was similar in both mass level and composition to that emitted from the Diesel vehicle with a DPF system. This particulate consisted mainly of volatile materials.

As observed from the heavy duty engines, most of the integrated MOUDI mass was associated with particles above 56nm for all vehicle technologies. This is illustrated in Figure 28 for all vehicle technologies tested over the cold start European drive cycles; integrated MOUDI particle masses were highest for the Euro II Diesel followed by the Euro III Diesel and the gasoline direct-injection vehicle. The masses for all other vehicles were very low, with the MPI gasoline and LPG vehicles being slightly lower than those of the Diesel with a DPF system.

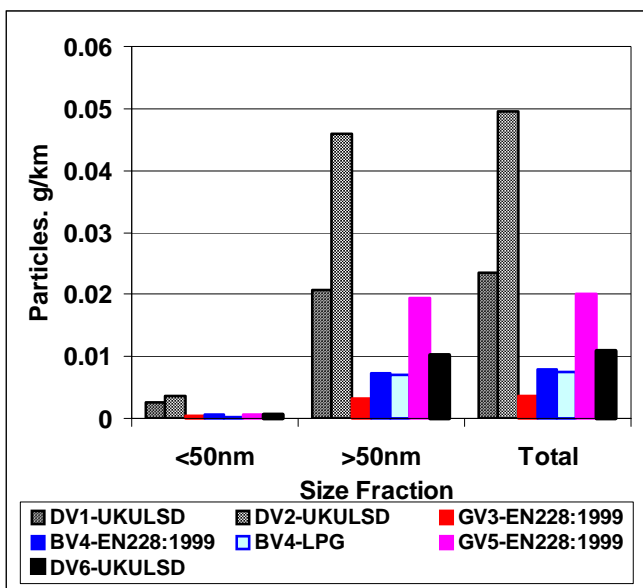


Figure 28 : Light Duty Vehicles : Integrated MOUDI Mass Emissions over European Drive Cycle for UK ULSD and EN228:1999

Particle number emissions for all vehicle technologies are shown in Figures 29, 30 and 31 for idle, 50kph and 120kph steady state conditions respectively.

At the idle condition, the conventional Diesel vehicles emitted higher levels of particles than the gasoline direct injection vehicle. However, the emissions of particles larger than 100nm were similar from the two vehicle types. The conventional gasoline vehicles, LPG and Diesel vehicle fitted with a DPF system all showed similar emission levels which were several orders of magnitude below those from the conventional Diesel vehicles. For the conventional Diesel vehicles, the idle condition was unique amongst the 5 test conditions tested; at this condition alone, these vehicles showed substantial nucleation and accumulation mode particle numbers together.

