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Particle Measurement Programme (PMP) Light-duty Inter-laboratory Correlation Exercise (ILCE_LD) Final Report

Jon Andersson, Barouch Giechaskiel, Rafael Muñoz-Bueno, Emma Sandbach, Panagiota Dilara

Institute for Environment and Sustainability

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Executive Summary

The Light Duty Inter-Laboratory Correlation Exercise has conducted testing at 9 test laboratories in the EU, Korea and Japan in order to demonstrate the practicality, robustness, repeatability and reproducibility of the particle emissions measurement techniques proposed by the Particle Measurement Programme (PMP). The exercise involved testing 16 light duty vehicles including 6 diesels equipped with wall-flow Diesel Particulate Filters (DPFs), 6 conventional diesel vehicles, 3 direct injection petrol engined vehicles and one conventional, multi-point injection petrol-engined vehicle. A DPF equipped Peugeot 407 was tested at all participating laboratories to allow the inter-laboratory reproducibility of measurements to be assessed. The DPF equipped vehicles tested included 2 light goods vehicle derivatives (a Mercedes Vito and a Mazda Bongo). Vehicles were tested over multiple repeats of the EU regulatory Type 1 emissions test. Measurements of solid particle number emissions, particulate mass and regulated gaseous emissions were taken over each test. In addition to particle number measurements made with a Golden System circulated between laboratories, particle number measurements were made with several alternative systems to compare the performance of different measurement systems.

The Golden System for particle number measurement (Matter Engineering rotating diluter, evaporation tube and ejector diluter plus a TSI Condensation Particle Counter) performed well. Daily validation checks at each lab did not highlight any problems in terms of system leakage, particle counter high and low responses and linearity. Comprehensive calibrations at the beginning and middle of the test programme confirmed the stable operation of the system. Minor damage was sustained to the first diluter unit in the Golden System but this was attributable to laboratories unfamiliarity with the equipment, its repair did not affect the performance of the measurement system or cause any shift in observed particle number measurements.

Mean particle number emissions were less than $2x10^{11}$ particles/km for DPF equipped diesels, including light goods vehicle derivatives, with repeatabilities of 27-78% (expressed as coefficients of variance). Repeatability was typically around 30% and the one major deviation from this (78%) was due to the DPF being in an unstabilised fill state resulting in emissions from the vehicle decreasing test after test as the DPF filled up and the DPF's filtration efficiency progressively increased. Subsequent to testing of this vehicle a DPF stabilisation protocol was adopted. One DPF equipped diesel did give higher mean results of around $6x10^{11}$ particles/km. This vehicle differed from the other DPF equipped vehicles in being fitted with a more porous cordierite DPF substrate than the more commonly used silicon carbide DPF substrates. The particle emissions trace from this vehicle showed solid particle emission levels following the drive cycle (as they do for a conventional diesel vehicle) unlike the trace for a more efficient DPF where solid particle emissions are practically eliminated except for during the cold start and final acceleration of the Type 1 test cycle.

Reproducibility of the measurement was assessed by testing a single DPF equipped 'Golden Vehicle' in all laboratories. This gave an all-labs mean of ~$8x10^{10}$ particles/km with a

reproducibility of 31% i.e. similar to the repeatability of the measurement on DPF equipped vehicles.

Conventional diesel vehicles gave particle number emissions of around $5x10^{13}$ particles/km i.e. more than two orders of magnitude higher than the DPF equipped vehicles. Direct injection petrol-engined vehicles mean particle number emissions were in the range $3x10^{12}$ to $1x10^{13}$ particles/km. The conventional, multi-point injection petrol-engined vehicle tested gave particle number emissions similar to the DPF equipped diesels.

A number of alternative measurement systems using the same operating principles as the Golden System were tested alongside it at the various laboratories. Full performance data for these systems demonstrating the extent to which they meet the PMP specification in terms of volatile particle removal and solid particle penetration efficiency was available for only one system. This system, which meets the PMP specification, gave good correlation with the Golden System results (R^2 of 0.93) with absolute numbers being around 15% lower than the Golden System results. Direct clones of the Golden System predictably gave even better correlation (R^2 over 0.98), again with absolute measurements being around 15% lower than those from the Golden System. All other measurement systems gave good correlation with Golden System measurements (R^2 between 0.8 and 0.9), although absolute particle number levels were around 40% lower than from the Golden System. These systems comprised components adapted for PMP use rather than specifically designed to meet PMP requirements and may well give substantially improved results if redesigned/optimised to meet the PMP system specification.

Particulate mass measurements to the PMP recommended procedure were made at each lab using different systems. No significant problems were experienced with this measurement approach. DPF equipped diesel vehicles were consistently below 1mg/km, with a mean typically around 0.57mg/km and repeatabilities of 26% or less (expressed as a coefficient of variance). Inter-laboratory reproducibility on the Golden Vehicle was also 35%, with a mean particulate mass emission of 0.34mg/km.

Conventional diesel vehicles gave mean particulate mass results in the range 11-40mg/km. Direct injection petrol-engined vehicles varied from 2-13.5mg/km mean particulate emissions, whilst the conventional multi-point injection petrol-engined vehicle gave mean emissions similar to the DPF equipped diesels.

The repeatability of the particulate mass measurement appears to be better than that of the particle number measurement when measuring emissions from DPF equipped vehicles, substantially better in the case of a particular vehicle. Both measurement techniques were capable of distinguishing between the conventional and DPF equipped diesel vehicles included in this exercise. In addition both were capable of distinguishing lean burn direct injection petrol engined vehicles from conventional petrol vehicles. However particulate mass proved incapable of distinguishing between high and low porosity substrates on DPF equipped diesels or identifying changes in DPF fill state. This shows that particulate mass is fundamentally insensitive as a measurement of post DPF particle emissions.

One of the clear conclusions of the testing was that DPF equipped diesel vehicles are not inherently stable particle emissions sources. Particle emissions were found to increase significantly (e.g. by around a factor of 4) immediately after a regeneration of the DPF and then decrease over time as mileage is accumulated. This suggests that the effective porosity of a DPF decreases as it accumulates a loading of soot. Although efforts were made to reduce the influence of this effect, the particle number repeatability data does include some variability due to this effect. The repeatability data therefore includes to some extent the inherent variation in DPF vehicle particle emission levels in addition to the variability in the measurement technique. The particulate mass measurement is insensitive to these variations in particle emissions and so its repeatability is not affected by differences in DPF fill state.

In addition, background particulate mass measurements from the dilution tunnel from 4 repeat tests at a certain lab gave a mean result equivalent to 0.441mg/km across the test cycle with a standard deviation of 0.096mg/km. Significantly, this is actually higher than the total particulate mass measurement for DPF vehicles at many labs, suggesting that the measurement cannot be easily distinguished from background contributions. Background measurements of particle number were equivalent to $2x10^8$ particles/km across the test cycle, with a standard deviation of $7x10^7$ particles/km. This is around 55 times lower than the lowest vehicle test result indicating that, unlike particulate mass, particle number measurement is indeed able to discriminate between vehicle emissions and background levels. For these reasons particle number measurement is considered superior to particulate mass for assessing the particle emissions performance of DPF equipped diesel vehicles.

Investigative experiments were conducted to study measurement of particle emissions during DPF regeneration. These showed an increase in volatile particle emissions of several orders of magnitude, however solid particle emissions as measured by the Golden System were increased by a factor of less than 2. This suggests that, in principle, there is no reason why regeneration particle number emissions should not be accounted for at type approval using the distance weighted average procedure currently applied for particulate mass. However, since investigative measurements were taken on one vehicle only, further testing is recommended before this is introduced into legislation.

Investigative work on the Golden System suggested that the first diluter stage alone was sufficient to remove 99% of volatile particles during normal testing. However, during DPF regeneration testing, a significant number of semi-volatile particles were observed to penetrate the first diluter. The evaporation tube proved to be 99% efficient at removing these particles therefore ensuring that the 99% volatile particle removal efficiency was achieved. It is therefore recommended that the evaporation tube and secondary diluter (to prevent particle losses by thermophoresis) are retained in the PMP recommended particle measurement system in order to permit future extension of measurements to regeneration conditions. Similar conclusions were reached regarding the specified inlet characteristic of the particle number counter (50% efficiency at 23nm particle diameter etc). Under normal operating conditions <23nm volatile particles are adequately removed by the first diluter, however under regenerations a significant number of volatile particles are seen penetrating the first diluter. There is a risk that some of these are merely shrunk by the evaporation tube and not

completely eliminated. Consequently it is considered prudent to retain the specified inlet characteristic.

During the test programme a dilution tunnel pre-conditioning procedure (running the Golden Vehicle for 20 minutes at 120kph steady state) was run to minimise re-entrainment of particles deposited during testing of higher emitting vehicles. Where a laboratory is testing a mix of high and low emitting vehicles it is recommended that this procedure is used prior to tests on low emission vehicles. However, where only low emission vehicles are being tested, this tunnel pre-conditioning may be dispensed with. Investigative experiments suggest that if this pre-conditioning has not been run on the test vehicle that there may be a reduction in cold start particle emissions.
Investigative testing on DPF stabilisation after regeneration suggested that at least 35% of the regeneration interval mileage should be accumulated after regeneration before a vehicle is tested in order to ensure repeatability for the purposes of type approval testing.

PARTICLE MEASUREMENT PROGRAMME (PMP) LIGHT-DUTY INTER-LABORATORY CORRELATION EXERCISE (ILCE_LD) FINAL REPORT

1 INTRODUCTION

The effect of exhaust emissions from road vehicles on public health has long been a concern. Legislation limiting the pollutant emissions of new vehicles is well established in many regions of the world. One emission of special concern is particulate matter. In vehicle exhaust this consists of tiny solid particles and liquid droplets ranging in size from a few nanometres to up to around one micrometre in diameter. Current legislative emissions standards regulate particle emissions in terms of the total mass of particulate matter emitted per kilometre travelled. This is effective at controlling emissions of larger size particles, but particles at the smaller end of the size range contribute little to the total mass of particulate matter emitted.

There is a growing consensus amongst health experts that particles in the ultrafine (<100nm diameter) size range may be those which are having the greatest adverse effect on human health. The main driver behind Particle Measurement Programme (PMP) is the impact of particles on human health. The PMP has no medical expertise and does not seek to pre-judge the advice that may emerge from medical experts with respect to the most crucial particle characteristics affecting human health. Nonetheless, current medical opinion suggests that reductions in particle emissions will lead to improved air quality and health and the PMP has therefore moved forward on the basis of the precautionary principle. This and the potential limitations of current regulatory procedures at forcing technology that would control these particle emissions led to the setting up of the PMP as a Working Group of the UN-ECE GRPE. PMP is essentially a collaborative programme of Government sponsored research projects. However the Working Group, chaired by the UK, exists to co-ordinate the research and ensures that the programme is open to contributions from a wider audience. National Governments, individual laboratories, exhaust aftertreatment and fuel industry representatives have all provided significant input to the programme. The automotive industry has also participated in the PMP Working Group though it does not support the principles of the inter-laboratory correlation exercise.

1.1 Objectives

The mandate given to the PMP Working Group by GRPE was to develop new particle measurement techniques to complement or replace the existing particulate mass measurement, with special consideration to measuring particle emissions at very low levels. These techniques should include a detailed specification of test procedures and equipment, be suitable for Light Duty Vehicle and Heavy Duty Engine type approval testing and be suitable for use in transient testing. Since, within the EU, type approval testing to demonstrate compliance with emissions standards involves a limited number of tests which could take place at one of many laboratories, good repeatability and reproducibility from laboratory-to-laboratory are key requirements for regulatory measurement techniques. PMP has therefore sought to demonstrate the repeatability and reproducibility of the proposed techniques. PMP was also tasked with accumulating data on the performance of a range of engine/vehicle technologies when tested according to the proposed procedures.

1.2 Size Range Considerations

It was desirable for the development of particle mass and number methods to consider the size range measured. For the particle number method, an integrated number within a defined size range and volatility was appropriate. For particle mass, the size range measured is less obvious, but has always been an aspect of the filter approach: the upper limit is effectively set by the use of a 'Chinese hat' probe - this was shown in the UK DOT/DOE/SMMT Particulates Measurement programme [1] to be a d50 of approximately 3µm. The lower size for filtration is determined by the diffusion characteristics of the filter medium under the sampling flow regime, and for the filter types used in automotive applications >99% capture occurs at ~20nm. More importantly, for mass collection the current filter medium generally employed, Pallflex T60A20, has a low initial capture efficiency of ~96.4% for 0.3µm particles [2], so another aim of the revised method was to select a filter with improved initial efficiency.

2 NATURE AND SCOPE OF THE ILCE_LD

2.1 History of the PMP

The governments of France, Germany, the Netherlands, Sweden and the United Kingdom agreed to a collaborative programme aimed at developing analytical systems by which ultrafine particles could be measured to facilitate control in a regulatory framework. The eventual outcome would be a system, or systems, that would replace or complement the existing method of particulate mass measurement. This work has been taken forward in the UN-ECE forum where the government of Switzerland joined the consortium. Japanese and Korean governments have also contributed to the recent validation work.
The resulting Particle Measurement Programme (PMP) working group, chaired by the United Kingdom's Department for Transport, developed a three-phased approach to complete the work.
In the first two phases of the programme, a wide range of measurement instruments and sampling systems were assessed over standard regulatory tests.
In the PMP Phase 1 study, measurement systems addressing several key particle properties including mass, number, active surface and chemistry were evaluated along with appropriate dilution methods, sample conditioning and consideration of cost and logistical aspects.
Phase 2 subjected the best performing systems from Phase 1 to more rigorous evaluations in order to confirm the results of Phase 1 and determine fundamental levels of repeatability within a single laboratory during a variety of steady state and transient tests on both engine-out and post-DPF exhausts. The testing from Phase 2 concluded that a revised filter mass measurement method and a particle number method both, based upon sampling from a standard dilution system, best met the original objective of the programme. The two recommended systems were:

- A filter method based broadly upon those currently used in Europe and the US and that proposed for the US for 2007 type approvals
- A particle number method using a Particle Counter, a selected size range and sample pre-conditioning to eliminate volatile particles

Draft revised versions of the light-duty vehicle (DR83 [3]) and heavy-duty engine (DR49 [4]) particulate regulatory sampling annexes have been prepared from the current regulatory documents: R83 [5] and R49 [6].
The new documents integrate the PMP particulate and particle approaches into the existing regulatory framework and also form the bases for two test protocol documents written as laboratory guides for testing within PMP Phase 3 the "Inter-Laboratory Correlation Exercises" (ILCE).

2.2 Brief Overview

The inter-laboratory correlation exercises of the PMP are designed to enable an evaluation of the repeatability and reproducibility of particle number and mass measurements made with the systems recommended following the PMP Phase 1 and Phase 2 studies.

The light-duty exercise also includes the assessment of the robustness of the draft test protocol (DR83) and the evaluation of several alternative measurement systems developed and constructed according to the measurement system requirements of the DR83.
At least 5 repeat measurements over transient cycles tested to type-approval standards were performed on each vehicle tested at each laboratory. To provide a reference, the laboratories of the European Commission's Joint Research Centre (JRC), located in Ispra, Italy performed the first, an intermediate set and the final test in the sequence of laboratories. Including JRC, 9 different laboratories participated in 11 measurement sets.
A reference 'Golden Vehicle' was employed as the 'transfer standard': a Peugeot 407 2.0 HDi diesel car equipped with an OEM Diesel Particulate Filter (DPF) and active regeneration system as well as a 'golden particle measurement system' (GPMS). These were circulated to all participating laboratories during the exercise. The 'Golden Engineer' funded by the UK Department for Transport (DfT) undertook the role of assisting in the proper implementation of the test protocols and together with the JRC which also acted as programme manager, supervised the execution of the programme.
The Inter-laboratory Correlation Exercise was performed according to the requirements of the Inter-laboratory Guide ([7] LD_ILG – Appendix 1). It included both filter based particulate mass measurements and real-time particle number measurements to be performed in parallel on light-duty vehicles under transient conditions on a chassis dynamometer. The driving cycle used was the New European Driving Cycle (NEDC). Regulated gaseous emissions were measured at the same time as particulate and particle emissions, using established regulatory measurement techniques.
A modified standard exhaust dilution system comprising a full flow primary tunnel with constant volume sampler (CVS) is used as the starting point for both mass and number sampling during the tests. The dilution air used for the primary dilution of the exhaust in the CVS is charcoal scrubbed and then passed through a secondary filter (HEPA type) to remove particles and particle precursors and ensure a very low background needed in order to measure the very low emissions of DPF equipped diesel vehicles. Preconditioning protocols are employed to ensure that test-to-test and vehicle-to vehicle carry-over effects are minimised.

2.3 Test Vehicles

In total 17 vehicles were tested in the ILCE_LD including wall-flow DPF, conventional Diesel vehicles, port-fuel and directly injected spark-ignition vehicles. The results of 16 vehicles are presented in this report: one conventional Diesel vehicle was determined to be of Euro 3 specification and its test results have been omitted.
DPF-equipped Diesel test vehicles spanned the major vehicle size-classes from a light-duty van down to an A-class vehicle.

2.3.1 Golden Vehicle

The Peugeot 407 HDi 2.0 litre Golden Vehicle (Au-DV1) was supplied to PMP by The Association For Emissions Control by Catalyst (AECC), and is shown in Figure 1 installed on the chassis dynamometer at JRC. It should be noted that this vehicle is not necessarily considered to be representative of best available technology but the Peugeot HDi FAP type represented the most mature DPF technology present on the market at the commencement of the PMP Phase 3 study and was fully Euro 4 compliant (Table 1).

Table 1: Golden Vehicle's Regulated Emissions - Compliant With Euro 4

Type Approval Emissions Data (g/km)		Euro 4 limits
CO	0.031	0.500
CO_2	155.0	-
HC + NOx	0.182	0.300
NOx	0.166	0.250
PM	0.001	0.025

The Peugeot 407 is a turbocharged common rail direct injection Diesel vehicle (Table 2) equipped with an FAP Aftertreatment system. The PSA FAP system employs an oxidation catalyst upstream of an uncoated Silicon Carbide wall-flow Diesel Particulate filter plus cerium based fuel borne catalyst (FBC) and uses post-injection and EGR shut-off to generate an exotherm when periodically regenerating the DPF.

Table 2: Technical information – Golden Vehicle

Golden Vehicle	Diesel with DPF (FBC)
VI Number	VF36DRHRH21028953
Vehicle Identifier	Au-DV1
Vehicle Model/Reg.	Peugeot 407 - AG04 NYM
No. Of Cylinders	4
Aspiration	Turbocharged
2 or 4 Stroke	4
Fuel Delivery	Common rail D.I.
Capacity (cc)	1997
Test Inertia (lbs)	3500
Kerb Weight (kg)	1590
Transmission	6 speed manual
Catalyst#1	Oxidation Catalyst
Catalyst#2	Si-C DPF

Figure 1: Golden Vehicle

2.3.2 Other Vehicles

The 15 vehicles tested in addition to the Golden Vehicle were predominantly of Euro 4 specification, though the two vehicles tested in Japan had local calibrations. A summary of all additional vehicles is given in Table 3.

Table 3: Additional Vehicles Tested In the ILCE_LD

Vehicle	Type	Lab	Code
Peugeot 407 HDi FAP 2000 cc	DPF Diesel [Oxicat, uncoated DPF, FBC]	All	Au-Vehicle
BMW 525d catalysed DPF equipped, 2500 cc	DPF Diesel [Oxicat, catalysed DPF]	RICARDO	DPF#1
Mazda Bongo catalysed DPF, 2000cc	DPF Diesel [Oxicat, catalysed DPF]	NTSEL	DPF#2
Toyota Avensis D-CAT 2000cc	DPF Diesel [Oxicat, deNOx, catalysed DPF]	SHELL	DPF#3
Mercedes Vito Van DPF 3000cc	DPF Diesel [Oxicat, catalysed DPF]	SHELL	DPF#4
Peugeot 206 HDi FAP	DPF Diesel [Oxicat, uncoated DPF, FBC]	UTAC	DPF#5
FIAT, Idea, MPI, EURO-4, TWC, 1400cc	Port-injected gasoline	JRC	MPI Vehicle
Mitsubishi, Carisma, GDI, TWC/deNOx 1800 cc	Direct-Injection Gasoline (lean)	RWTUV	GDI Vehicle#1
VW, GOLF FSI, TWC/deNOx 1600 cc	Direct-Injection Gasoline (lean)	JRC	GDI Vehicle#2
Toyota Crown G-DI, 3000cc	Direct-Injection Gasoline (lean)	NTSEL	GDI Vehicle#3
BMW 120d PMFC 2000cc	Conventional Diesel	SHELL	non-DPF#1
Audi A2, TDi, EURO-4, Oxicat, 1500 cc	Conventional Diesel	RICARDO	non-DPF#2
VW, GOLF TDi, non-DPF, Oxicat, 1900 cc	Conventional Diesel	RWTUEV	non-DPF#3
Honda Accord i-CTDi, EURO-4, Oxicat/deNOx, 2200 cc	Conventional Diesel	LAT	non-DPF#4
Kia Pride, non-DPF, 1500cc	Conventional Diesel	NIER	non-DPF#5
Vauxhall Astra, CDTi, 1700cc	Conventional Diesel	SHELL	non-DPF#6

2.4 Golden Particle Measurement System

The particle number measurement system employed within the ILCE_LD is known as the Golden Particle Measurement System (GPMS). Like the Golden Vehicle and Golden Engineer, the system is described as Golden only in that it represents an internal standard providing a link between testing at the various laboratories and provides continuity within the test programme.

The DR83 describes the proposed performance of the measurement system for regulatory measurements. At the outset of the ILCE_LD, and noted in the LD_ILG, it was anticipated that the performance of the GPMS might not meet the full requirements of the DR83, and that other measurement systems developed subsequent to the commencement of the ILCE_LD might equal or exceed the GPMS' performance. Nevertheless, the GPMS has proven to meet virtually all of the DR83 requirements and has tested successfully over a sustained period and range of vehicle technologies.

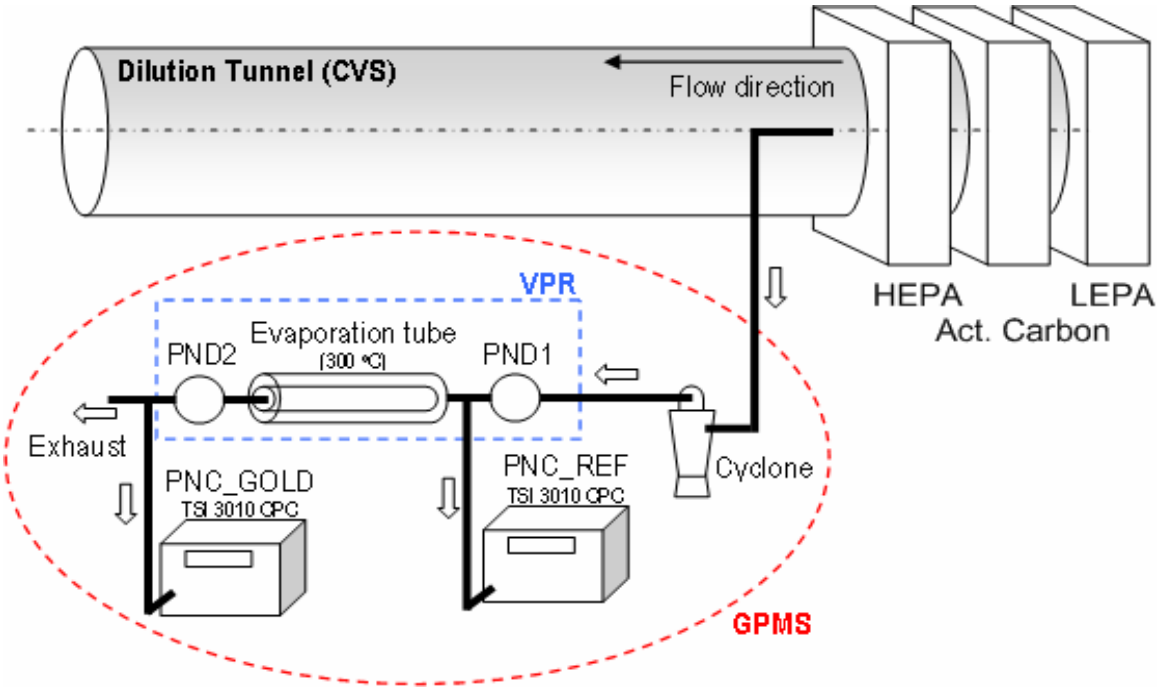
2.4.1 Number

The development philosophy of the particle number measurement system was to enable the accurate, repeatable and reproducible sampling of a well-defined particle from a very low background environment. It was also considered desirable to minimise required changes to the current type approval facilities, to employ an understandable metric and for the system to be simple to operate. The system was developed with an objective for the lowest possible particle losses – to avoid the possible requirement for correction factors.

2.4.2 Measurement System

A schematic of the sampling system design is shown in Figure 2, and a detailed technical description can be found in the DR83.

Figure 2: Schematic of the Golden Particle Measurement System



The sampling system comprises:

Efficient Dilution Air Filtration

- A standard full-flow CVS equipped with highly efficient dilution air filters for particles and hydrocarbons that reduces particle contributions from the dilution air to near zero

Size Pre-classification

- A sampling probe and cyclone pre-classifier which serve to protect the downstream system components from particulate contamination and set a nominal upper size limit for the particle size measured to 2.5µm

Hot Dilution

- A first particle number diluter (PND1) which heats the sample aerosol to 150°C while diluting in order to evaporate volatile particles and reduce the partial pressures of the gas phase species to prevent recondensation at the diluter exit

Evaporation and cold dilution

- A low particle loss externally heated evaporation tube (ET) in which the sample is heated to 300°C and held for ~0.2 seconds while semi-volatile particles are evaporated. Any particles that remain in the aerosol after this point are considered to be 'solid' particles. This definition of 'solid' particles is analogous to the definition of regulatory gaseous hydrocarbons: defined as those materials that are measured by flame ionisation detector (FID) downstream of a filter heated to 192°C.
- Immediately after exiting the ET the sample enters a second particle number diluter (PND_2), where it is cooled by dilution: the partial pressures of the gas phase

species are further reduced to prevent recondensation, the concentrations of particles present controlled such that they are below 10^4 cm^{-3} and thermophoretic losses are minimised.

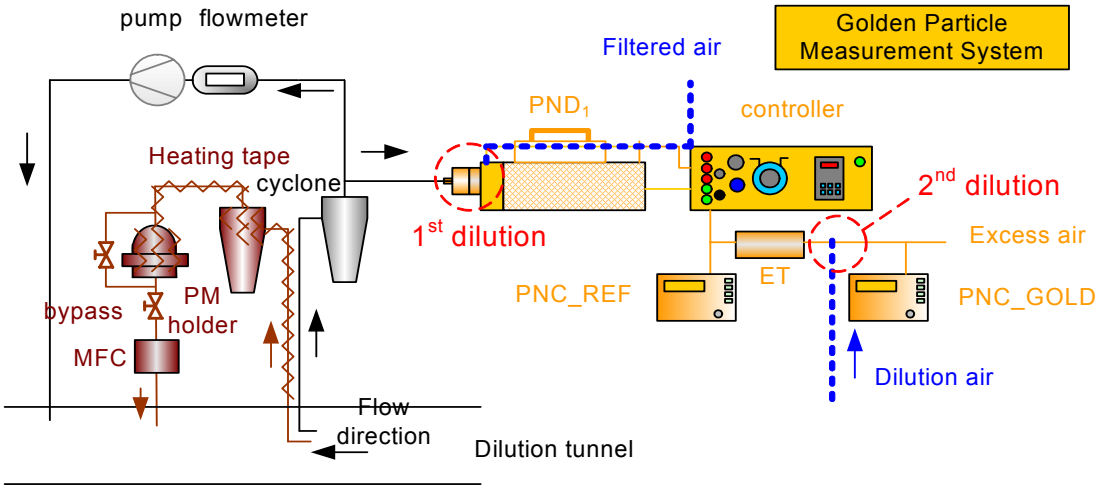
Particle number counting

- A particle number counter (PNC_GOLD) with a strictly controlled counting efficiency curve receives the sample as it exits PND_2. This sets a nominal lower limit of ~23nm to the size range measured. The strictly controlled counting efficiency curve is considered necessary to exclude the possible confounding of measurement data by low volatility hydrocarbons manifesting as a nucleation mode present below 20nm while including the primary carbon sphere size of ~20nm.

For the ILCE_LD a second, nominally identical particle counter (PNC_REF) has been positioned between PND_1 and the ET. Inspection of data from this instrument enables the function of the ET to be evaluated. Comparisons between PNC_GOLD and PNC_REF enable valid operation of both PNC units to be confirmed.

A further schematic of the GPMS and the most frequently tested mass measurement system is shown in Figure 3. It should be noted that while this figure shows the PM sampling probe to be positioned downstream of the number probe, these were actually situated in parallel.

Figure 3: GPMS and Mass Systems' Componentry



Transporting transfer and sampling components along with the measurement system avoided possible variances in the performance of the GPMS at test laboratories due to differences in installation. This left the sample probe and transfer distance between probe and PND_1 as the only real differences between labs' installations.

2.4.3 Definition of 'PMP Solid Particles'

The solid particles measured by the GPMS, and therefore by the draft regulatory procedure, are defined by the measurement procedure as:

- Sampled from the primary CVS by the measurement equipment

More specifically:

- Between ~23nm and 4µm in diameter
- Of sufficiently low volatility to survive evaporation after a residence time of 0.2s at 300°C.

2.5 PMP Mass Measurement System

In the PMP ILCE_LD the filter-based method was employed as the reference method, and for conventional Diesels a similar approach has been shown to give results consistent with the current European method [8].

2.5.1 Mass

The development philosophy of the particulate mass measurement system was to adapt the practically achievable elements of the mass method proposed for heavy-duty approvals in the US for 2007, along with selected amendments to improve data quality, to create an enhanced European light-duty procedure.

2.5.2 Measurement System

A schematic of the mass measurement system is shown in Figure 3.
For DPF equipped Diesel testing, several changes were made to the standard European method of particulate emissions measurement. These were:

- Application of highly efficient dilution air filters for particles and hydrocarbons that reduces mass contributions from the dilution air to near zero
- The application of a cyclone pre-classifier with a 50% cut-size at between 2.5µm and 10µm to limit the contribution of reentrained and wear materials to the filter mass
- External heating of the filter holder and transfer tubing to permit aerosol stabilisation of >0.2s at 47°C +/-5°C prior to sampling and to ensure close control of the filter face temperature to 47°C +/-5°C. External heating was achieved by either direct surface heating (most labs) or by situating the cyclone, transfer tubing and filter holder in an enclosed vessel. In the second case, the sample probe in the CVS was also heated.
- The use of a single 47mm filter rather than primary and back-up filters to eliminate weighing errors and the back-up filter as a source of volatile artefact
- The filter medium provides at least 99% filtration efficiency for 0.3µm particles at 35l/min (~50cm/s filter face velocity).
- The use of one filter for the entire NEDC rather than separate urban and extra-urban phases to eliminate multiple weighing errors and the back-up filters as a source of volatile artefact
- Controlled filter face velocity range (50cm/s to 80cm/s) to improve reproducibility

2.5.3 Definition of PMP Particulate Mass

The PM definition remains broadly unchanged from the current definition: all materials sampled using the prescribed method on to a filter at or below 52°C. This is now literally correct since the method does not employ a backup filter.

2.6 Alternative And Additional Particle Measurement Systems

2.6.1 Number: Alternative Systems

Within the ILCE_LD several laboratories tested alternative particle measurement systems (ALT_SYS). These were defined as systems that were designed and constructed to meet the requirements of the LD_ILG and/or DR83 (Appendix 4).

These alternative systems took one of two forms:

- Clone Systems: equipment that was comprised of nominally identical components to those present in the GPMS

Clone systems were tested at three laboratories.

- OEM systems: equipment that was provided by an alternative manufacturer to the provider of the GPMS.

Two OEM systems, provided by Dekati and Horiba (Figure 4), were tested at four different laboratories. Of these, the Horiba Solid Particle Counting System (SPCS) was specifically designed to meet the DR83 criteria, and was tested in two laboratories. The Dekati system was a modified version of the Fine Particle Sampler (FPS) used in the recent European PARTICULATES programme [9].

All alternative systems contained the following principle components:

- Pre-classifier (a downstream sub-sample from the cyclone used for the GPMS was permitted)
- First particle number diluter
- Evaporation tube
- Second particle number diluter
- Particle number counter with modified counting efficiency

Alternative systems were assessed for compliance with the DR83 and LD_ILG and for similarity with the GPMS in order to determine whether any differences were influential in emissions levels measured. This comparative assessment is presented in Appendix 4.

Figure 4: The ALT_SYS From Horiba

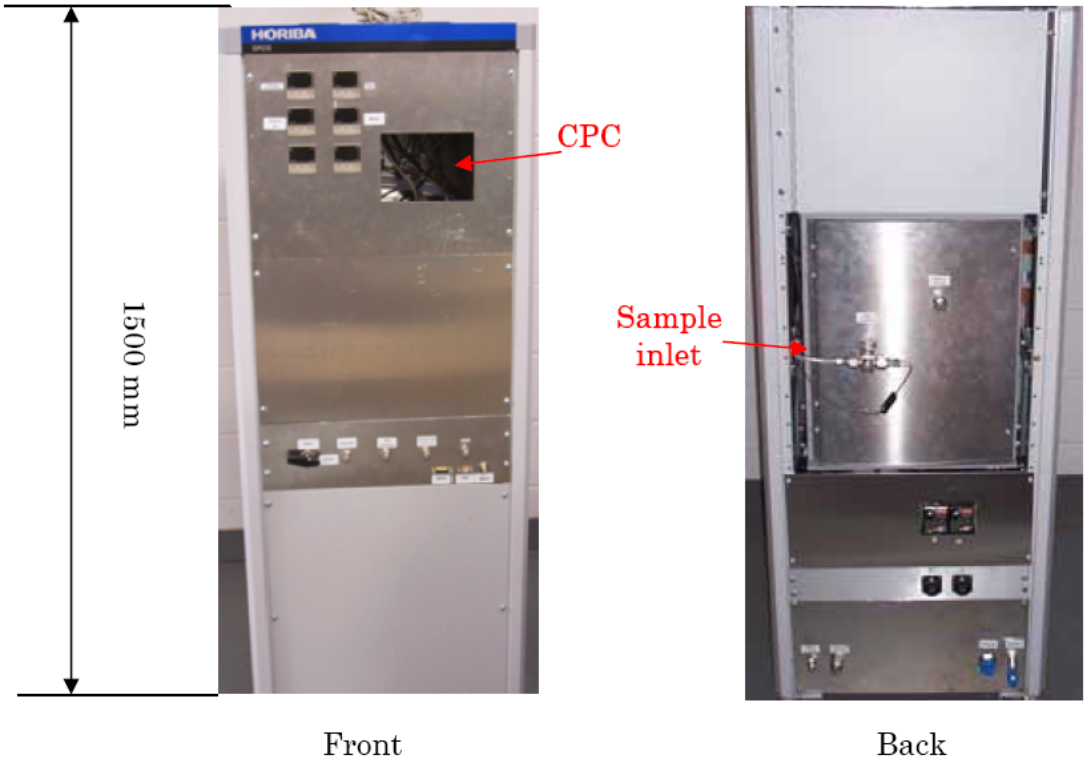
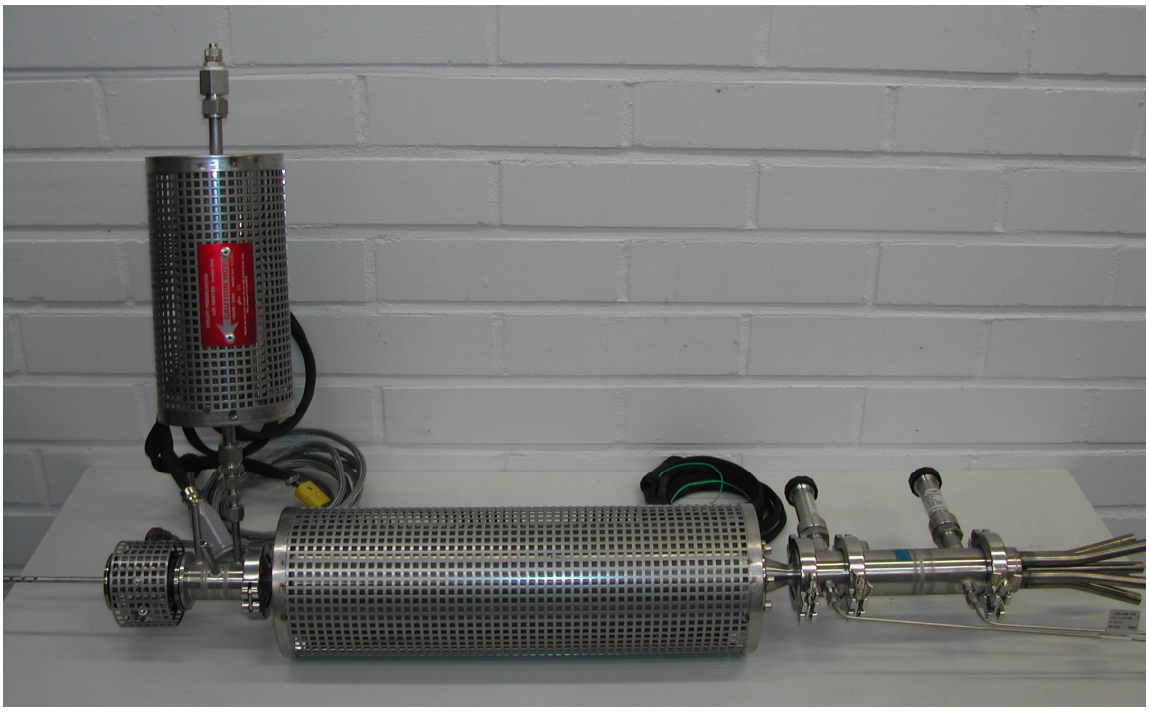


Figure 5: The ALT_SYS From Dekati



2.6.2 Number: Additional Systems

Within the ILCE_LD several laboratories tested additional particle measurement systems (ADD_SYS). These were defined as systems that were designed to measure particles in a similar manner to the requirements of DR83 and the LD_ILG – for example using hot dilution, or containing an evaporation tube – but not containing all the essential components of the GPMS or alternative systems.

Additional systems tested are summarised below:

(1) No evaporation tube

- Cyclone – hot diluter – cold diluter – modified CPC

(2) No secondary diluter

- Cyclone – hot diluter#1 (Dekati FPS) – thermodenuder - modified CPC
- Cyclone – hot diluter#2 (Dekati Ejector)– thermodenuder - modified CPC

(3) No cyclone, secondary diluter or evaporation tube, ELPI as particle counter

- Ejector – hot diluter - ELPI

Results from additional systems were compared with GPMS results and differences in emissions considered in the light of individual system specifications.

2.6.3 Mass

A laser induced incandescence (LII) instrument was employed at Lab#7 to measure the mass concentrations of elemental carbon emitted by several vehicles including the Golden Vehicle.