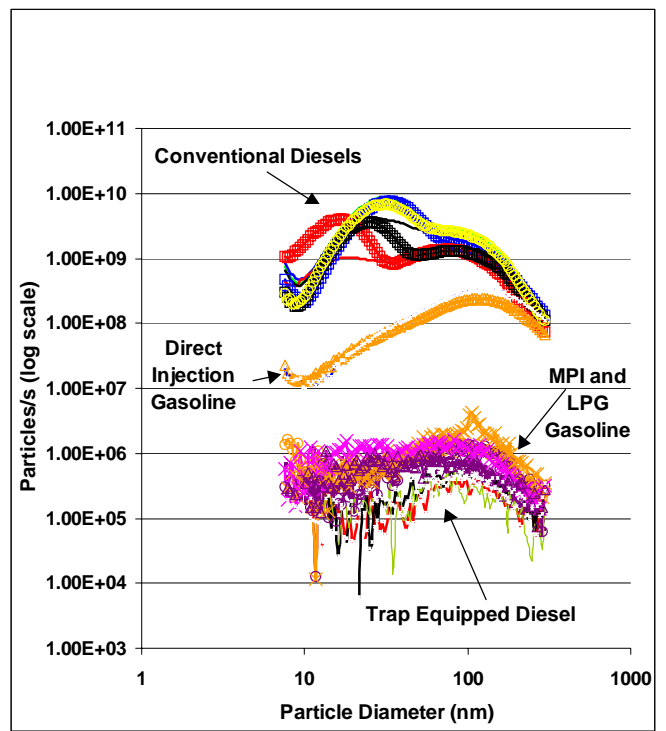


Figure 29 : Light Duty Vehicles : Particle Number and Size at Idle

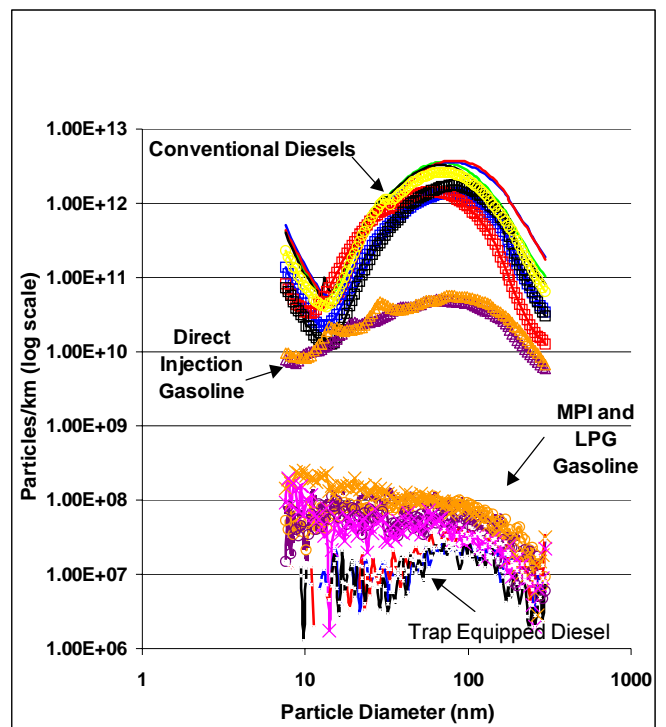


Figure 30 : Light Duty Vehicles : Particle Number and Size at 50kph

At all other conditions, single accumulation modes were observed. This is quite different to the heavy duty Diesel engines. The heavy duty Diesel engines are calibrated for soot reduction and hence accumulation mode reduction. At conditions where soot has been minimised in this way, nucleation mode particles can form when sufficient volatile material is available. Conversely, light duty Diesel calibration has focused more towards the reduction

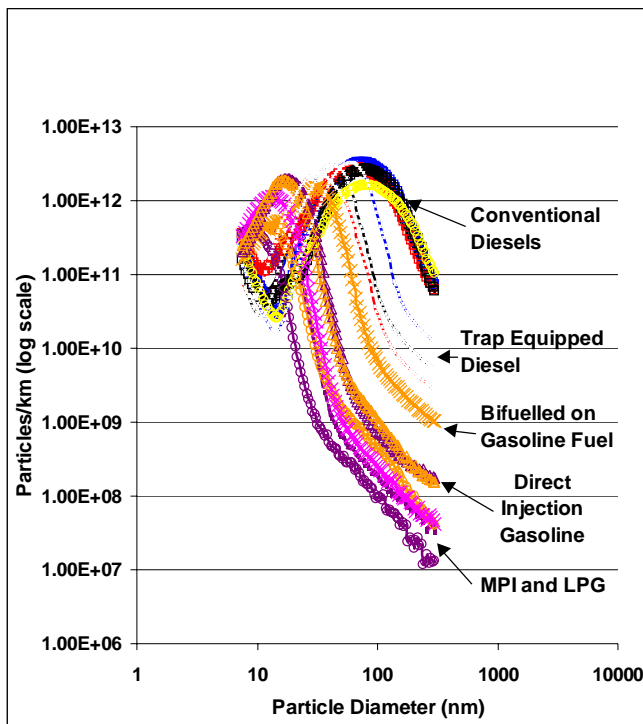


Figure 31 : Light Duty Vehicles : Particle Number and Size at 120kph

of NO_x; in-cylinder soot concentrations tend therefore to be higher and nucleation mode particles are suppressed.

Similar trends were observed in the size distribution data at 30kph, 50kph and 70kph. Therefore, the data from 50kph condition sufficiently illustrates all these data (Figure 30). The ranking of vehicle technology with respect to particle number can be seen to be similar to that at idle, with conventional Diesel vehicles emitting highest numbers within a dominant accumulation mode. The gasoline direct injection vehicle emitted particle numbers an order of magnitude lower within the accumulation mode. Emissions from the port-injected vehicles fuelled with gasoline and LPG were two orders of magnitude lower still. These vehicles showed nucleation as well as accumulation mode particles. Lowest numbers of all were emitted from the Diesel vehicle with a DPF system fitted.

Particle size distributions measured at 120kph (Figure 31) were distinctively different from those of all the other conditions measured. Though, depending on the vehicle technology, either the nucleation or accumulation modes dominated. Total particle number emissions were of similar magnitude.

The size distributions from the conventional Diesel engines were similar to those seen at 30, 50 and 70kph with just a dominant accumulation mode present.

At 120km/h the gasoline direct injection engine operated under high temperature homogeneous

lean conditions, with perturbations approaching stoichiometric. Under these conditions no carbonaceous material was produced and as a consequence the formation of a singular nucleation mode peak was apparent. At lower speeds the engine operated under stratified or homogeneous lean conditions, producing an accumulation mode which dominated the distribution.

The conventionally fuelled gasoline vehicles and the LPG plus the Diesel vehicle equipped with a DPF system all emitted large numbers of nucleation mode particles at the 120kph condition. The magnitude of emission was similar with all technologies, though the largest modal sizes for nucleation particles were emitted from the Diesel vehicle equipped with a DPF system.

The mechanism for the formation of the nucleation mode at this operating condition might be similar to those from the heavy duty engine when fitted with a DPF system. In the absence of carbonaceous material, and in the presence of sulphates and low volatility condensable materials, nucleation particles can be formed. The availability of these condensable materials may be due to thermal desorption of the low volatility materials from the exhaust system at high temperatures.

Figures 32 and 33 show the particle number emissions and size distributions obtained from the light duty diesel vehicles over the ECE phase and composite European drive cycles respectively.

At all conditions tested, the conventional Diesel vehicles emitted particle numbers of a similar order, with levels from the Euro II vehicle slightly higher than those from the Euro III vehicle. Differences attributable to fuels were minimal, though Swedish Class I emitted significantly lower accumulation mode particles than the other fuels tested. During transient operation, nucleation mode particles tended to be formed in response to decelerations whilst accumulation mode particles followed accelerations. Therefore, over the European drive cycle both accumulation mode and nucleation mode particles are emitted.

Over the ECE cycle, the Diesel vehicle fitted with a DPF system showed very low particle number emissions with the UK ULSD fuels as well as with the Swedish Class I fuel. When operating on the EN590:1999 fuel, the vehicle emitted significantly higher accumulation and nucleation mode particles. With the UK ULSD fuel only, significant numbers of nucleation mode particles appeared to derive from the start of the ECE phase, while high levels of accumulation mode particles were derived from the 120kph part of EUDC. Nevertheless, the main source of nucleation mode particles for all fuels was across the high temperature, 120kph, part of the EUDC.

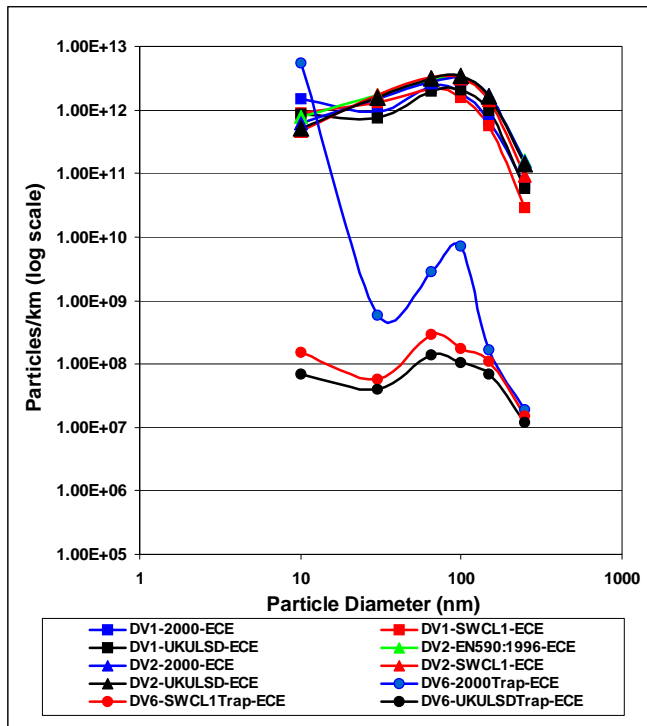


Figure 32 : Light Duty Diesel Vehicles : Particle Number and Size Emissions Over ECE Part Of The European Drive Cycle

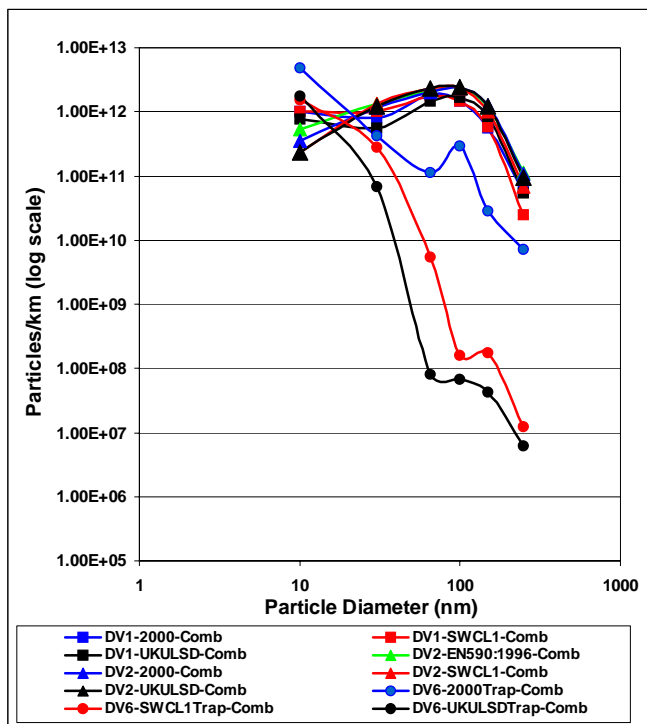


Figure 33 : Light Duty Diesel Vehicles : Particle Number And Size Emissions Over Composite European Drive Cycle

The gasoline direct injection engine showed the presence of both an accumulation mode and a nucleation mode. The engine operated in both stratified and homogeneous conditions over the drive cycle showing analogies with both gasoline and Diesel engine types. Accumulation mode particles were emitted readily over both parts of the

cycle in response to accelerations. Large numbers of nucleation mode particles were emitted over the 120kph part of the cycle in a similar manner to the gasoline vehicles and Diesel with a DPF system fitted. When operating on the ULS fuel, the gasoline direct injection engine emitted a lower number of accumulation mode particles and regulated particulate mass than when operating on EN228:1999 fuel. As a consequence the nucleation mode was relatively larger.