These data were used to indicate the nature of solid particles emitted by the Golden Vehicle during the NEDC cycle.

2.6.4 Other Equipment

An Engine Exhaust Particle Sizer (EEPS, [10]) was used during the third set of tests at lab#1. This instrument was employed to determine the number emissions and size distributions of particles in the range ~5nm to ~500nm during transient cycles.

These data were used to indicate the effectiveness of GPMS system components during NEDC cycle, steady state and DPF regenerations on the Golden Vehicle.

2.7 Test Programme

Nine test laboratories participated in the ILCE_LD. The test programme commenced in November 2004, with the final set of NEDC bookend tests completed during June 2006. To provide a reference, JRC (Ipsra, Italy) performed the first measurements, an intermediate set and the final tests in the sequence of laboratories.

2.7.1 Laboratories

The participants of the ILCE_LD and programme timings are summarised in Table 4.

Table 4: Participating Laboratories and Timescale

Order	Laboratory	Location	Lab Identifier	Start Date	End Date
1	JRC#1	Ispra, Italy	Lab#1r1	11-Nov-04	17-Nov-04
2	AVL_MTC	Sweden	Lab#2	30-Nov-04	03-Dec-04
3	Ricardo Shoreham Technical Centre	UK	Lab#3	30-Jan-05	07-Feb-05
4	RWTUEV	Essen, Germany	Lab#4	28-Feb-05	11-Mar-05
5	Laboratory of Applied Thermodynamics	Thessaloniki, Greece	Lab#5	06-Apr-05	19-Apr-05
6	JRC#2	Ispra, Italy	Lab#1r2	11-May-05	31-May-05
7	NTSEL	Japan	Lab#6	30-Aug-05	22-Sep-05
8	NIER	Korea	Lab#7	25-Oct-05	11-Nov-05
9	Shell Global Solutions	Chester, UK	Lab#8	22-Mar-06	12-Apr-06
10	UTAC	Paris, France	Lab#9	16-May-06	30-May-06
11	JRC#3	Ispra, Italy	Lab#1r2	13-Jun-06	26-Jun-06

2.7.2 Test Protocol for the Golden Vehicle

The test protocols of the ILCE_LD are described in the LD_ILG which is attached to this document as Appendix 1. These were directly derived from the R83 and the DR83, but were designed to be more prescriptive in key areas in order to maximise repeatability and reproducibility.

Where possible testing on the Golden Vehicle was conducted in an identical manner at all laboratories, this included:

Test Fuel and Lubricant

- Golden Vehicle operation was always on a reference fuel and lubricant from single batches shipped to all laboratories. A defined lubricant change procedure was employed to ensure identical oil ageing at each laboratory to remove this as a possible contributory factor in results variability

- The test fuel and lubricant were supplied by Concawe.

  The PMP Phase 3 Diesel fuel was a CEC reference fuel; RF 06-03 (Appendix 2) with the following properties:

  - 53 Cetane Number
  - 8ppm sulphur
  - 4.4% polycyclic aromatics
  - 835kg/m^3 density

  The test lubricant was a fully synthetic, 0W/40 PAO (polyalphaolefin) based oil with < 0.2% sulphur content.

2.7.3 Vehicle Preparation

- In the first test laboratory, the Golden Vehicle was flushed and filled with the test fuel, in subsequent laboratories the fuel tank was either topped up or flushed and filled.

- Coefficients for road load were provided to each laboratory and confirmed by coast-down tests each time the golden vehicle was put on the dyno.

2.7.4 Test Order

- Test order eliminated the possibility of contamination of test results by a previously tested vehicle. This was achieved by testing any low particulate emitting vehicles prior to less clean vehicles each day. If part of any given day's test matrix, the Golden Vehicle was always the first to be tested.

  For example, at Lab#3 the Golden Vehicle, a second DPF equipped Diesel and a non-DPF Diesel were tested each day in the order given.

2.7.5 Vehicle Preconditioning

- The Golden Vehicle was always the last vehicle to be conditioned in the test facility on the day prior to any tests on that vehicle
- All tests on the Golden Vehicle were conducted first thing in the morning to ensure that the last emissions experienced by the test facility were from that same vehicle.
- Golden Vehicle preconditioning concluded with the standard Diesel conditioning (3 x EUDC), but this was preceded by a 120kph steady state cruise of 20 minutes duration. This 120kph steady state raised the temperature of the vehicle's exhaust system, transfer tube to the CVS and CVS tunnel to a level above that experienced during a standard NEDC test. This purged the exhaust and transfer system of materials from previous vehicles that may have contaminated the test result, and ensured that any small contribution from the 3 x EUDC cycle conditioning would be replicated exactly from test-to-test reducing variability. After the 3 x EUDC conditioning was complete, the CVS tunnel was left running with the vehicle still attached to enable materials released from the exhaust and sampling system during cooling to be drawn away.
- The Golden Vehicle was always coupled to the CVS transfer line by a metal-to-metal join during testing to avoid the possibility of exhaust contamination by the high-temperature breakdown of elastomer coupling elements.

2.7.6 Special Case Preconditioning: DPF Regeneration

- During testing at certain laboratories, and in response to high DPF soot loading, active DPF regenerations were observed to occur either during the 120kph, 20 minutes preconditioning or during the EUDC part of an NEDC cycle. If this occurred, testing was stopped and 300km low speed (~80kph) mileage accumulation performed to partially fill the DPF. The vehicle was then preconditioned (120kph, 3 x EUDC) and testing recommenced.
- Some laboratories elected to passively regenerate and mileage-accumulate the Golden Vehicle to avoid the possibility of an active regeneration occurring during their test set. This was achieved by driving the Golden Vehicle on the chassis dynamometer for at least 15 minutes at 140kph followed by 300km low speed

(~80kph) mileage accumulation. The PMP preconditioning (120kph, 3 x EUDC) was then performed the night prior to the start of testing.

2.7.7 Testing on Additional Vehicles

Additional vehicles were tested with their 'as received' fuels and lubricants, though laboratories were free to change to the PMP reference fuel and lubricant if they wished
Pre-conditioning was restricted to the standard required by the current European light-duty regulations: 3 x EUDC for Diesel vehicles, and ECE + 2 x EUDC for gasoline PFI and DI vehicle types.
If regenerations were observed on additional DPF equipped Diesel vehicles, testing was continued without attempts to load the DPF.
Particulate mass sampling from conventional Diesels was performed on two filters: one each for the urban and extra-urban phases, though neither was equipped with a back-up. Two filters were used to avoid excessive pressure drops across the sample filters when capturing carbonaceous particulate matter.
Particulate mass sampling from gasoline PFI, gasoline DI and additional DPF equipped Diesel vehicles was undertaken according to the procedure described for the Golden Vehicle.

2.7.8 Additional Investigations

Subsequent to the final set of NEDC cycle measurements (Lab#1r3) a number of additional experiments were undertaken. These experiments were designed to further investigate sampling and measurement issues plus influences on emissions levels encountered during the entire ILCE_LD. Topics studied included:

- Effects of vehicle preconditioning – prior to NEDC
- Effects of the cyclone pre-classifier
- Different filter media
- Influence of the back-up filter
- DPF regenerations
- DPF fill rate and stabilisation
- Transient cycle particle size distributions

Results of these are presented in Sections 4.3 and 6.

3 STATISTICAL ANALYSES

In the ILCE_LD, the variability (spread) of data from each vehicle, laboratory and measurement system has been assessed based upon a simple statistical approach using the sample standard deviation, *s*.
An approach based upon this has been used to establish similarity and difference between sets of data from the same vehicle at different laboratories and from different vehicles at the same laboratory. Regression analysis was used to compare different measurement systems sampling from the same vehicle at the same laboratory.

3.1 Definitions

The experiments in a laboratory that measure the emissions of *n* NEDC cycles of a vehicle comprise the sample (where x_1, x_2,…, x_n are the results). The sample has a *mean* of ($\bar{x}$) and a *standard deviation* (*s*). Deviation (s^2) is the square of the standard deviation *s*. These can be calculated as follows:

$$\bar{x} = \frac{x_1 + x_2 + \ldots + x_n}{n} = \frac{\sum_{i=1}^{n} x_i}{n}$$

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

The standard deviation *s* is an index of how closely the individual data points cluster around the mean. This variability is due to random variations of the properties being measured and to the fluctuations of some factors (such as measurement equipment, the operators and environmental conditions). When repeat tests are performed in the same laboratory in a short period of time and with these factors as constant as possible then the variation is called '*within laboratory variability'*. The ratio of the standard deviation *s* to the average value $\bar{x}$ is called *Coefficient of Variance* (*CoV*) and is referred as the *repeatability* of the specific laboratory.

$$CoV = \frac{s}{\bar{x}}$$

The variability of the (mean) results from different laboratories is called '*inter-laboratories variability'*. The ratio of the standard deviation of the mean results of the labs (σ_τ) over the average value (x_τ) is called *Coefficient of Variance* (CoV_τ) and is referred as the *reproducibility*.

$$CoV_1 = \frac{s_\tau}{x_\tau}$$

It should be noted here that the reproducibility of the particle number concentration is based on the use of the same instrumentation (GPMS) in all laboratories. Once the measurement technique is established, laboratory-to-laboratory variability will also include variability due to different measurement systems at each laboratory. However, as the particle number measurement is a new method and laboratories did not have their own measurement systems, the reproducibility of the same system that travelled to all labs has been used here. The comparability of the various particle number systems used in the laboratories (i.e. ALT/ADD_SYS) has been considered separately.

The range of values in which we are confident (at a 95% level) that the true value of the mean falls is called the *confidence interval CI* and for unknown population standard deviation a 100(1-a) confidence interval on the mean value of the population μ is (n<30):

$$CI = \bar{x} \pm t_{(a/2,n-1)} \frac{s}{\sqrt{n}}$$

where $t_{(a/2,n-1)}$ is the t-statistic for *a/2* probability and *n-1* degrees of freedom. For a sample of n=5 and a=0.05 then t=2.7 and

$$CI = \bar{x} \pm 2.7 \frac{s}{\sqrt{5}} = \bar{x} \pm 2s$$

So for the specific case of n=5, plots with error bars of two standard deviation give the 95% confidence interval. This will be analyzed in the next paragraph.

3.2 Significance

Standard deviation is useful when the absolute magnitude of the within group variance is of interest. However, standard deviations are not appropriate variance estimates for assessing statistical significance between means because they do not reflect the sample size. In contrast to standard deviations, standard error bars do make use of the sample size. Specifically, the standard error is equal to standard deviation divided by the square root of the sample size. This particular error information is highly relevant to statistical means comparisons. However, standard errors do not convey information regarding the criterion associated with an *a* level (the probability that the null hypothesis will be rejected in error when it is true; or a decision known as a Type I error). In contrast to standard error bars, confidence intervals solve this problem. That is, confidence intervals do reflect a criterion associated with an *a* level. Specifically, the size of the confidence interval is simply the standard error multiplied by a criterion (e.g., *t* or *F*), which can be found in a statistical table using information about degrees of freedom and a given *a* level.

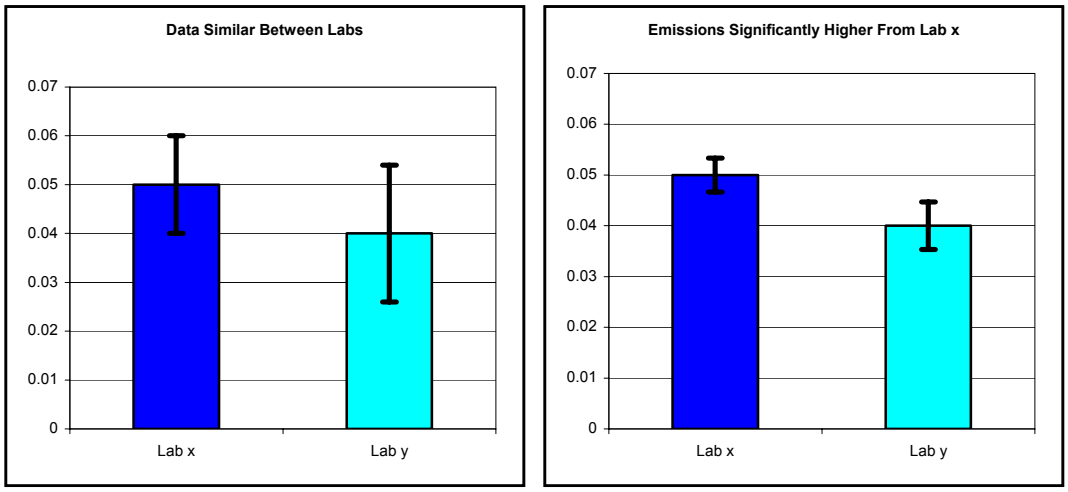
This means that in the case of two samples it is possible to find if the difference between the two groups is significant at the (e.g. 5%) level by plotting the means with the (e.g. 95%) *CI*. When the error bars do not overlap, then the means are statistically different (p<0.05). For the specific case of n=5, it was shown that the 95% CI are equal to the mean plus/minus two standard deviations.

However, when more than two means are compared, the analysis of variance uses a pooled (i.e., one estimate of mean variance across all condition means) variance estimate. Thus, to properly assess statistical differences graphically, the graphically displayed variance should also be a pooled variance estimate. However, the confidence

intervals that are typically used reflect the variances within each condition rather than the pooled variance that is used in the statistical tests. Nevertheless by using the 2*s* error-bars for a sample size of 5, comparisons of means are still possible (this is like conducting t-tests for 2 samples each time).

In summary, when data from the ILCE_LD are compared within this report, for example mean emissions data from two vehicles or two labs, error bars indicating ±2*s* are added to each chart datum. If these error bars overlap the emissions of the two vehicles are considered statistically similar, if the error bars do not overlap, the mean of one dataset may be considered to be significantly different to the other. Differences at ±2*s* are approximately equivalent to differences at a 95% confidence interval.
The example shown in Figure 6 illustrates how low standard deviations permit easier discrimination between datasets.

Figure 6: Similarity and Difference Between Laboratories



3.3 Discrimination Of Valid Tests, Outliers And Consequences

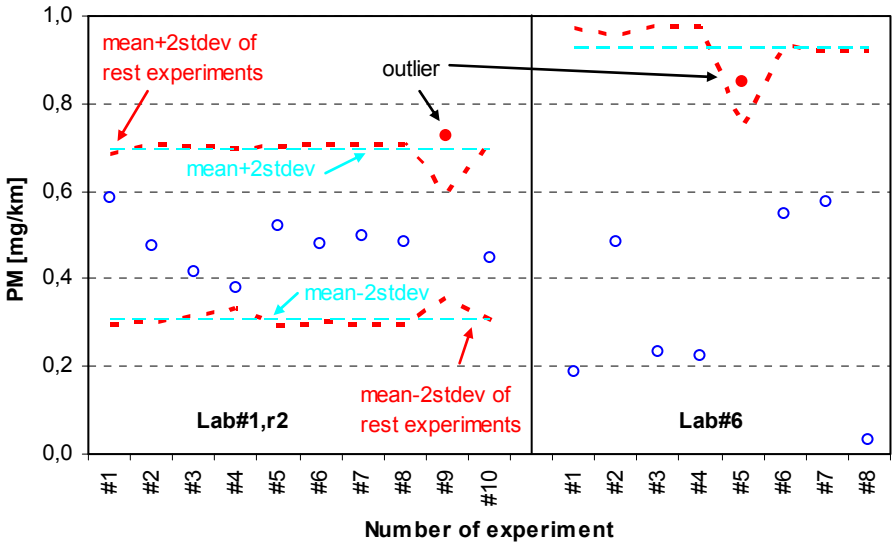
During the ILCE_LD, test results were discarded from the database based upon the test procedural criteria present in the R83 and specifically based upon the particulate mass repeatability since this was considered to be the 'reference method'. All data including excluded results are presented in Appendix 3.

3.3.1 Valid tests and outliers

Generally, it is suggested to distinguish the outliers in two categories:
True outliers (non valid tests): Are the measurements that should not be taken into account because the procedures were not followed or something went wrong during the measurement and the reason is known. For example if the preconditioning was not correct, the cycle was aborted, or the driver did not follow the speed pattern correctly the measurement should be considered non valid.
(Probable) outliers: These measurements are substantially different when compared to the majority of the measurements and the reason is not known. One method that is used to distinguish these outliers is the "2 standard deviation" method. In this method a measurement is considered an outlier when it lies outside 2 standard deviations of the

measurements (true outliers (non valid tests) shouldn't be taken into account). However when the sample size is small (e.g. less than 10) it is possible to consider an outlier a measurement which lies outside 2 standard deviations of the rest of the measurements ("modified 2 standard deviation method"). Figure 7 shows this method for two labs. Note that the modified 2 standard deviation method increases the outliers and biases the results. For example measurement #5 at Lab#6 wouldn't be considered an outlier with the normal 2 standard deviation method.

Figure 7: Identification of outliers with the 2s and modified 2*s* methods



During the ILCE_LD, test results were discarded from the database based upon the test procedural criteria present in the R83 and specifically based upon the particulate mass repeatability. The ILCE guide required that a minimum of 5 tests be performed on the Golden (and other vehicles). Additional tests were carried out if one or more of the initial tests appeared to be an outlier. Since filter based mass was considered to be the reference method in the ILCE_LD, a result was defined as an outlier if the specific particulate mass for that test lay outside ±2*s* of the mean of the remaining tests.
This approach has the effect of 'tuning' the dataset to produce the best possible quality particulate mass results, but it should be noted that since particulate mass and particle number methods are measuring different metrics and chemistries, outliers on a mass basis are infrequently outliers on a number basis. This basis of discrimination may be to the detriment of the number dataset. From a total of 103 measurements with the golden vehicle 30 were true outliers (non valid tests) and 8 were considered outliers based on the PM criterion. The number of PM outliers would be reduced to 2 if the normal 2*s* criterion was used (rather than the modified 2*s* criterion).

3.4 Comparison of methods

In parallel with the GPMS other systems were used to measure the particle number. Linear regression analysis was used in this report to compare these systems.
A predictive model is fitted to the data and then this model is used to predict values of the dependent variable (or outcome) from one independent variable (or predictor).

The idea of regression is to fit a line that best describes (minimizes the errors ε_i) the data measured and then estimate the gradient (slope) b_1 and intercept b_0 of this line:

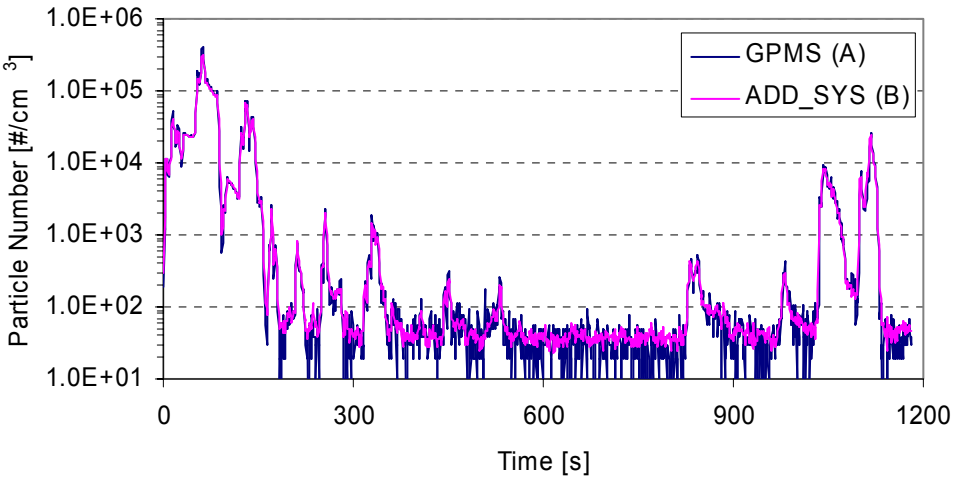
$$y_i = b_0 + b_1 x_i + \varepsilon_i$$

The slope is an indication of the % difference between the systems and the intercept is the offset. The coefficient of determination R^2 represents the percentage of the variation in the outcome that can be explained by the model. However what we interpret is a percentage of agreement between the two systems as there is no causal relationship between the two systems. However, R^2 should be used with caution because it can be large even if the variables do not relate in a linear fashion. In the specific tests the systems were compared second-by-second so there is a large set of data pairs that lead to high R^2.

An underlying assumption for the regression analysis is that the independent variable (in our case the GPMS measurements) is measured without error, so the fitted line minimizes the errors in the y direction (in our case ALT_SYS). However it is well known that all methods have an error. Better approaches for comparison of methods would be the Deming regression or the reduced major axis (RMA) method for example. A simple method[11] would be by plotting the difference between the two methods (x_i-y_i) with their mean (x_i+y_i)/2. The bias is equal to the mean of the differences between the two methods and if the differences are normally distributed then 95% of the differences will lie between the mean +/-2s of the differences.

In our case the differences of the methods increase as the average value changes so ideally we should (logarithmically) transform the data before applying the procedure described. This procedure was not followed as the absolute differences of the systems are not of importance at this point and it would require extensive graphical analysis. Throughout our analyses we assume that the GPMS measures without errors.

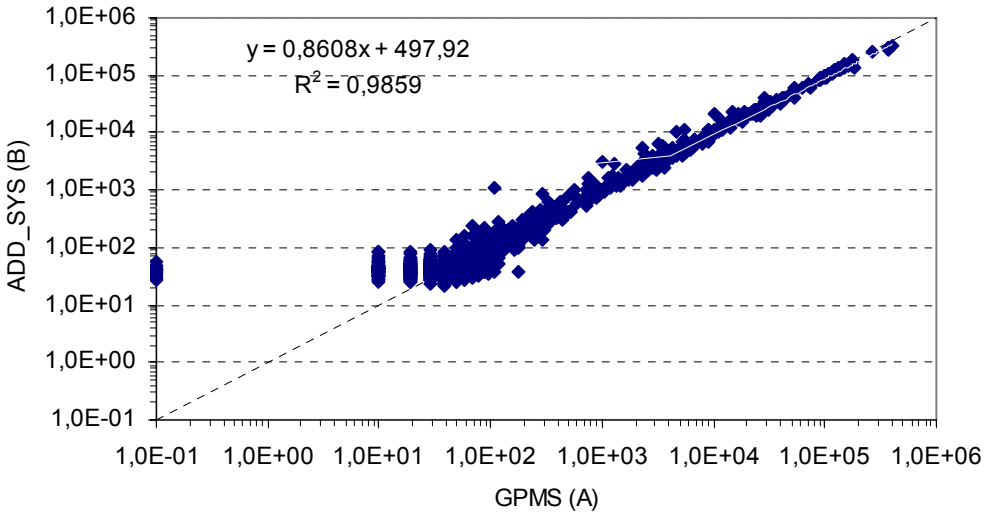
Figure 8: Real time measurements of the GPMS and ADD_SYS.



As an example for the above mentioned methods Figure 8 shows the comparison between the Golden system (method A) and the EJ+TD system in Lab#5 (method B). The scatterplot (and the regression analysis) of the two systems can be seen in Figure 9.

The results of the regression analysis are shown in the same figure (slope 0.86, intercept 498, coefficient of determination R^2 0.986).

Figure 9: Scatterplot of the two methods



4 EMISSIONS RESULTS: PARTICULATE MASS (PM)

Particulate mass measurements comprised the reference method in the PMP ILCE_LD, with the statistical approach selected in order to give best possible PM repeatability data.

4.1 Valid Test Results From The Test Programme

Mean NEDC cycle PM emissions from the Golden Vehicle are presented in the following sections. All data, excluding mass based and R83 criteria outliers, were used to generate the data shown. Data that are excluded were identified using conventional emissions regulation criteria [12] and the mass criterion described in Section 3.3.1. Comparative data are shown in histogram form with 2*s* error bars. Repeatability data are shown as *CoV*s. For the Golden Vehicle only, Reproducibility is shown as the CoV_{τ} of the lab-to-lab mean.

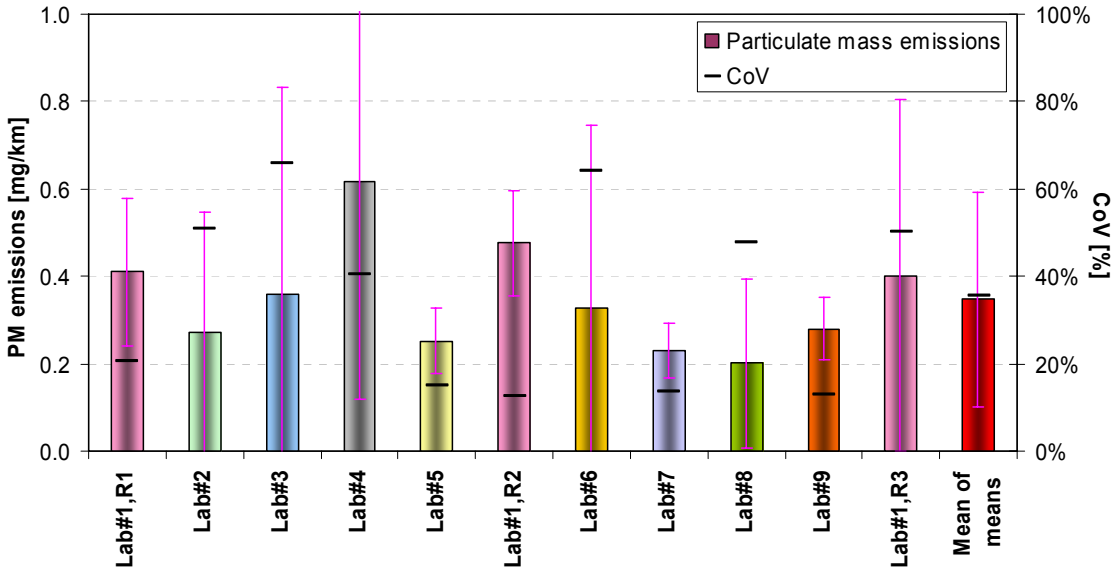
4.1.1 Intra-Lab And Inter-Lab Variability: Golden Vehicle

Figure 10 shows that PM repeatability varied considerably from laboratory-to-laboratory with *CoV*s ranging from 10% to ~65%. Mean emissions levels also varied considerably: from ~0.2mg/km to ~0.6 mg/km, though there was no obvious relationship between higher mass emissions and improved repeatability. Typical filter masses were ~20µg, though results ranged from <5µg to 60µg.

The high *CoV* levels may have been influenced by the occurrence of regenerations during testing at some of the labs. For example, regenerations were observed during testing at Lab#3, Lab#4, Lab#8 and Lab#1,R3 and these labs showed *CoV*s of greater than 40%. However, high *CoV*s were also observed at some of the remaining labs (e.g. Lab#2, Lab#6 >50%).

The reproducibility level of the mass analysis across all labs was ~35%: equivalent to ~0.11mg/km at a mean emission rate of 0.34mg/km.

Figure 10: Repeatability And Reproducibility Levels For NEDC Particulate Mass Measurements From The Golden Vehicle



4.1.2 DPF and MPI Vehicles

While emissions levels were consistent at below 1mg/km (Figure 13) (mean 0.57mg/km), repeatability results from the other DPF-equipped Diesel vehicles tested in the ILCE_LD were either similar to, or better than, the Golden Vehicle's reproducibility level. As Figure 11 shows, all vehicles showed *CoV*s of 26% or lower, and two vehicles showed *CoV*s below 10%. At <1mg and ~40% respectively, PM emissions and repeatability from the MPI vehicle were consistent with the levels from the DPF-equipped Diesels.

5 NEDC tests were performed on DPF#4 following a regeneration that occurred during the preconditioning cycles. These showed a *CoV* of ~25% after the final test (a zero result) was excluded as a mass outlier. Figure 12 indicates that there may have been an apparent drift down in PM results following the regeneration, but the reduction in emissions between the first and last test was smaller than the difference between the 2nd and 3rd tests and this effect is not believed to be significant.

4.1.3 All Vehicles

Emissions levels from the conventional Euro 4 Diesels ranged from ~11mg/km to ~40mg/km (Figure 13). Though emissions from one vehicle was higher than the Euro 4 limit, production tolerances and deterioration mean that this result is consistent with in-service compliance data and the vehicle is still representative of type. Repeatability ranged from ~2% to 11%, with the best repeatability observed from one of the lowest emitting vehicles.
Emissions from the G-DI vehicles showed significant differences: ~2mg/km, 8mg/km and 13.5mg/km though the latter was a vehicle calibrated for Japanese driving. All three vehicles were lean burn types.

Figure 11: Repeatability Levels All DPF vehicles

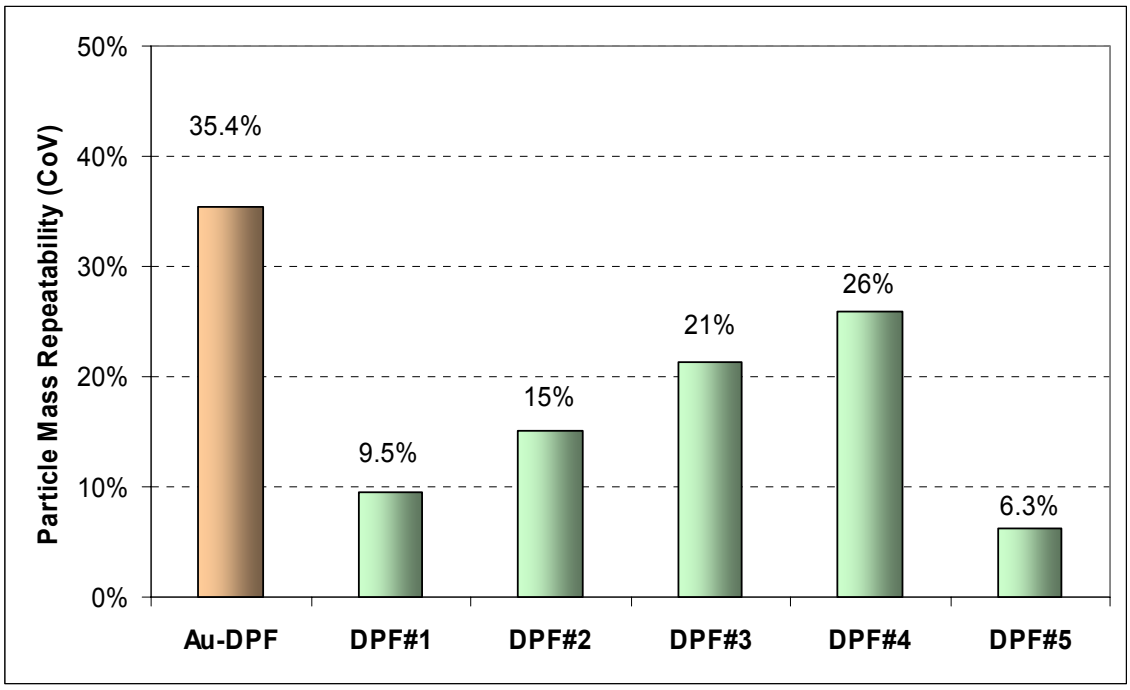


Figure 12: 5 PM Measurements on DPF#4

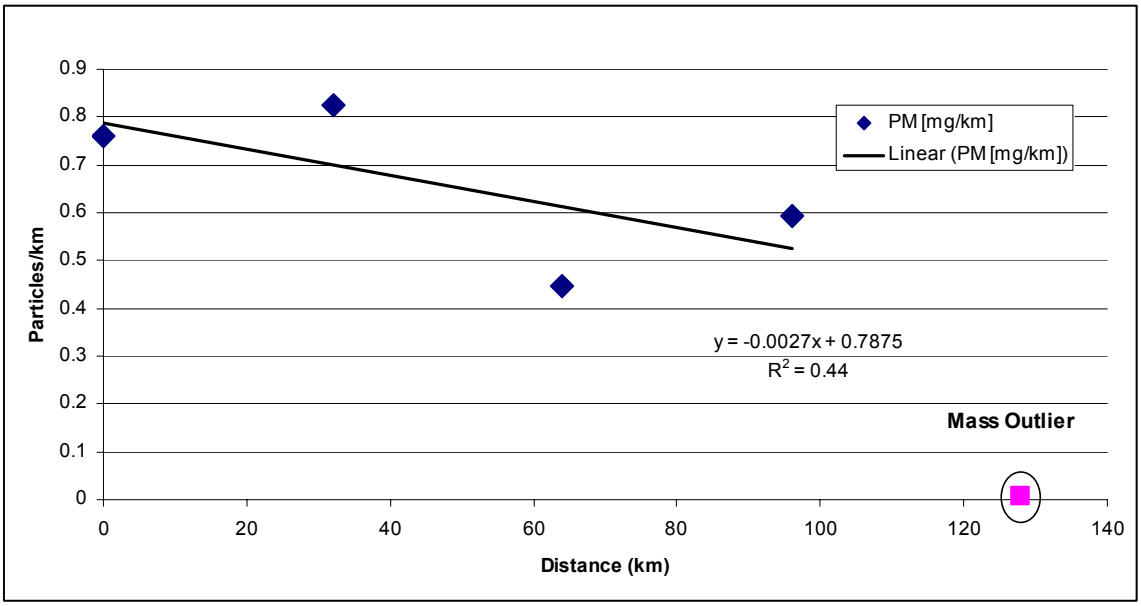
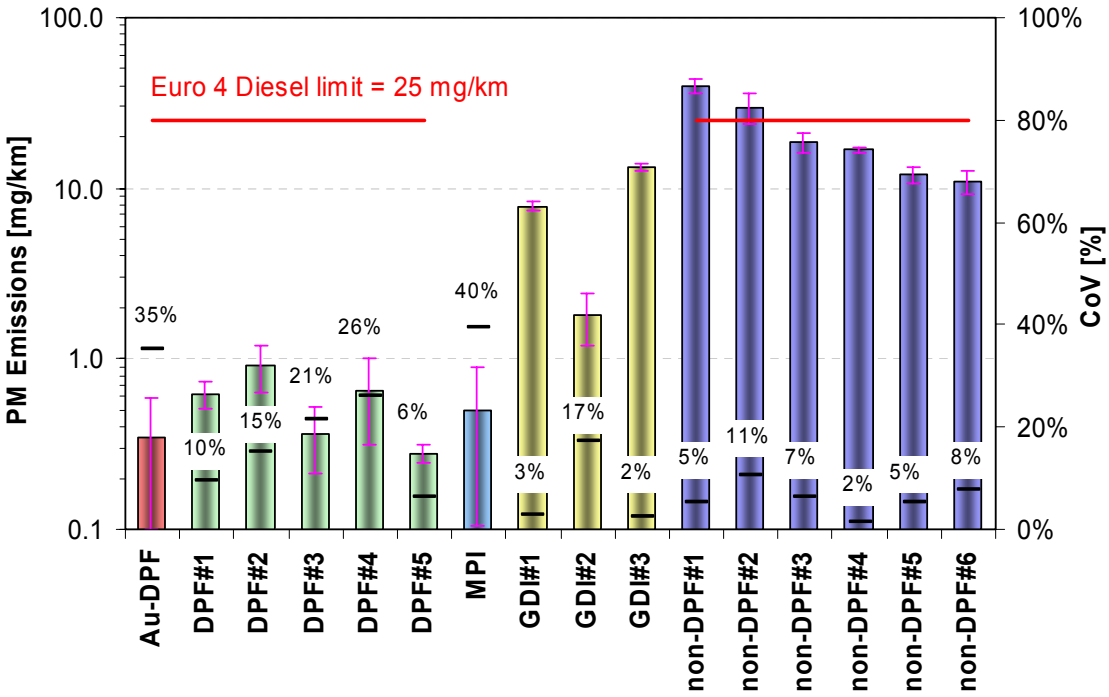


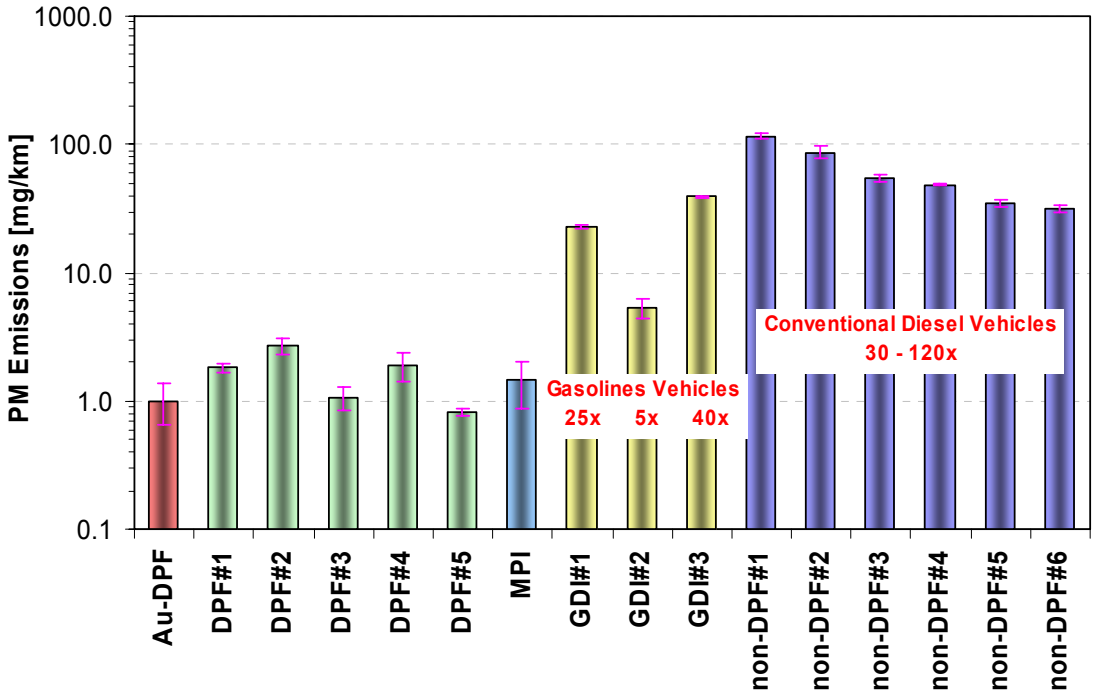
Figure 13: PM Emissions levels and Repeatability – All Vehicles



The highest emitting Euro 4 Diesel vehicle produces ~120x the PM emissions levels of the Golden Vehicle, and the lowest emitting ~30x (Figure 14).

Using the PMP mass method and 2*s* error bars, it is possible to discriminate between the 8mg/km G-DI vehicle (but not the 13.5mg/km) and the 11mg/km Diesel Vehicles.