Conventional gasoline vehicles emitted only minimal accumulation mode particle levels during transient operation, but slightly higher levels under cold start conditions. Nucleation mode particles were emitted in response to both acceleration and deceleration events. Highest cycle particle numbers were emitted at the high temperature 120kph condition. Fuel effects were minimal.

Integrated particle number emissions over the European drive cycle and steady state conditions are shown in Figure 34 for all vehicles tested with UK ULSD or EN228:1999 fuels. In general, the

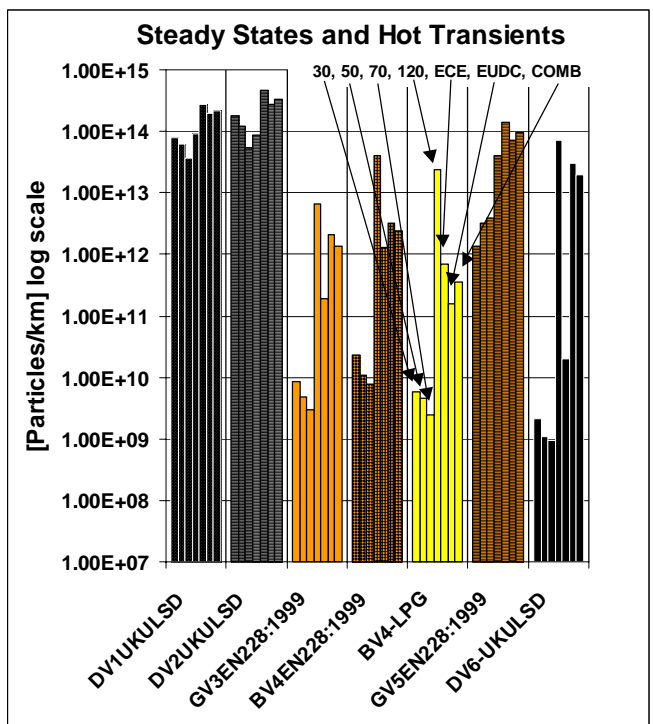


Figure 34 : Light Duty Vehicles : Integrated Particle Number Emissions

particle number emissions from the conventional gasoline and trap equipped diesel vehicle covered a much wider range than emissions from the conventional Diesel vehicles. Emissions ranged from $10^9 - 10^{10}$ /km at speeds up to 70kph, but at 120kph they increased up to $10^{13}-10^{14}$ /km. The conventional Diesel emitted particle numbers of

10^{13} – 10^{14} /km irrespective of operating condition.

Total particle numbers from the gasoline direct injection engine at 120kph were similar to those over the drive cycle at an order of magnitude higher than those from the other steady state conditions. Differences between operating conditions were less than those from the conventional gasoline vehicles.

European cycle emissions from the conventional gasoline engines were elevated relative to the 30, 50 and 70kph steady state conditions, but lower than those observed at 120 kph. Emissions from the bi-fuel vehicle were slightly lower when operated with LPG than when operated with gasoline.

The Diesel vehicle equipped with a DPF system emitted particle numbers over the ECE part of the cycle several orders of magnitude lower than those over the EUDC part of the cycle. During transient operation no significant accumulation mode particles were emitted. The main source of nucleation mode particles and therefore total particles were over the high temperature 120kph part of the EUDC.

9. CONCLUDING COMMENTARY

There were two types of particles emitted from the engines and vehicles tested. These particles were defined as nucleation mode particles when smaller than 50nm and as accumulation mode particles when larger than 50nm. The accumulation mode particles consisted mainly of carbonaceous materials and the nucleation mode particles were primarily comprised of condensed volatile materials. While trends for the accumulation mode particles were generally in line with those of particle mass, no relationships between nucleation mode particles and regulated mass were observed.

It has been demonstrated that the measurement of both nucleation and accumulation mode particle types can be repeatable. However, the nucleation mode particles were much more sensitive to the prehistory of the engine/vehicle, sampling and dilution parameters than the accumulation mode particles.

A trade-off between nucleation and accumulation mode particles was observed. Where carbon nuclei were present in sufficient numbers, the volatiles condensed preferentially on those nuclei and the accumulation mode dominated the total particle number. In the absence of sufficient carbon nuclei, but in the presence of sufficient condensable materials, such as low volatility hydrocarbons, sulphate and metal nuclei, these materials generate nucleation mode particles. Therefore, some engine technologies which are optimised for lowest soot production can form significant numbers of nucleation mode particles under some test

conditions despite the near elimination of accumulation mode particles.