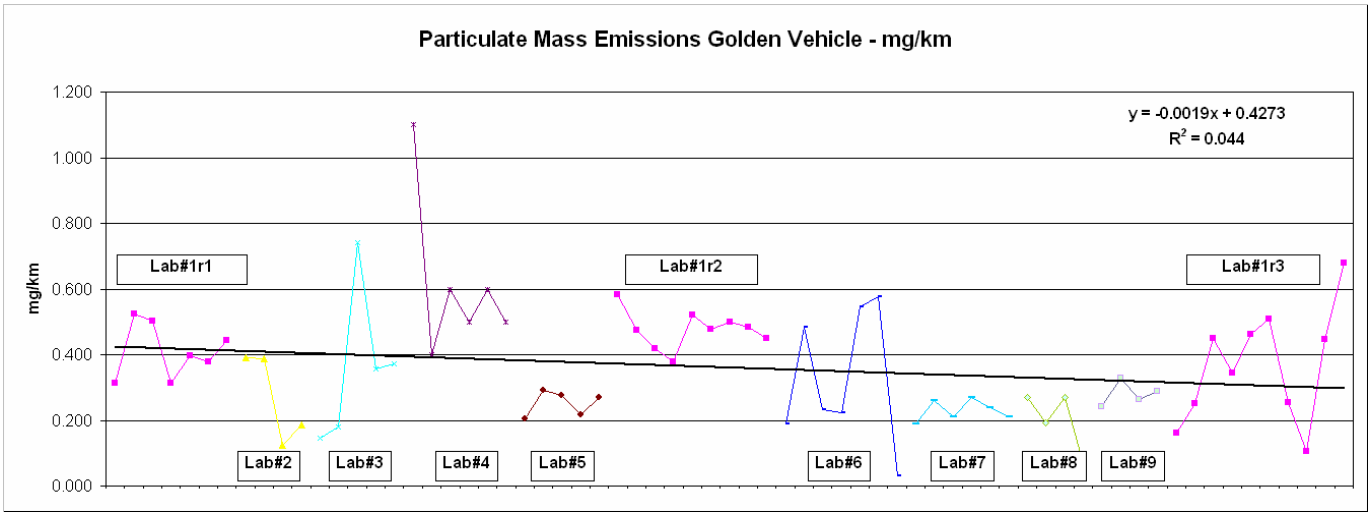
Figure 14: PM Emissions Normalised to Golden Vehicle Levels



4.2 Long-Term Golden Vehicle Behaviour

Particulate mass emissions from tests on the Golden Vehicle recorded throughout the test programme are shown in Figure 15. There was no obvious trend in emissions levels across the test programme, though lab-to-lab differences are clear.

Figure 15: Long-term Trend in PM Emissions – Golden Vehicle



4.3 Measurement System Investigations

4.3.1 Relationship Between PMP And Current Regulatory Measurements

Since it is more prescriptive but does not radically alter the methodology, the PMP mass measurement method is generally compliant with the current regulatory method.

The main sampling differences between the methods are:

- PMP eliminates the use of back-up filters
- For DPF-equipped Diesel and gasoline-fueled vehicles PMP uses a single filter for the combined urban and extra-urban phases of the NEDC, rather than separate filters
- PMP uses a sharp cut cyclone rather than a shrouded probe
- PMP mandates the use of TX40 glass-fibre/Teflon filters (or similar)
- PMP controls filter sampling and filter face temperature to 47°C +/- 5°C rather than merely setting an upper limit (52°C).

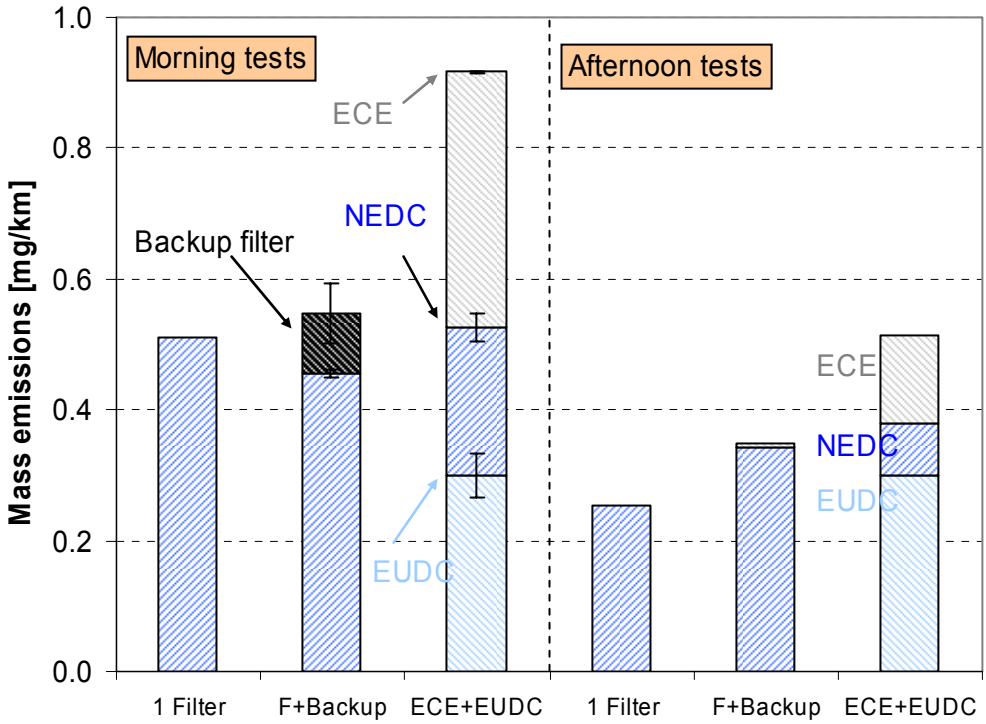
A limited number of experiments were undertaken after the conclusion of the validation testing to investigate the influences of these factors.

4.3.2 Single vs Multiple and Backup Filter Effects

Figure 16 shows the mass emissions levels from the Golden Vehicle recorded using a single filter for the entire NEDC (1 Filter), a single filter with a back-up (F +Backup) and using two filters without back-ups (ECE+EUDC). Error bars show 1-standard deviation. Experiments were undertaken twice in the same day.

A comparison between the 1 Filter and F + Backup results shows that the backup filter collects up to ~25% of the primary filter mass level (consistent with HD work, [8]) and that the back-up filter mass is more variable than the primary filter mass.
Removal of the back-up filter appears to reduce the overall PM by up to 25% per filter.
The most substantial effect though, is the increase in apparent mass emissions between the 1 filter result and the ECE+EUDC result. This increase, up to ~50% in these experiments, is probably due to the doubling of any volatile collection artefact related to the filter medium used.
These results are specific to Diesel vehicles equipped with highly efficient wallflow DPFs and may not represent effects from higher porosity substrates which may leak carbon. However from the most efficient DPF types, combining the effects of eliminating backup filters and moving from 2 filters to a single filter per NEDC cycle suggests that measured PM levels will be reduced by 30% to 50% relative to the current filter method. This should be taken into account when the revised measurement technique is adopted in legislation and a new regulatory limit is determined.

Figure 16: NEDC Cycle Mass Emissions Results – Different Filter Configurations



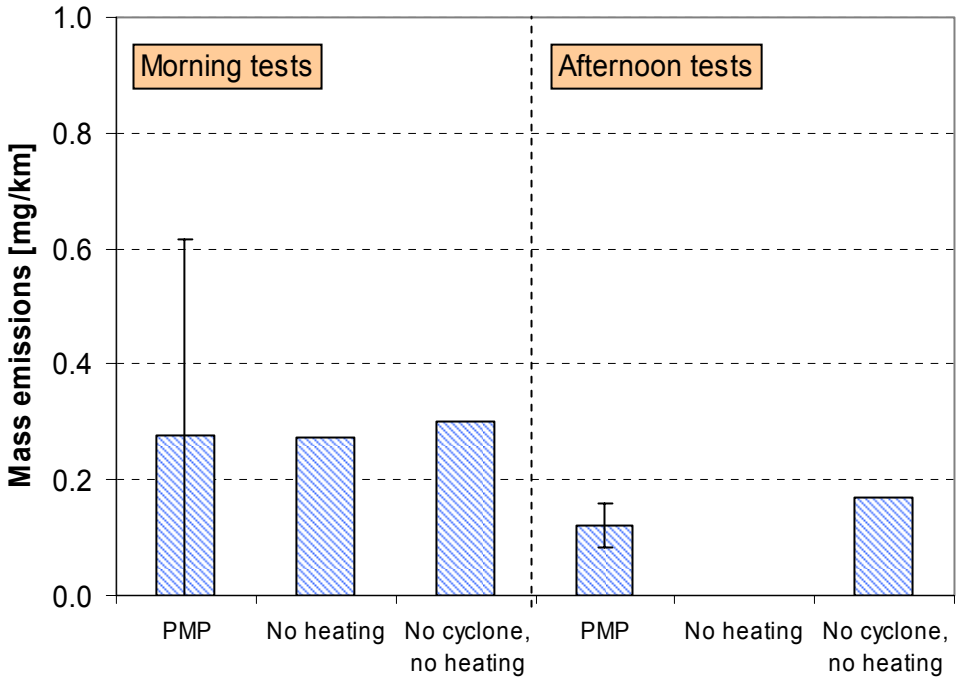
4.3.3 Cyclone and Filter Heating Effects

Limited testing has been conducted using the PMP mass method with and without the cyclone and sampling system heater employed.

As Figure 17 shows, it appears that there is either no effect of the cyclone and heating (morning data) or the heating and cyclone effect a small reduction in particulate mass emissions (afternoon data). Either way, these effects are small compared with the single Vs 2-filter effect described in Section 4.3.2.

It should be noted that the cyclone is in place to avoid contamination of the filter sample with large particulate materials re-entrained from the exhaust or dilution tunnel walls. The release of these materials will be sporadic and the beneficial effect of the cyclone not clear in one-off tests. Similarly, the sampling system heating is designed to permit stabilisation of volatile components of exhaust aerosol prior to and during sampling. The chemistry of the exhaust aerosol may be critical to the requirement for the heating approach and dependent on vehicle: in particular measurements from G-DI vehicles may benefit from this approach.

Figure 17: Effects of Cyclone and System Heating on PMP Mass Emissions



4.3.4 Filter Media Effects

Laboratory#1 (two sets of experiments) and Laboratory#6 performed comparative measurements using TX40 and Teflo filters (Figure 18) on the Golden Vehicle. Neither laboratory was able to perform both measurement sets simultaneously, so comparisons shown are from the average of several tests with each method.

With the exception of the filter medium, all other sampling parameters were constant and Teflo filters were treated with an antistatic neutraliser prior to weighing in order to dispel any static charge. This is particularly important following testing.

No significant differences were determined between methods, though when the measurements error bars are considered a background level similar to the filter loading was found at Lab#1. This background level is thought to contribute to the masses found on both Teflo and TX40 filters and is almost certainly comprised of volatiles. This can be seen in Figure 19, which shows that while the mass background was equivalent to the mass collected from the emissions cycle, the solid particle number background (where volatiles are eliminated by the VPR) is between 100 and 1000 times lower than the measured particle number emissions.

Background levels at Lab#5 were ~50% of those observed at Lab#1.

These tests were only conducted on a single vehicle with its own unique exhaust chemistry. It is not clear from these limited experiments if there are any benefits associated with using Teflo filters rather than TX40 filters.

It is clear that the particle number method permits much wider discrimination between background levels and sample levels than the mass method.

Figure 18: Comparison of Mass Emissions With 2 Different Filter Media

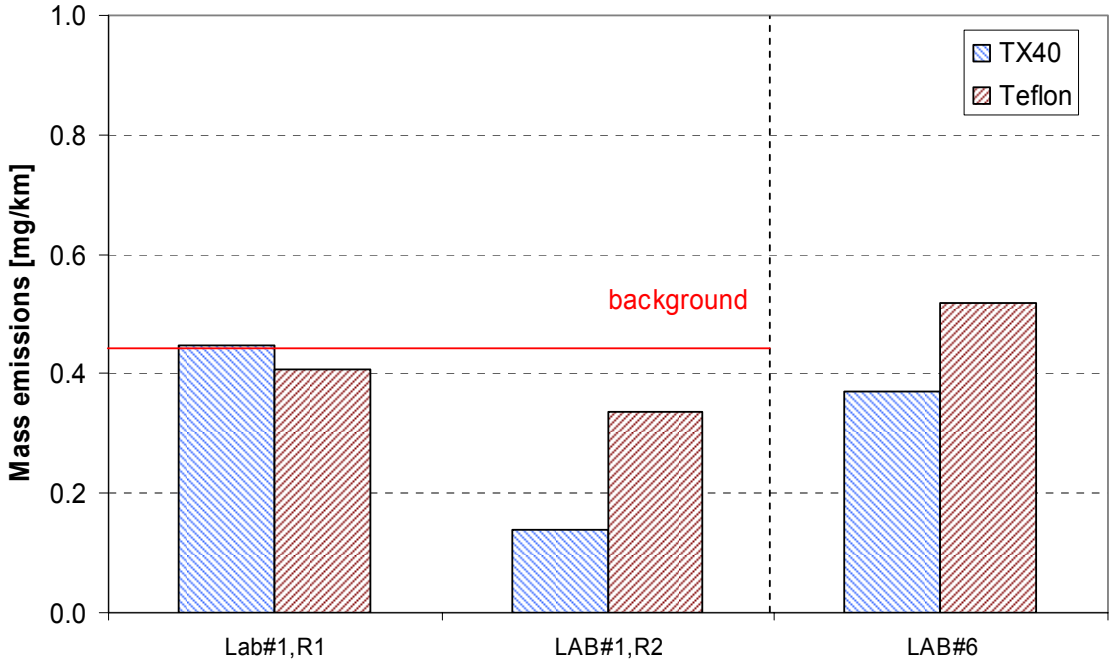
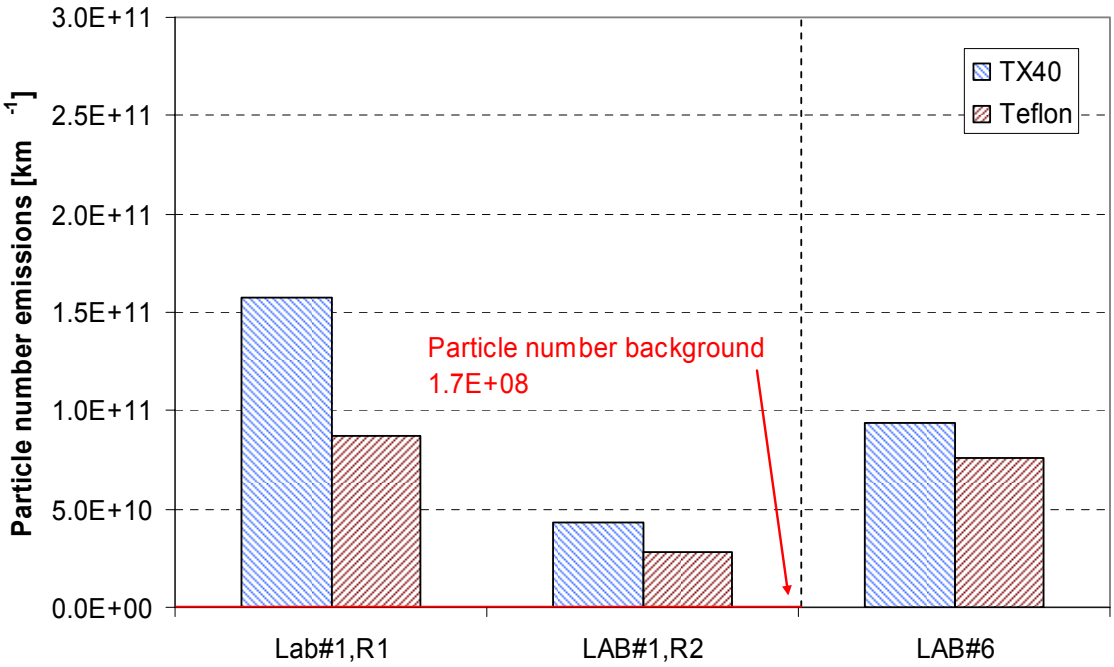


Figure 19: Particle Number Emissions and Background During Filter Media Tests



4.3.5 Weighing Parameters

At Lab#3, a number of experiments were conducted to investigate the effects of weighing parameters on recorded masses and to establish the repeatability of the balances employed.

4.3.5.1 Reference Weights

Four reference weights: 500mg, 200mg, 100mg and 50mg were weighed on a daily basis. The lightest of these, 50mg, was close to the typical 47mm filter mass.

As Table 5 shows, the 1µg balance employed gave a consistent response throughout the two-weeks test programme, with variability (as standard deviation) equivalent to the readability of the balance. From these data it was confirmed that balance effects could be eliminated from any responses to ambient conditions observed in reference filter analyses.

Table 5: Results of Reference Weight Analyses

	MT5 1µg balance					Temp	Humidity	
Date	50 mg	100 mg	200 mg	500 mg		Set-point	Set-point	
						Δ°C	Δ%	
31-Jan-05	50.002	100.002	199.999	500.002		0.5	-2.0	
01-Feb-05	50.003	100.003	199.999	500.003		0.5	0.0	
02-Feb-05	50.002	100.003	199.999	500.002		0.0	-2.0	
03-Feb-05	50.002	100.003	200.000	500.003		0.5	-2.0	
04-Feb-05	50.002	100.003	200.000	500.003		0.0	-2.0	
07-Feb-05	50.001	100.003	200.000	500.002		1.0	-2.0	
08-Feb-05	50.002	100.003	200.000	500.003		0.7	-2.0	
Average	50.002	100.003	200.000	500.003		0.5	-1.7	
Max	50.003	100.003	200.000	500.003		0.0	-2.0	
Min	50.001	100.002	199.999	500.002		1.0	0.0	
STDEV	0.001	0.000	0.001	0.001		0.4	0.8	

4.3.5.2 Reference Filter Weighings

The temperature and pressure conditions in the weighing room over the duration of the PMP Phase 3 test work were very stable: temperature was controlled to within 1.6°C of the set-point and pressure remained almost constant at 103.2 kPa ±0.6kPa.

Temperature Control

Within the narrow band of temperature observed, there were no obvious effects on reference filter weight.

Humidity Control

Humidity was less well controlled in the weighing room, sometimes ranging considerably on an hourly basis around a mean of 43% RH. The longer-term humidity was more stable, reflecting the cyclic nature of the humidity control device in the weighing room.
At certain times the relative humidity figures drifted outside the currently prescribed European limits (45% +/- 8%). It should be noted that all temperature and humidity readings were instantaneous sightings taken simultaneously with the reference filter weighings. When humidity figures were outside the prescribed limits (highlighted in red in Table 6), the sample filters were left in the weighing room and then reweighed (along

with the reference filters) within the 80 hour permitted period. In this way, all sample filters were weighed with permissible humidity levels.

Table 6: Environmental Data – Weighing Room

Date	Time (start)	Baro. (kPa)	Rel. Humidity % rh	Temperature Δ°
January 31, 2005	11:25:20	103.41	37.3	0.20
January 31, 2005	13:39:06	103.28	39.2	0.20
January 31, 2005	17:06:33	103.17	42.8	0.60
February 1, 2005	10:10:13	103.44	61.3	1.10
February 2, 2005	09:04:47	103.76	36.4	1.00
February 3, 2005	10:19:18	103.76	49.8	0.80
February 3, 2005	11:17:51	103.76	39.1	0.40
February 3, 2005	11:49:15	103.76	41.7	0.70
February 4, 2005	09:56:54	103.29	41.2	1.20
February 4, 2005	14:26:49	103.29	49.5	1.60
February 7, 2005	10:17:03	102.48	35.8	0.30
February 7, 2005	17:40:07	102.48	37.4	0.50
February 8, 2005	10:58:45	102.60	47.1	0.40
February 8, 2005	11:01:00	102.60	47.1	0.40
February 10, 2005	18:24:55	102.46	40.0	0.30

The variation in weighing room humidity at almost constant temperature allowed the instantaneous effects of humidity on reference filter weights to be determined. Data shown are drawn from two reference filters weighed within a few seconds of each other. Figure 20 illustrates that for reference filter#2, a variation in relative humidity of 16%: from 37% to 53%, leads to a mass gain of ~7µg on the filter.

Figure 20: Reference Filter Weight#2 - Variation with Humidity

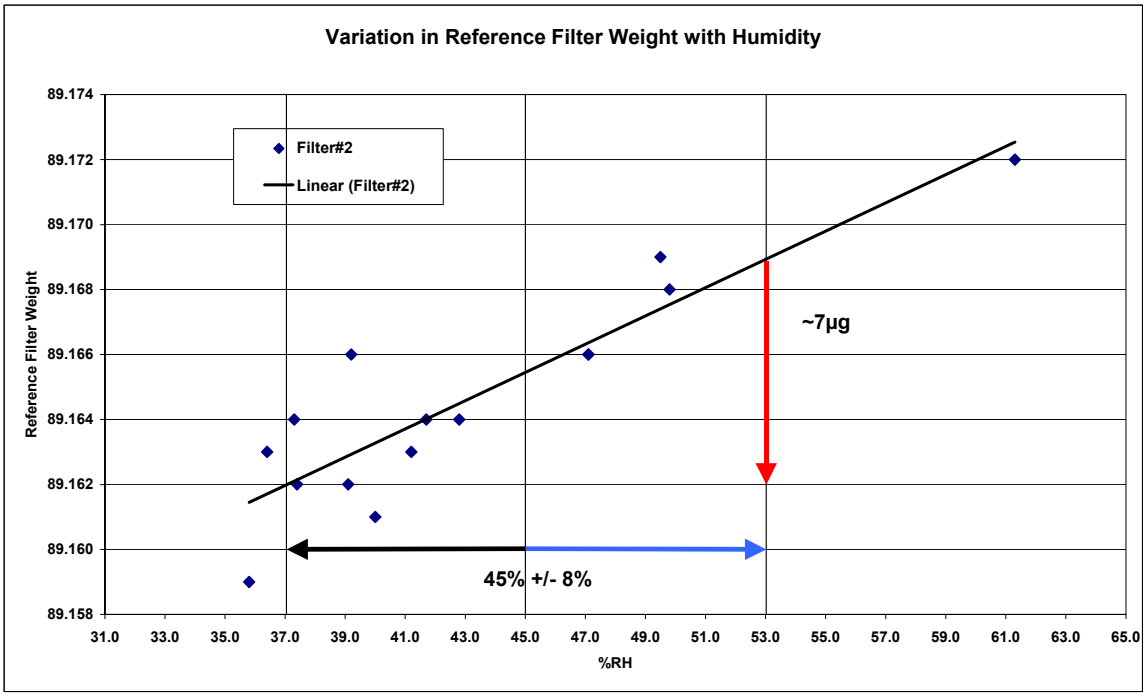
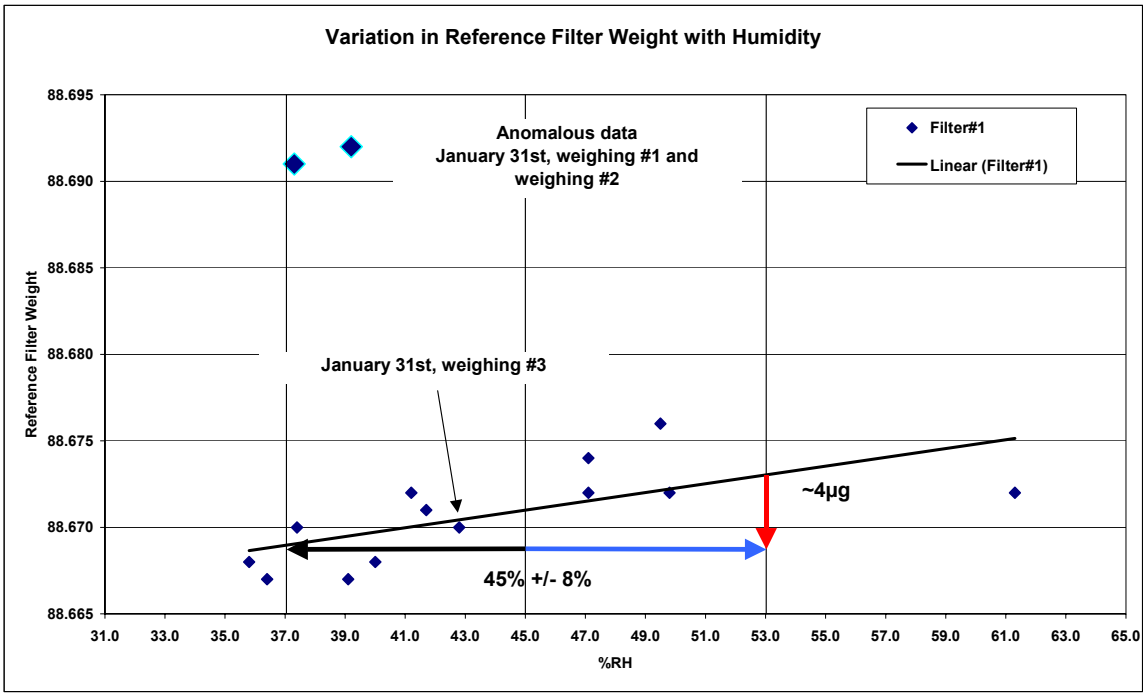


Figure 21 shows a similar trend of increasing reference filter#1 masses with increased humidity. However, with filter#1 the mass gain was less: ~4µg for the 16% increase in humidity. From Golden Vehicle tests, these variations in humidity ~7µg for reference

filter#2 and ~4µg for reference filter#1 would represent increases in PM emissions of ~0.15mg/km and ~0.08mg/km respectively.

Figure 21: Reference Filter Weight#1 - Variation with Humidity



The first two weighings of filter#1 on January 31st were anomalously high, both in the light of a subsequent weighing and the fact that filter#2, which was weighed at the same time, did not show the same elevated masses.
Table 7 shows the actual filter masses from the reference filter weighings, and shows that if the two anomalous readings from January 31st are ignored, the rolling averages of the reference filter weighings never fall outside a +/-5µg window for either filter.

Table 7: Running Averages - Reference Filter Weighings

Date	Baro. (kPa)	Rel. Humidity % rh	Temperature Δ°	Filter #1 (mg)	Rolling Average #1 (mg)	Filter#1 Change (µg)	Filter #2 (mg)	Rolling Average #2 (mg)	Filter#2 Change (µg)
January 31, 2005	103.41	37.3	0.20	88.691	88.691	0	89.164	89.164	0
January 31, 2005	103.28	39.2	0.20	88.692	88.692	0	89.166	89.165	1
January 31, 2005	103.17	42.8	0.60	88.670	88.684	-7	89.164	89.165	0
February 1, 2005	103.44	61.3	1.10	88.672	88.681	-3	89.172	89.167	2
February 2, 2005	103.76	36.4	1.00	88.667	88.678	-3	89.163	89.166	-1
February 3, 2005	103.76	49.8	0.80	88.672	88.677	-1	89.168	89.166	0
February 3, 2005	103.76	39.1	0.40	88.667	88.676	-1	89.162	89.166	-1
February 3, 2005	103.76	41.7	0.70	88.671	88.675	-1	89.164	89.165	0
February 4, 2005	103.29	41.2	1.20	88.672	88.675	0	89.163	89.165	0
February 4, 2005	103.29	49.5	1.60	88.676	88.675	0	89.169	89.166	0
February 7, 2005	102.48	35.8	0.30	88.668	88.674	-1	89.159	89.165	-1
February 7, 2005	102.48	37.4	0.50	88.670	88.674	0	89.162	89.165	0
February 8, 2005	102.60	47.1	0.40	88.674	88.674	0	89.166	89.165	0
February 8, 2005	102.60	47.1	0.40	88.672	88.674	0	89.166	89.165	0
February 10, 2005	102.46	40.0	0.30	88.668	88.673	0	89.161	89.165	0

4.3.5.3 Overview

It is clear that with the very low filter masses observed with from the Golden Vehicle vehicle (at Lab#3, 5 to 25µg) a large variation in weighing room humidity may have a significant impact on the measured filter mass. This suggests that humidity control should be tightened to a narrower bandwidth, perhaps +/- 2%. However, it may be

reasonable to permit a greater range of permitted humidity set-point values since it appears to be the variation in this rather than the absolute humidity level that leads to reference filter weight variation. In addition, higher humidities (>60%) are recommended [13] to minimise static charge effects with Teflon membrane filters.

Since the amount of mass collected on sample filters from post-DPF measurements may be very low (<25µg), the main source of variation in the measurement arising from humidity will be from the interaction between the filter medium and the environment. In order to minimise this, it is simply necessary to ensure that the conditions (temp, pressure, humidity) for the pre-weighing and post-weighing of that filter are closely matched, rather than ensuring that they sit within a broader range of pre-defined criteria.

4.3.6 Vehicle Preconditioning Effects on Particulate Mass Emissions

During the ILCE_LD, a number of experiments were conducted in order to establish any effects of different vehicle preconditioning on particulate mass emissions from the Golden Vehicle. The various preconditionings considered are listed in Table 8.

Table 8: Various Vehicle Preconditionings

First Precon	Second Precon	Soak
120kph; 20 mins	3 x EUDC	>6h
120kph; 10 mins	1 x EUDC	6h
None	2 x EUDC	6h
None	None	>6h
None	None	None

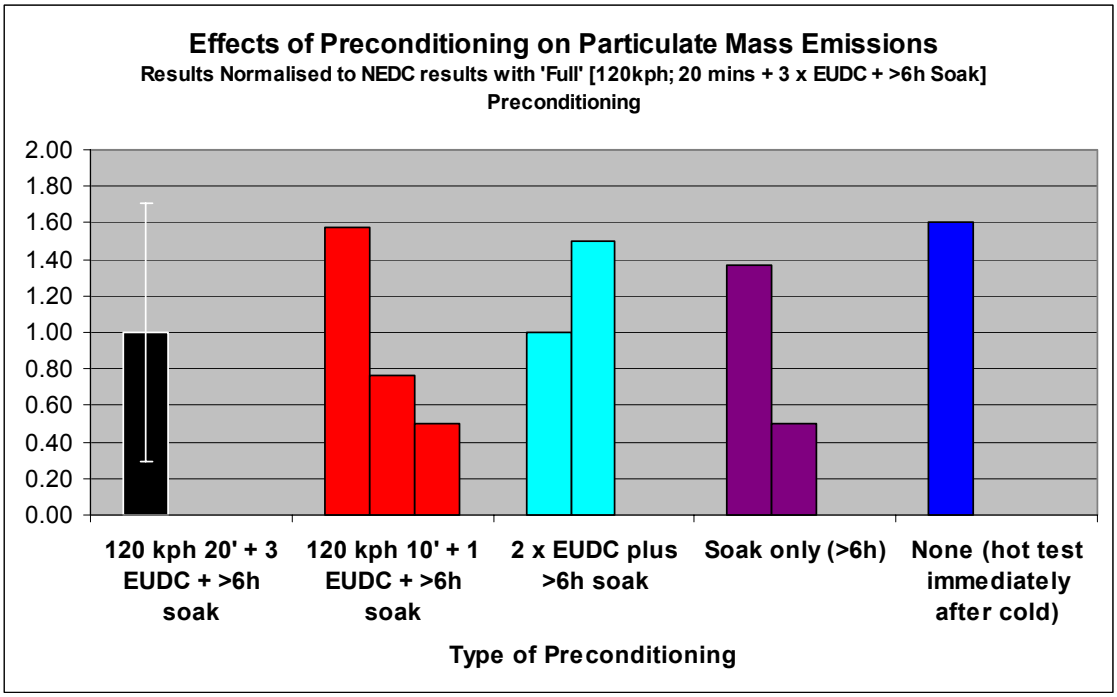
Figure 22 compares emissions from NEDC tests following the various preconditionings. In each case, the emissions level is normalised to an NEDC result from a cold start test conducted with the full PMP Preconditioning procedure (120kph; 20 minutes + 3 x EUDC + >6h soak) that was undertaken earlier on the same day or on the previous day.

Each result is also compared with mean Golden Vehicle NEDC PM result (+/- 2*S*) from the entire ILCE_LD. All data are drawn from tests undertaken with a partially filled DPF to avoid effects of fill-state on results.
From these data, it is clear that the preconditioning procedure has no effect on the particulate mass emissions from the Golden Vehicle. This is consistent with the understanding that the majority of the mass collected by the filter medium is via gas adsorption. It is possible that the solid particle emissions of the vehicle were affected by the preconditioning procedure, but the mass method is unable to resolve these from volatile effects.

4.3.7 Background Particle Mass Levels and Limit of Detection

Experiments conducted at the end of Lab#1,R3 testing considered the background levels of mass present in the CVS tunnel as collected by the PMP method. Since any true testing must consider the contribution of the background, filters were drawn from the CVS tunnel. Samples were drawn at the start of each day prior to any testing for 1180s – the duration of the NEDC cycle.

Figure 22: Effects of Vehicle Preconditioning on Particulate Mass Emissions



The mean mass collected during 4 replicate background analyses the mean mass collected was 20.8µg with a standard deviation of 4.6µg. If sampled from the NEDC cycle, these would equate to 0.441mg/km and 0.096mg/km respectively.
It is commonly accepted that the limit of detection (LOD) for a method can be calculated as 3 x the standard deviation of a blank measurement. If this approach is applied here, the LOD for the mass measurement method would be ~13.8µg per filter or 0.288mg/km for the NEDC cycle.

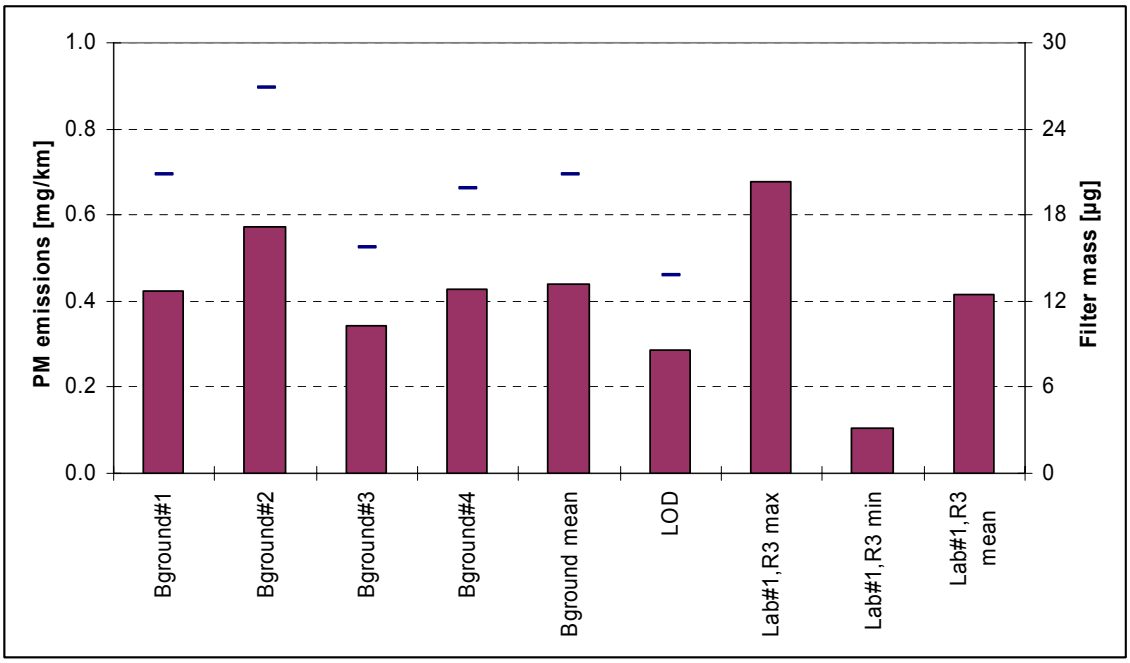
Figure 23 compares background PM levels with the range of PM emissions observed from the Golden Vehicle during the sets of measurements conducted at Lab#1,R3. In mg/km terms, the LOD is higher than the minimum emission observed during tests at Lab#1,R3 by a factor of 2.5 and in addition, the mean background is higher than the mean emissions from the Golden Vehicle during Lab#1,R3 tests.

While the background levels measured from the CVS may not be entirely representative of the system contribution during the thermal transients of an NEDC test, it is clear from this study that subtraction of a background could lead to a high proportion of zero results and the appropriateness of allowing this should be considered carefully in future regulations.

The high LOD and similarity between background levels and the quantified vehicle particulate emissions suggests that the mass method is insufficiently accurate for measuring the emissions of such vehicles (i.e. DPF equipped diesel) for regulatory purposes.

It is also worthy of note that when Lab#4 initially tested the Golden Vehicle using a HDD intake air filter (believed to be ~60% efficient) at the entrance to the CVS and then switched to a HEPA filter, this resulted in a significant reduction in PM emissions.

Figure 23: Comparison of Background PM and LOD with Sample PM Lab#1,R3. Bars show the PM emissions and lines the filter mass.

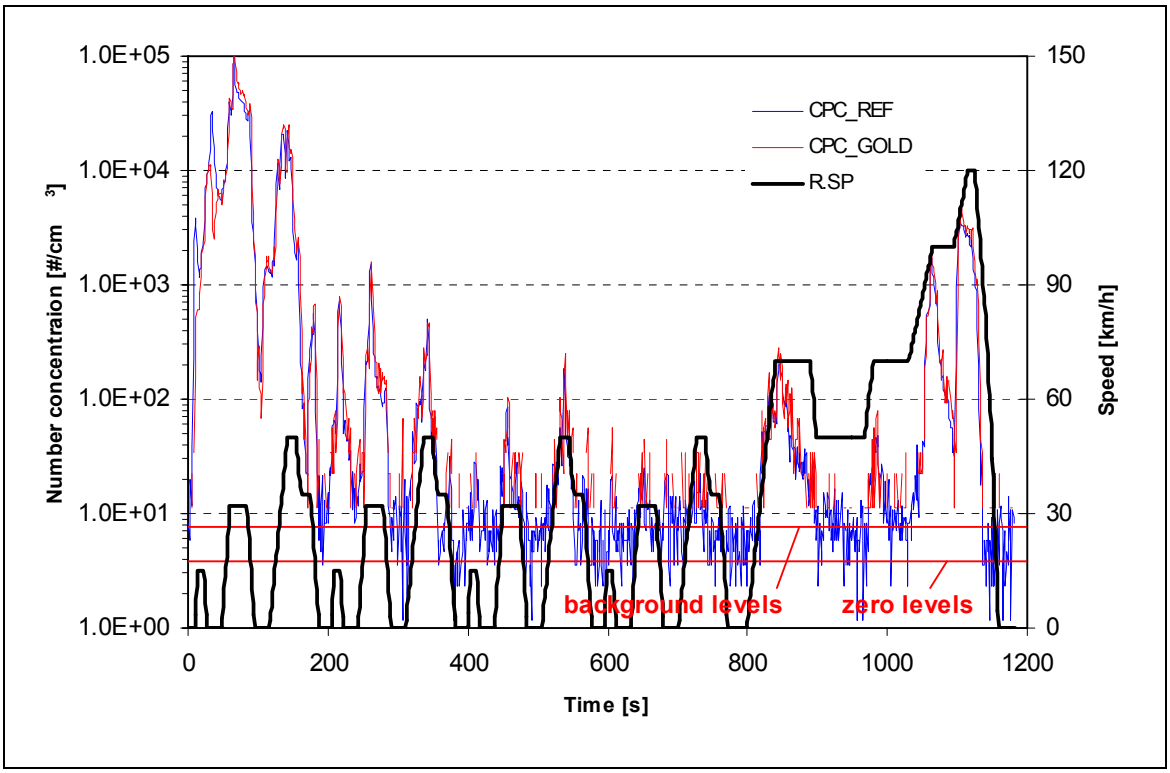


5 EMISSIONS RESULTS: PARTICLE NUMBERS (PN)

5.1 Valid Test Results From The Test Programme

Mean NEDC cycle particle number emissions from the Golden Vehicle are presented in the following sections. All data, excluding mass based and R83 criteria outliers, were used to generate the data shown. Results of non valid tests are also excluded.
NEDC particle number emissions were dominated by the urban phase (Figure 24, shown corrected for dilution) with emissions approaching background levels between 400s and 800s. The EUDC cycle makes a small contribution (typically <3%) to the NEDC cycle total number emissions.