Both fuel specifications and engine technologies influenced particle number emissions. However of those tested, no single fuel nor engine technology reduced nucleation and accumulation mode particle numbers plus particle mass concurrently at all operating conditions.

Stricter legislation for both light duty and heavy duty Diesel technologies has resulted in reduced particle mass when tested over the regulated cycle. This has generally been reflected in reductions of accumulation mode particles.

The largest effect of a single technology was observed with the Diesel Particulate Filter (DPF). Particulate mass and accumulation mode particles were reduced by several orders of magnitude. However, at some higher temperature conditions significant numbers of nucleation mode particles were observed. The formation of nucleation mode particles at high temperature conditions has been also observed with other low soot emitting technologies; conventional multi-point injection vehicles fuelled with gasoline and LPG and from the gasoline direct injection vehicle.

Generally, for both gasoline and Diesel vehicles' steady state tests, driven speed had a relatively small effect on particle number emissions. Exceptionally, at 120kph, particle numbers from the MPI gasoline, LPG and DPF equipped Diesel vehicle were increased by several orders of magnitude relative to the other conditions. Thus at 120kph, the total particle number emitted was similar with all engine technologies. However the contribution of the nucleation and accumulation modes to these totals were different. Accumulation mode particles dominated with the conventional Diesels and nucleation mode particles dominated with the gasoline vehicles and from the DPF system equipped Diesel vehicle.

For all other test conditions, the total particle number emissions were highest from the conventional Diesel vehicles at an order of magnitude higher than those from the gasoline direct injection vehicle. The conventional MPI vehicles fuelled with gasoline and LPG plus the Diesel vehicle fitted with a DPF system emitted several orders of magnitude lower particle numbers than the conventional Diesel vehicles.

Both particle mass and particle number emissions were lower from the heavy duty Euro III CNG engine than from the heavy duty Euro III Diesel engine.

Fuel effects were in general small compared to the effects of engine technology. For the heavy duty Diesel engines, the fuel effects were larger within the nucleation mode region and the effect of engine

technology was larger with the accumulation mode particles. The light duty Diesel vehicles tended not to emit significant levels of nucleation mode particles except at idle. With both conventional light duty and heavy duty Diesel technologies, Swedish Class I fuel tended to emit lower particulate mass and number.

Effects of fuel specification on the gasoline vehicles, CNG engine and DPF equipped Diesel vehicle were small. However, with the gasoline direct injection vehicle, the Ultra Low Sulphur gasoline fuel emitted significantly lower particle number and regulated particulate mass than the standard pump fuel.

This study has provided a comprehensive data base regarding the effects of a range of engine/vehicle technologies and fuel specifications on particle mass, number and size. It also has given valuable insight into the issues of sampling, dilution and measurement methodologies. This study has shown that despite the limitations of current particle number measurement instrumentation and the sensitivity of particle number measurements to sampling and dilution parameters, the data within one programme can be sufficiently repeatable if strict test and measurement protocols are applied.

However, it becomes obvious that the data acquired and conclusions drawn from different studies cannot be practically compared unless identical measurement and sampling standards have been employed. In particular, the availability of reliable calibration standards for both accumulation and nucleation mode particles are required to ensure correct set-up of particle number and size distribution measurement instrumentation. In view of the sensitivity to sampling conditions, representative as well as consistent measurement and sampling methodologies are needed.

Full conclusions are contained in the DETR/SMMT/CONCAWE Particulate Research Programme Final Report and the General Conclusions can be found in the Appendix 2 of this report.

10. OUTLOOK

This section outlines areas of priority for further research. Further detail can be found in Appendix 3.

10.1 Further Fleet Characterisation

This programme examined several vehicles from a limited fleet. Therefore the investigations undertaken within this programme should be extended to better represent the current and future fleets.

10.2 Advanced Technologies

New engine and aftertreatment technologies may present new particle production challenges and solutions. These should be investigated.

10.3 Real World and Off-Cycle Testing

The relationships between particle production from regulated emissions cycles and that observed in the real world is uncertain. Moves towards cycles which more closely represent real world driving, and measurements methods including dilution parameters should be investigated.

10.4 Fuels and Lubricants

The specific influences of fuel and lubricants should be studied by testing matrices where key parameters of interest, such as sulphur, volatility and aromatic content are decoupled.

10.5 Instrumentation and Test Procedures

Further work is required to develop and agree sampling and measurement standards for particle size and number so that comparable data sets can be produced. Test procedures for both nucleation and accumulation mode particles require investigation. Though greatest uncertainty for particle number emissions is the formation of nucleation mode particles.

11. ACKNOWLEDGEMENTS

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CONCAWE, DETR, SMMT

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Ford	Shell Global Solutions
Perkins Engines	Toyota.