Figure 24: Transient Cycle Particle Production from the Golden Vehicle



5.1.1 Intra-Lab And Inter-Lab Variability: Golden Vehicle

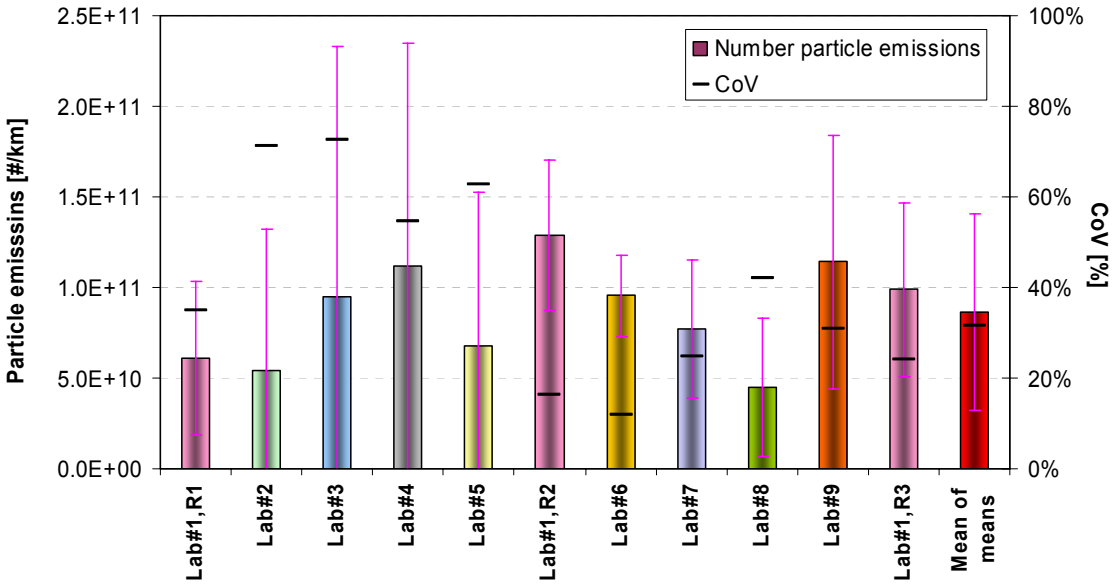
Mean NEDC emissions of particle numbers from the Golden vehicle ranged from ~$5x10^{10}$/km to ~$1.3x10^{11}$/km. Figure 25 shows that while the reproducibility level was ~31%, repeatability between laboratories ranged from 12% to 72%.

The apparent poor repeatability was due to two factors:

- Variability introduced by conducting more than one test on a vehicle within a day and related to preconditioning.

The 5 tests conducted at Lab#2 were undertaken during a period of 3 days, with morning and afternoon tests on 2 days. In each case, emissions from the afternoon tests were ~25% lower than the morning results (due to the different preconditioning).

Figure 25: Particle Number Emissions, Repeatability and Reproducibility, Au-DV1



The main difference between the tests in these laboratories was the intermediate preconditioning – Lab#2 merely used 3 x EUDC between tests, rest labs used 120kph plus 3 x EUDC. In all cases, tests following a 120kph preconditioning plus 3 x EUDC generated higher emissions than those following tests with just 3 x EUDC preconditioning.

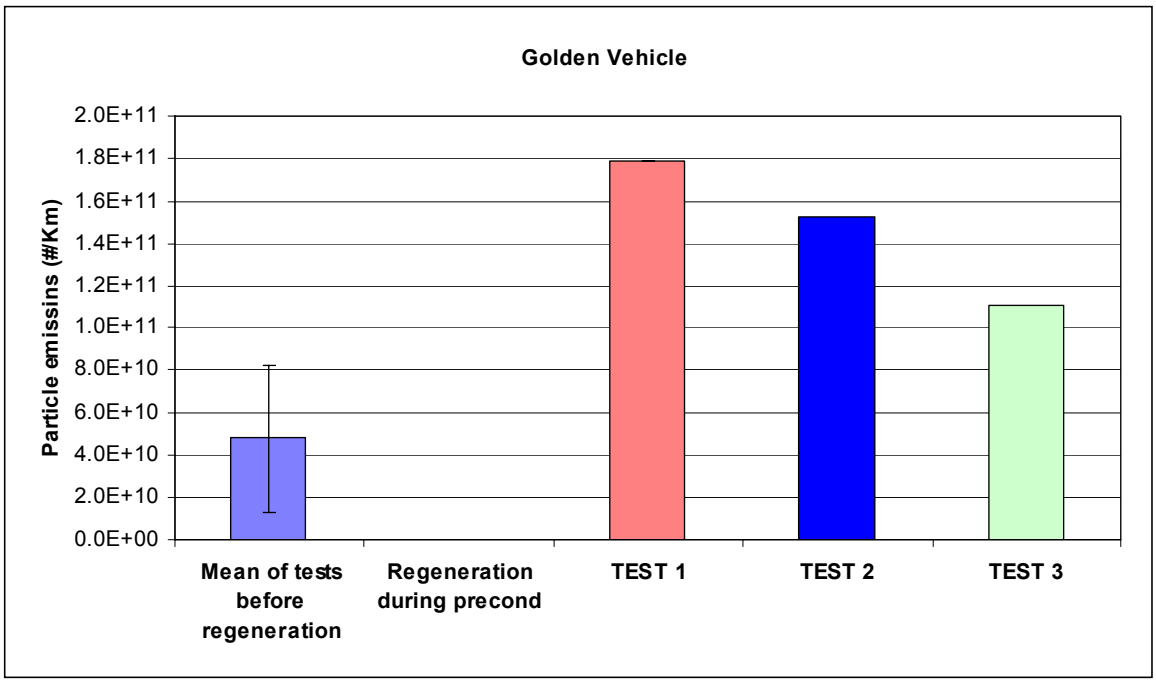
This effect is believed to be related to carbon entering the walls of the DPF and then escaping during the initial phases of the urban cycle – a phenomenon which is discussed further in Section 6.1.

- Variability as a function of DPF loading

Several laboratories observed scheduled regenerations during the test programme. These regenerations introduced significant step changes into the emissions results from the Golden Vehicle. Figure 26, for example, shows results from Lab#3 where emissions increased by a factor of ~4 in the first NEDC test following a scheduled regeneration and then decreased as further tests (and conditionings) were performed.
The regeneration influence on particle number emissions is believed to be related to DPF-fill state and filtration efficiency. This is discussed further in Section 6.1.

The reproducibility level of the particle number emissions is determined by comparing the mean data from each lab. Reproducibility is less affected by periodic regenerations and cold start effects: these are smoothed by the averaging process.
It is important to note that the major sources of variability of the measurements made on the Golden Vehicle can be attributed to the vehicle's emissions control system and not to the operation of the GPMS. The only valid way to assess the true variability of the GPMS would be to measure a known and constant source of particles, but such information is of little importance in the planned use of the system in testing real life vehicle emissions.

Figure 26: Particle Number Emissions Variability Affected by Regeneration



5.1.2 DPF Vehicles

As Figure 27 shows, with one notable exception, repeatability levels of the other DPF-equipped Diesels tested in the ILCE_LD are similar to the reproducibility level of the Golden Vehicle (31%) at 27% to 35%.

Figure 27: Repeatability Levels of All DPF vehicles

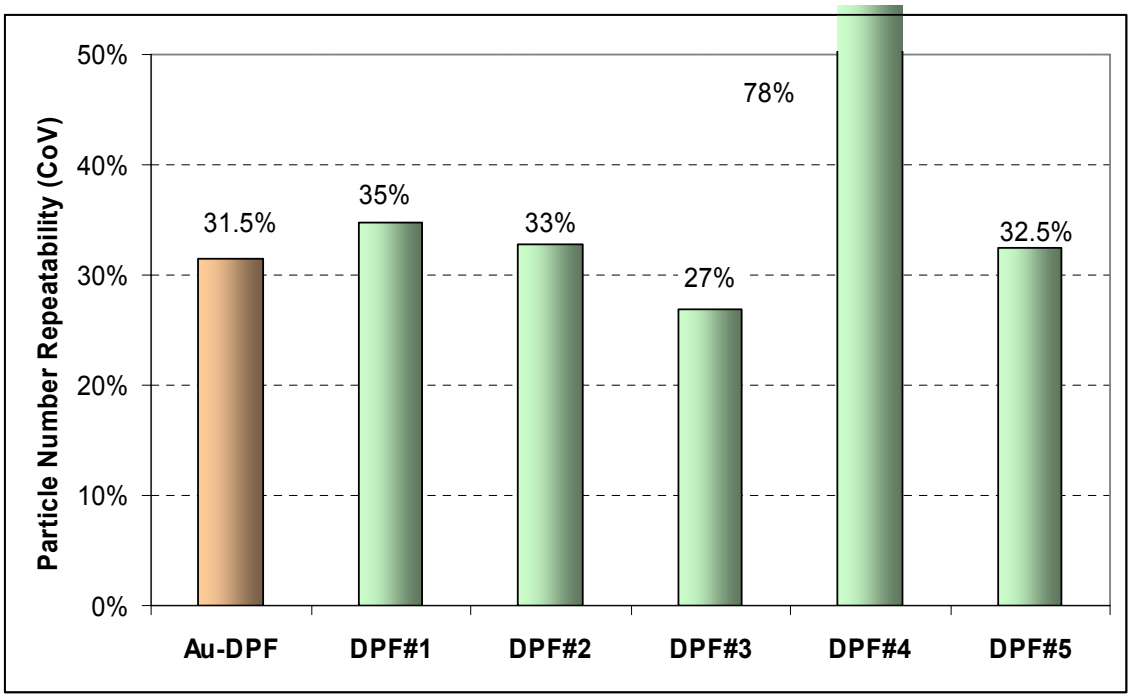
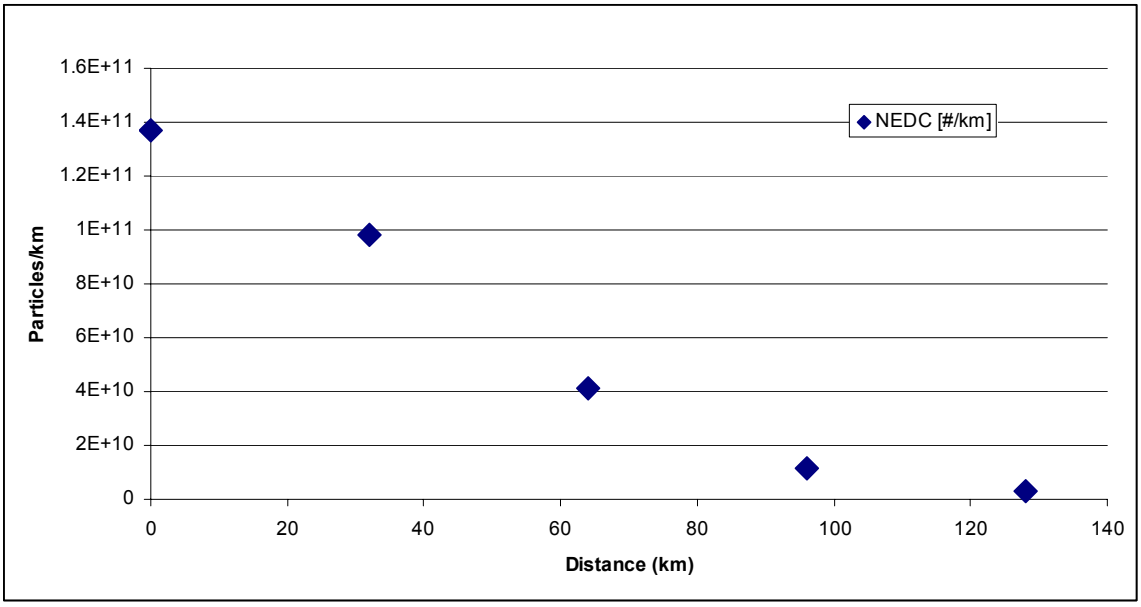


Figure 28: DPF#4 Particle Number Emissions Variability Related to DPF Fill



The exception, DPF#4, was the LDV: this experienced a scheduled regeneration directly before the first NEDC test and showed a continuous reduction in particle numbers as mileage increased (Figure 28) and the DPF filled. Note that the final test shown in this chart is omitted from the ILCE_LD dataset as a particulate mass outlier. The high (78%) variability quoted for DPF#4 was calculated from the first 4 tests only.
Other DPF-equipped vehicles which did not experience regenerations either directly before or during testing, did not exhibit the variabilities shown by the Golden Vehicle (Figure 26) and DPF#4 (Figure 28) and thus showed improved repeatability.

5.1.3 All Vehicles

Total particle number emissions, the reproducibility level from measurements on the Golden Vehicle and the repeatability results of all other vehicles are shown in Figure 29. Repeatability levels for the G-DI vehicles are generally better than those from the DPF equipped Diesels (5 – 26%), and excellent repeatability (2-7%) is seen by the non-DPF Diesels. MPI particle number repeatability (25%) is similar to that observed from the best DPF-equipped Diesels, perhaps indicating that this level is indicative of real repeatability (exclusive of any DPF regeneration effect) at below 1mg/km emissions levels.
Mean emissions from the DPF-equipped Diesels were lower than 10^{11}/km except for DPF#3 which can be considered a special case. Emissions from the MPI were statistically similar to the Golden Vehicle, while G-DI emissions levels were 40 to 140 times higher. Conventional Diesels' emissions were >2 x 10^{13}/km
The highest DPF-equipped vehicle particle number emissions (~6 x 10^{11}/km) were measured from DPF#3. This vehicle is known to have a more porous wall-flow filter as part of a novel emissions control system that includes several catalyst bricks in series. The porous, wall-flow filter medium is employed to limit overall system back-pressure, but passes solid particles (Figure 30) that are probably carbonaceous, in response to drive-cycle transients in an emissions pattern similar to that observed from non-DPF

Diesels. It should be noted that emissions from this vehicle were still lower than from any of the G-DI types.

Generally the repeatability of the particle number data improves with the magnitude of particle number emissions (Figure 31). This effect spans a factor of ~4000 between the lowest DPF-equipped vehicle, with emissions ~$1.5x10^{10}$/km, and the $6x10^{13}$/km emissions from the highest non-DPF vehicle (Figure 32).