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APPENDIX 1

TABLE A1.1 - BRIEF VEHICLE SPECIFICATIONS

Vehicle Identifier	Fuel Type & Emissions Specification	Injection & Vehicle Types	After-treatment	Displacement cm ³	Other information
DV1	Diesel, Euro III	DI (PC)	Under-floor Oxicat	1996	Proportional EGR
DV2	Diesel, Euro II	DI (LCV)	None	2496	Mechanical EGR
GV3	Gasoline, Euro II	MPI (PC)	Under-floor TWC	1796	Two lubricants tested
BV4	Gasoline/LPG Euro II	MPI (PC)	Under-floor TWC	1761	Bifuelled Vehicle
GV5	Gasoline Euro III type	G-DI (PC)	2 Oxicats and Under-floor lean NOx trap	1988	Early Calibration for Europe
DV6	Diesel, Euro III	HDI (PC)	Oxicat and DPF	2200	Cerium regeneration additive

TABLE A1.2 - BRIEF ENGINE SPECIFICATIONS

Engine Identifier	Fuel Type & Emissions Specification	Injection Cylinders Total Capacity	After-treatment	Max Power Max Torque	Other information
EI	Diesel, Euro I	D1, 6, 12, 17	None & CRT™	283kW@1900 rpm 1920Nm@1180 rpm	Mechanical FIE, Turbo & intercooler
EII	Diesel, Euro II	DI, 6, 5, 9	None	173kW@2500 rpm 800Nm@1500 rpm	Turbo & intercooler
EIII	Diesel, Euro III	DI, 6, 10.82	None	310kW@1900 rpm 2050Nm@1275 rpm	No data available
CNG	GNG EEV technology, Euro III	MPI, 6, 9.50	TWC	180kW@2100 rpm 1050Nm@1100 rpm	Closed loop stoichiometric control

APPENDIX 1

TABLE A1.3 : DIESEL FUEL SPECIFICATIONS

FUEL PROPERTIES/FUEL	EN590:1996	EN590:1999	SWCL1	UKULSD
Cetane Number	53	52	52	54
Cetane Index	54	50	51	56
Density (15°C) kg/m ³	841	842	812	835
Distillation (°C)				
T10	233	224	198	227
T50	281	265	226	281
T95	337	340	279	339
Sulphur mg/kg (ppm)	500	300	<10	50
Mono-aromatics (%vol)	20.6	16.2	4	13.9
Di-aromatics (%vol)	3.4	4.2	0.4	2.2
Tri-aromatics (%vol)	0.5	0.8	0	0.3
Total aromatics (%vol)	24.5	21.2	4.4	16.4
Viscosity at 40°C (mm ² /s)	2.95	2.76	3.00	3.07
Carbon (%)	86.5	86.4	85.7	86.1
Hydrogen (%)	13.5	13.4	14.3	13.7

TABLE A1.4 : GASOLINE AND LPG SPECIFICATIONS

FUEL PROPERTIES/FUEL	EN228:1996	EN228:1999	ULS	LPG
Research Octane N°	95	98	97	
Motor Octane N°	85	85	89	93
RVP (kPa) @37.8 °C (40°C LPG)	85	54	55	1341
H:C Ratio	1.78	1.78	1.95	
E 70°C	34	27	18	
E 100°C	55	50	48	
E 180°C	96	94	98	
Final Boiling Pt	202	196	181	
Sulphur Content mg/kg(ppm)	480	130	22	
Total Aromatics (%vol)	39.7	36.1	28.8	
Mono Aromatics (%vol)	39.2	35.7	28.7	
Di Aromatics (%vol)	0.4	0.5	0.1	
Tri + Aromatics (%vol)	0.1	<0.1	<0.1	
Carbon%	87.46	87.1	86.0	
Hydrogen %	12.99	12.9	14.0	
Density @ 15°C kg/m ³	741	757	734	542

APPENDIX 1 (CONT'D)

TABLE A1.4.1 - LPG DETAILS

The following supplementary information was also available for LPG:

Composition by carbon number			
C2	% molar		< 0.1
C3	% molar		93.1
C4	% molar		6.9
C5	% molar		< 0.1
Composition by chemical class			
Total Unsaturation	% molar		18.94
Dienes	% molar		< 0.1
Ethylene	% molar		< 0.1
Alkynes	% molar		< 0.1

TABLE A1.5: GASEOUS FUELS' SPECIFICATIONS

Property	CNG	G20	G25
H:C Ratio	3.94	4	4
% CH₄	94.7	100	86
% C₂H₆	4.1	-	-
% C₃H₈	0.8	-	-
% N₂	0.4	-	14

TABLE A1.6: ENGINE AND VEHICLE SPECIFIC FUEL TESTS

Vehicle/Engine	Fuel Type	Fuels Tested
Euro I	Diesel	EN590:1996, EN590:1999, SWCL1, UKULSD, Industrial Diesel
Euro II	Diesel	EN590:1999, SWCL1, UKULSD, Emulsion: UKULSD + 10% H ₂ O
Euro III	Diesel	EN590:1999, SWCL1, UKULSD
CNG	Gas	CNG, G20, G25
DV1	Diesel	EN590:1999, SWCL1, UKULSD
DV2	Diesel	EN590:1999, SWCL1, UKULSD
GV3	Gasoline	EN228:1996, EN228:1999, ULSG
BV4	Bifuelled Gasoline/Gas	EN228:1999, LPG
GV5	Gasoline	EN228:1999, ULSG
DV6	Diesel	SWCL1, UKULSD

APPENDIX 2: GENERAL CONCLUSIONS

1. There were two types of particle emitted from the engines and vehicles tested. These particle types formed modes in two size regions which at <50nm and >50nm, were defined as nucleation and accumulation regions respectively. Accumulation particles appeared as modes in the number distribution peaking at above 50nm and were primarily carbonaceous, while nucleation particles occurred at or below 50nm and were primarily comprised of condensed volatile materials.
2. The measurement of nucleation mode particles proved to be more sensitive to experimental conditions than the measurement of accumulation mode particles. Hence conclusions regarding the nucleation mode are subject to greater uncertainty than those concerning the accumulation mode.
3. The engines and vehicles tested produced particles in which the carbon to volatiles ratio varied considerably. Where carbon nuclei were present in sufficient numbers, the volatiles condensed preferentially on these nuclei and assisted the growth of the agglomerates which comprise the accumulation mode. Where insufficient carbon nuclei were present, the volatile hydrocarbon components condensed upon other nuclei, such as ~1nm sulphate particles and metallic nuclei, generating the nucleation mode.
4. Both fuel specifications and engine technologies influenced particle number emissions.
5. Neither fuel specification nor engine technology level reduced particle number emission of both nucleation (at or below 50nm) and accumulation (above 50nm) modes plus particulate mass concurrently at all operating conditions.
6. Legislation applied to heavy duty (HD) Diesels from EI and light duty (LD) Diesels from Euro II has reduced overall regulated particulate mass. This has been generally reflected in reductions in accumulation mode particle number.
7. Technology influences with light duty vehicles and heavy duty engines are different, and effects observed on one type are not simply translated to the other.
8. Fuel effects on heavy duty engines had greater influence on the nucleation mode region than engine technology effects.
9. A relative insensitivity to fuel was shown by accumulation mode particle size distributions from heavy duty Diesel engines and light duty Diesel vehicles. In general, the accumulation mode peak of the size distribution was present in the 60nm to 100nm region.
10. Particulate mass emissions from the EIII CNG HD engine were around 80% lower than the lowest emissions from the EIII Diesel engine. Accumulation mode particles were also substantially reduced. Nucleation mode particle emissions from the CNG engine were also lower than Diesel engine levels.
11. Total particle number emissions from conventional heavy duty Diesel engines ranged from ~ 10^{14} to 10^{15} /kWh the lower figure for R49/ESC cycles and the higher for ETC cycles. Cycle emissions from the HD CNG and trap equipped Diesel were typically an order of magnitude lower.
12. Nucleation modes were generally absent from light duty Diesel vehicle emissions except at idle.
13. Total particle numbers measured from multi-point Injection (MPI) light duty gasoline vehicles were found to be several orders of magnitude lower than from conventional Diesels, but levels from the DPF equipped Diesel approached those from MPI technologies.
14. At all operating conditions, regulated particulate mass emissions and particle size distributions from light duty MPI LPG were similar to those from MPI gasoline vehicles.
15. At 120kph, all vehicle technologies produced similar particle numbers irrespective of particle size distribution. Gasoline/LPG and DPF equipped Diesel size distributions were dominated by nucleation mode particles, while conventional Diesels showed dominant accumulation modes.
16. Total particle number emissions from conventional light duty Diesel vehicles ranged from ~ 10^{13} to 10^{14} /km irrespective of operating conditions. The emissions from G-DI vehicles were typically an order of magnitude lower.
17. Total particle number emissions from light duty gasoline and trap equipped Diesel vehicles covered a much wider range than conventional Diesel vehicle emissions: 10^8 – 10^{10} /km from speeds up to 70 kph but increasing to $10^{13}/10^{14}$ /km at 120 kph. Those from the DPF equipped Diesel at 120kph were higher than from the gasoline/LPG vehicles at the same speed.
18. Matching Model 3934 SMPS systems produce very similar size distribution profiles when configured to measure the same size ranges under the same flow conditions. Comparisons of absolute magnitudes of these distributions proved dependent on accuracy of instrument set-up.

APPENDIX 2: GENERAL CONCLUSIONS (CONT'D)

19. When the same two SMPS instruments are configured to measure different size ranges; 7-320nm and 15-710nm, the locations of the accumulation modes are different.

20. Two SMPS systems, when identically configured, produced integrated particle numbers which agreed to ~20%.

21. Depending on the size distribution and particularly the presence of a nucleation mode, two SMPS systems measuring different particle size ranges will produce quite different integrated particle totals. Identical studies employing different size ranges may reach different conclusions based upon particle number emissions.

APPENDIX 3: OUTLOOK

The DETR / SMMT / CONCAWE Particulate Research Programme has characterised vehicle, engine and fuel technologies and investigated sampling and methodology issues. Neither the characterisation element nor the methodological aspect is complete and further research into these is suggested.

The future focus of legislation may be on particle number emissions rather than particulate matter or particle mass, since some health effect studies have suggested that the inhaled particle number or surface area may be important. This study shows that regulated particulate matter and particle number do not necessarily correlate. Therefore the focus of this outlook section will be upon particle number and particle number weighted size distributions only.

A3.1 FURTHER CHARACTERISATION

A3.1.1 Current Fleet

Further investigation into the emissions of vehicles and engines currently on the road, to establish whether improvements in technology have resulted in reductions in particle emissions. This may enable better foresight in to, for example, the consequences of further technology evolution in response to CO₂ reductions.

- ❑ There are substantial numbers of Euro I MPI and older pre-Euro I carburetted gasoline engines currently on the roads. The contributions of these to ambient particle and particulate levels may be substantial and significant, though the influence of these will diminish with time.
- ❑ Large numbers of IDI Diesels are present within the current vehicle fleet. Their particulate chemistry can be significantly different to that from direct-injected Diesels and determination of their particle production may reveal a different propensity for particle formation.
- ❑ As seen with the Euro II HDD engine during the current programme, the effect of engine

calibration on particle numbers can be significant. Therefore, it may be of value to test different types of HD Diesel engines representing the current fleet.

In order to generate a list of technologies which are important to evaluate, it should be necessary to first study the proportions of each technology within the current fleet and rank those according to expected contributions to the overall particle emissions. The actual selection for characterisation would be based on this list of important technologies.

A3.1.2 Advanced Technologies

Several types of advanced gasoline fuelled engines, light duty Diesel and heavy duty Diesel engines are currently proposed. Many of the proposed technologies will not reach full production. However, there may be some merit in screening these technologies for specific particle production characteristics.

A3.2 REAL WORLD AND OFF-CYCLE TESTING

This programme has demonstrated that the sequence of operating conditions can influence the particle emissions results obtained. However, the test work addressed only legislative cycle operation and was therefore restricted to the highly calibrated region of the operative map. There is a requirement to evaluate current technology vehicles and engines operating outside the regulated zone, perhaps on specially designed real-world cycles.

A3.3 PARTICULATE FILTERS/TRAPS

There are a range of different filter technologies available. Most systems however, are Cordierite or silicon carbide based wall-flow filters. These systems may employ different methods to regenerate, and not all are likely to become widely used.

The detailed evaluation of all these technologies would be impractical, therefore comparison of the

technologies currently prevalent with particular regard to the effects of ageing and durability should be considered.

With some technologies it is expected that hydrocarbons may be emitted after the filter, and some carbon may break through. This might have a significant effect on the particle emissions. However, these effects may not appear until later in a filter's lifetime.

A3.3.1 Other Aftertreatment Technologies

Other advanced aftertreatment devices such as electrochemical and plasma devices may influence particle production. Characterisation of these and comparison with DPF technologies could be undertaken.

A3.4 FUEL AND LUBRICANT EFFECTS

Within this programme, effects of individual fuel properties such as density, aromatics, fuel sulphur, cetane number plus lubricant parameters were not studied as de-coupled parameters. An EPEFE style fuels matrix could enable the influences of these parameters on particle formation to be established.

A3.4.1 Sulphur

The effects of fuel and lubricant sulphur could be studied to determine the influence of this parameter as a source of the condensation sites when nucleation modes form. Studies could be undertaken with current and future fuels and lubricants and with fuels and lubricants where sulphur level has been reduced as close to zero as possible.

A3.5 INSTRUMENTATION

Within these evaluations, existing instrumentation could be supplemented with new instruments such as the nano DMA (measuring down to ~3nm), total particle counters and particulate filters collected with and without denuders. Newly developed instrumentation could be compared against existing techniques. This will enable better determination of nanoparticle formation and allow elucidation of nanoparticle chemistry while providing a simple particle number concentration value.

A3.6 TEST PROCEDURES

The experience gained within this programme could be employed to determine a formal test procedure for measuring particle number emissions. Existing test facilities would be employed with current instrumentation.

The determination of test procedures would include

the consideration of the following:

- Instrumentation
- Application to standard emissions tests
- Dilution and environmental / tunnel conditioning factors
- Particle formation
- Tailpipe and exhaust system influences
- Size range considerations
- Units

There are different problems associated with the measurement of accumulation and nucleation mode particles and these may require different methods of varying complexity. A key challenge is to develop consistent methodologies which are representative of real world conditions.



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