Figure 29: Particle Number Emissions and Repeatability Data – All Vehicles

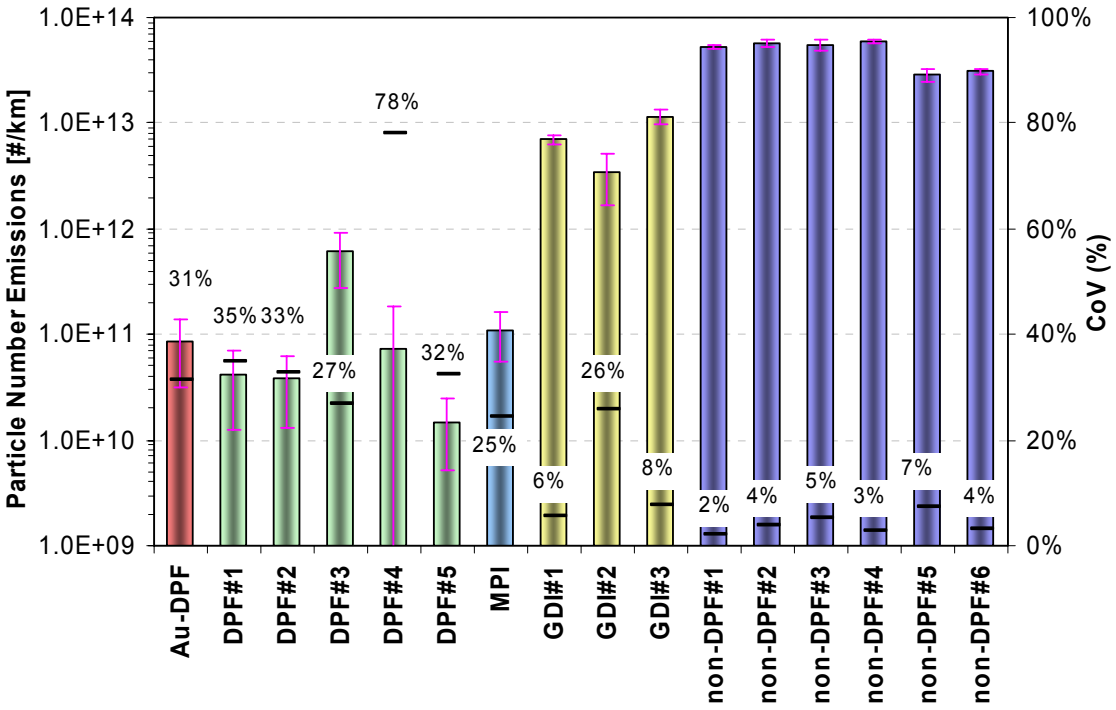


Figure 30: Porous Wall-flow DPF Shows non-DPF-like Particle Emissions Profile

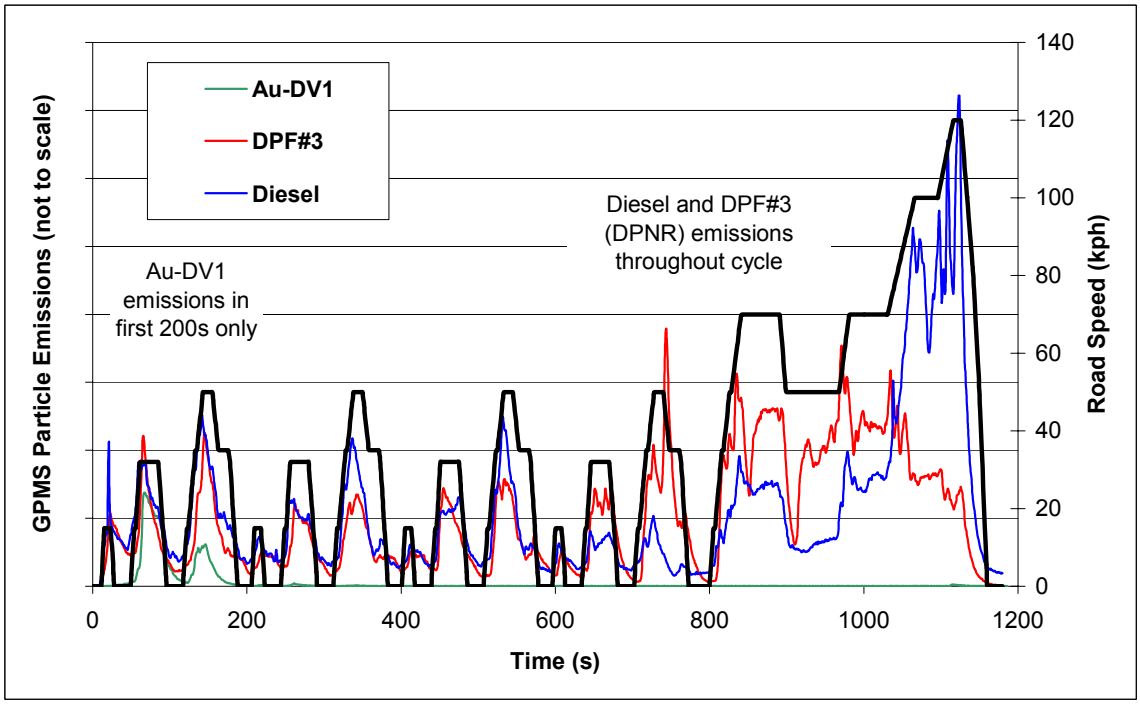


Figure 31: Particle Number Repeatability Improves with Emissions Magnitude

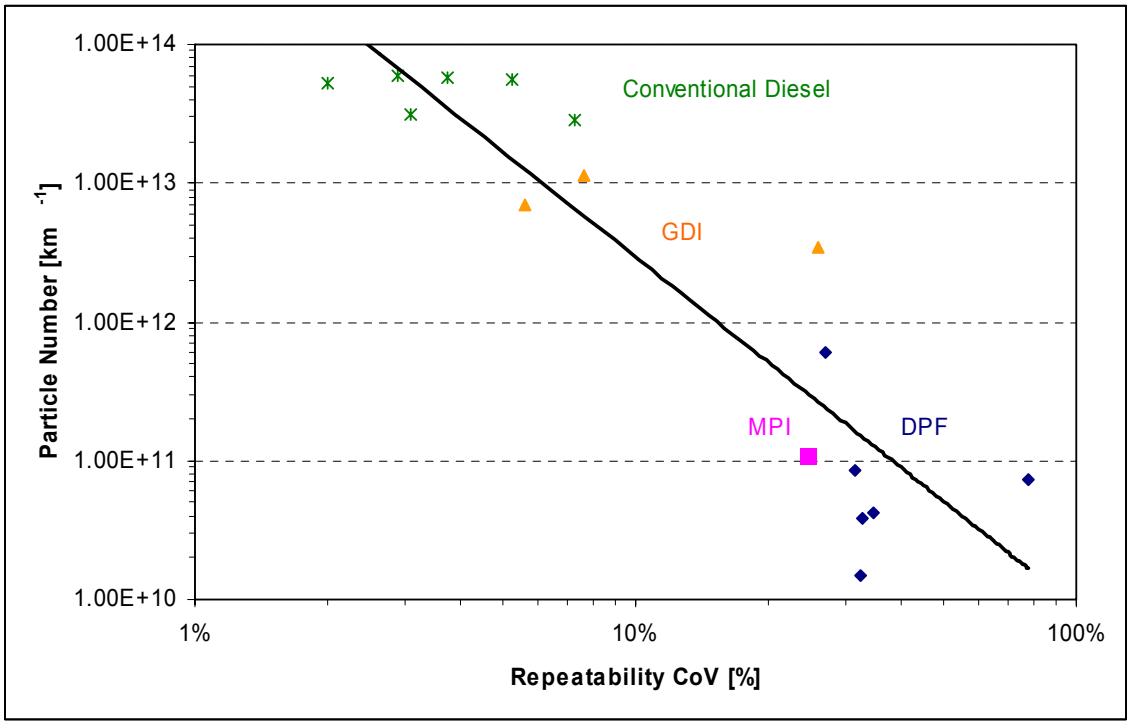
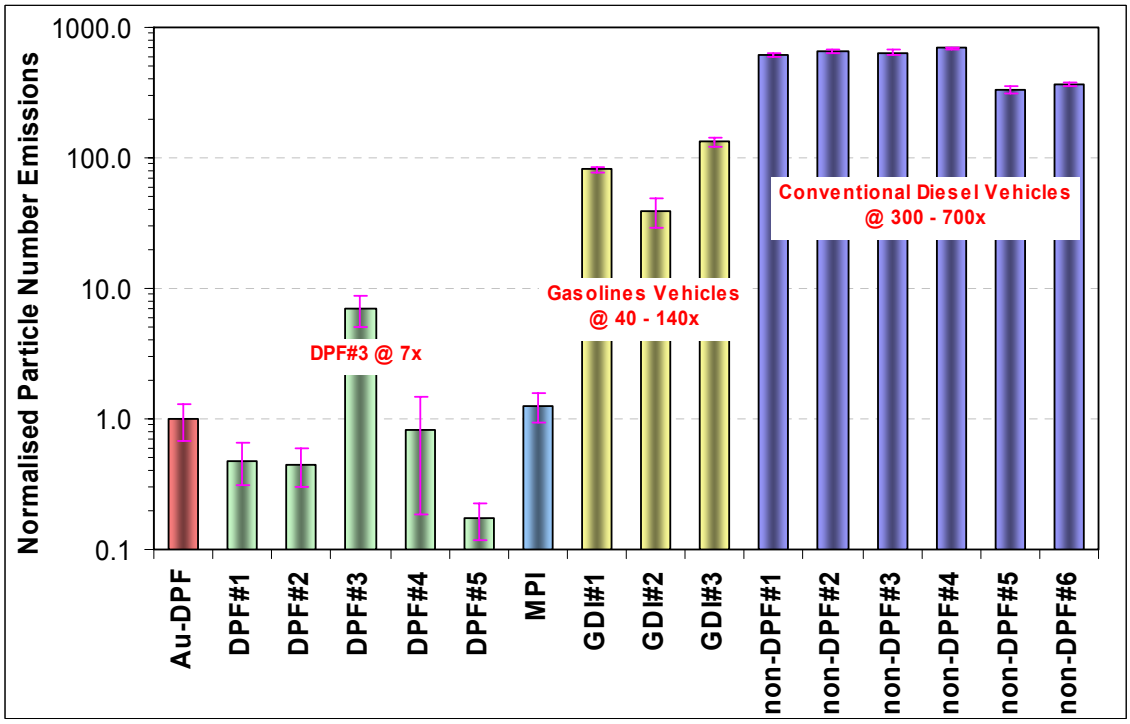


Figure 32: Particle Number Emissions Normalised to Golden Vehicle



5.2 Long-Term Golden Vehicle Behaviour

Particle number emissions from the Golden Vehicle recorded throughout the test programme are shown in Figure 33. There was no obvious trend in emissions levels across the test programme. Highest emissions were observed from tests immediately following regenerations and this effect was greater than lab-to-lab variance.

Figure 33: ILCE_LD Particle Number Emissions Showed No Long-Term Trend

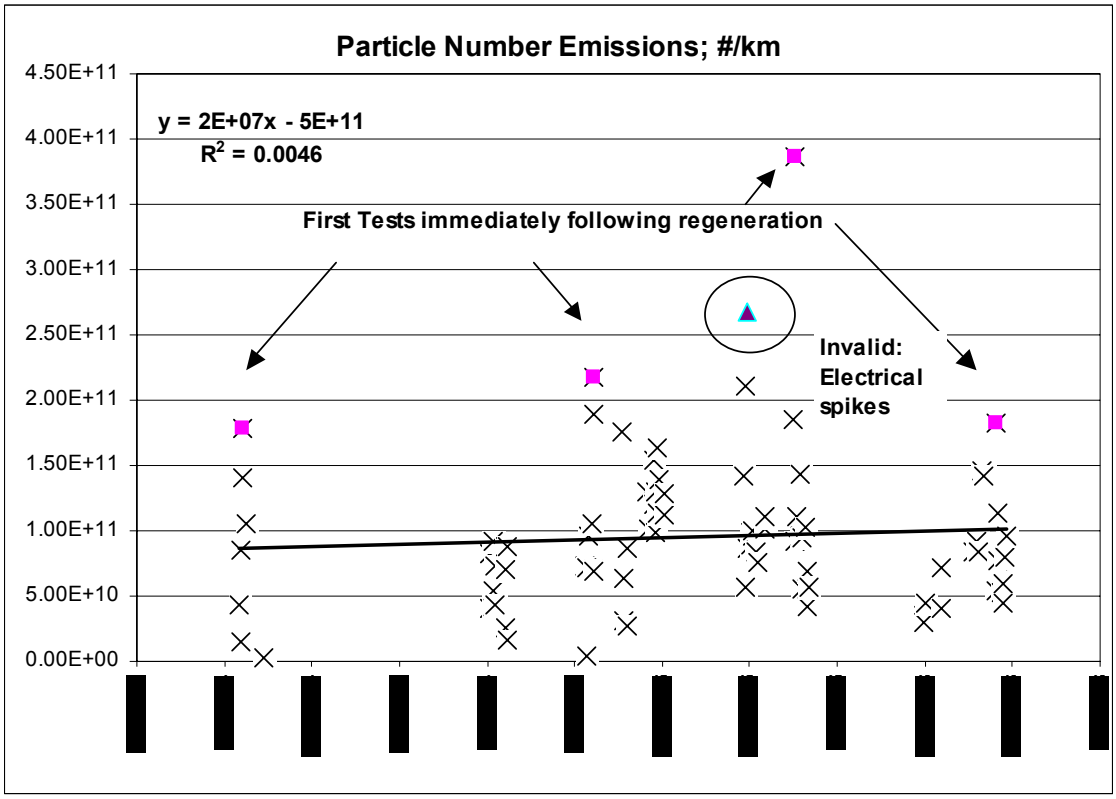
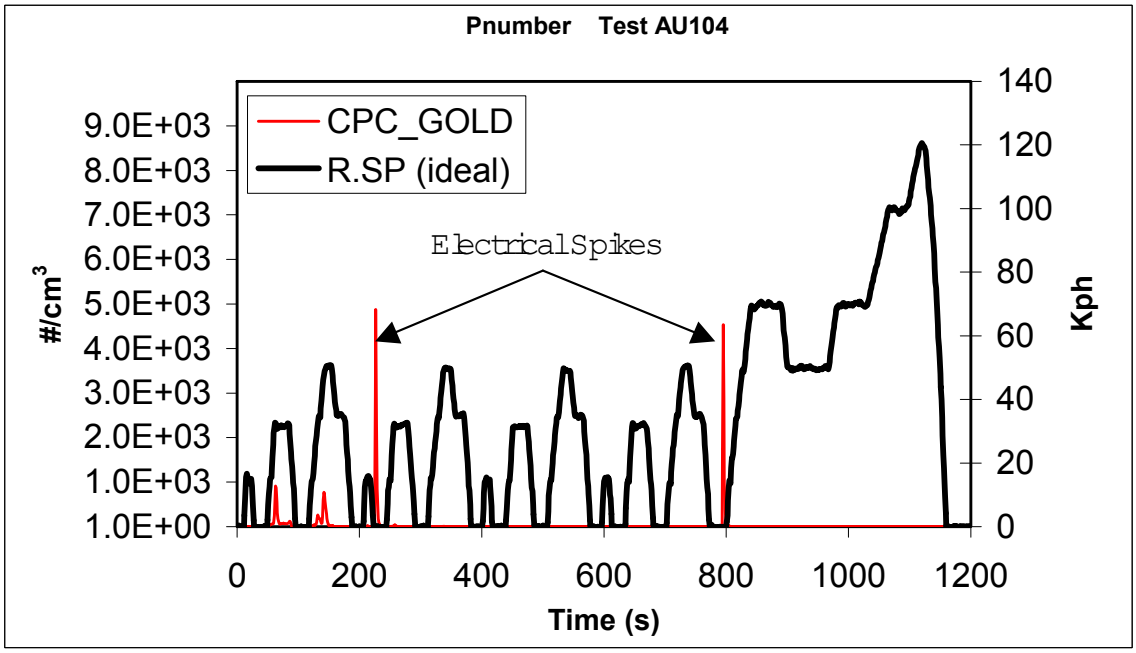


Figure 34: Electrical Spikes Increase Apparent Emissions From Au-DV#1



During one test at lab#7, two electrical spikes were observed (Figure 34). These resulted in an emission rate of ~$2.7x10^{11}$/km compared with an emissions level of ~9. $7x10^{10}$/km when the spikes were deleted. This result was not included in the valid results from lab#7. No electrical spikes were observed in data from any other labs.

5.3 GPMS Performance

5.3.1 Comparison of DPF-Vehicles' And Non-DPF Vehicles' GPMS Emissions Measurements

As shown in Figure 29, the repeatability levels of particle number measurements from the GPMS were considerably better for the conventional Diesels than for the DPF-equipped Diesels. As mentioned previously, repeatability appears to be related to total particle emissions: relatively few particles are measured from the DPF-equipped Diesels meaning that small differences in absolute numbers between tests comprise relatively large percentage differences.
The repeatability from conventional Diesel measurements is excellent, with *CoV*s ranging from ~2% up to ~7%. The chemistry of particles emitted from Euro 3 and 4 conventional Diesel vehicles is almost entirely carbonaceous [14], and the particles are virtually unaffected by the heating and dilution processes within the VPR.
The elevated repeatability levels observed from the DPF-equipped Diesel vehicles reflects both a reduction in particle concentration and a change in particle chemistry to include low volatility HC materials as well as extremely low levels of carbon agglomerates. However, the major influence on repeatability is the presence of the DPF.
There is clear evidence from the test programme (Figure 26, Figure 28) that particle number emissions increase immediately following DPF regeneration then progressively decrease as the vehicle accumulates mileage. Emissions finally stabilise after approximately 300km. This is consistent with the DPF emptying during regeneration and reaching a condition of lowest filtration efficiency. As further mileage is accumulated soot is released into the DPF, a filter cake begins to form as the DPF fills, this leads to increased filtration efficiency and lower particle number emissions. After a certain time the filter cake is complete and filtration efficiency and particle number emissions stabilise. Further soot emissions increase the exhaust backpressure but do not appear to affect filtration efficiency further.

The key implications of this effect are three-fold:

- Tests performed on DPF-equipped Diesels during the ILCE_LD were rarely undertaken during a stabilised DPF fill condition, so it is not possible to evaluate true repeatability of data from the particle measurement system on these vehicles. Instead, the variability of the DPF is being assessed.
- The particle number system has a low enough limit of detection and sufficient resolution to indicate particle number emissions differences related to the changes in filtration efficiency of the DPF.
- Number measurements from non-DPF Diesels, where the engine can be considered a stable particle generator, represent a truer measure of the measurement system repeatability.

5.3.2 Purpose of Reference PNC

The reference particle number counter (PNC_REF, Figure 2) was of identical specification to the Golden Particle Number Counter (PNC_GOLD). PNC_REF was included in the equipment provided to each test laboratory for two reasons:

- To enable direct operational comparison with the PNC present in the GPMS, ensuring that no damage to the PNC_GOLD was sustained during shipping and that no drift in operation had occurred. This comparison is based upon the premise that any damage to, or change in operation of, PNC_GOLD would have to be exactly replicated in PNC_REF for the relationship between them to remain unchanged. Such verification exercises are described in Section 5.5.6.

- To enable the effect and effectiveness of the evaporation tube (ET) to be determined. PNC_REF is positioned upstream of the ET and at a dilution ratio 10 times lower than PNC_GOLD. After correction for dilution, a comparison of PNC_REF and PNC_GOLD indicates the influence of the ET in eliminating volatile particles. If no difference is observed between PNC_REF and PNC_GOLD then no volatile particles are present upstream of the ET.

- The effectiveness of the ET at eliminating volatile particles is discussed in Sections 5.4 (required performance) and 5.6 (real emissions data).

5.4 GPMS Calibration

AEA Technology plc (AEA) performed independent calibrations of the GPMS throughout the PMP light-duty Inter-laboratory Correlation Exercise (ILCE). These calibrations were performed at the beginning, middle and end of the exercise, commencing January 2005 and ending January 2007, with intermediate calibrations performed in August 2005 and February 2006.

The results of these calibrations are presented here, along with a description of the calibration methods and summary of results.

All calibrations were made in accordance with the UN-GRPE PMP Phase 3 Inter-laboratory Correlation Exercise: Framework and Laboratory Guide [7].

All calibrations were performed at the operating conditions most commonly used in the ILCE:

PND1: 10 cavity disc, potentiometer setting of either 75% or 60%
Heated to 150°C
1 metre sampling hose

PND2: 2 bar of filtered dried compressed air
ET heated to 300°C

5.4.1 Calibration of the diluters (according to 8.5.2 [7])

The diluters (PND1 & PND2) were calibrated with carbon monoxide (CO) gas. For all four calibrations Messer certified 1000ppm carbon monoxide gas was used. Two models of analyser were used; a Thermo Environmental Instruments 48C CO Analyser (accuracy +/- 2%) for the January 2005 calibration and the remaining three calibrations used an ADC CO Analyser (accuracy +/- 1.74%).

The gas calibrations were performed using the 10-cavity disc (allowing dilution factors between around 10 and 300 to be measured), with the diluter heated to 150°C and ET heated to 300°C. All calibrations were performed using the 1 metre sampling hose (this is the sampling line which connects PND_1 to the controller).

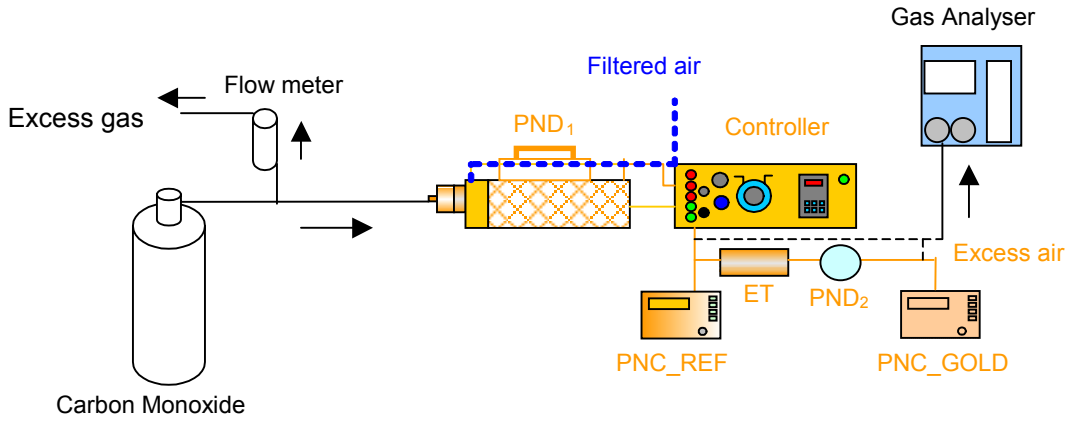
Calibration of PND_2 was always performed with PND_1 at the potentiometer setting most commonly used in the ILCE, this was 75% for the January 2005 calibration and 60% for the remaining three calibrations (note that after January 2005, for potentiometer settings above 60% the diluter indicated the rotating frequency was too high, therefore being out of range).

Experimental Set-up

The schematic diagram in Figure 35 describes the experimental set-up of the diluter gas calibration. Before each gas calibration the analyser was allowed to stabilise for a minimum of one hour before a zero and span was performed. The GPMS was heated and a zero check was performed on the system by connecting a HEPA filter to the inlet of PND_1 and recording the particle concentration on PNC_REF and PNC_GOLD. If the zero was less than 5 particles cm^{-3} the calibration proceeded, if the system failed a complete leak check was performed until the zero test was passed.

The gas was introduced into PND_1 via a small flow meter to ensure adequate flow was supplied without a large overpressure in the diluter being produced. The flow meter was connected using a 'Y' connector allowing excess gas, not required by PND_1, to be vented.

Figure 35: GPMS set-up for calibration of the diluters



The gas analyser was connected in place of PNC_REF and the flow rate of the analyser was adjusted to 1 $lmin^{-1}$ to simulate the flow rate of PNC_REF. The gas was introduced at around 0.5 bar and the analyser was allowed to stabilise before a measurement was taken. Once stabilised, the potentiometer was altered to the next setting and the concentration was again allowed to stabilise. This was repeated for all potentiometer settings. Once complete the dilution ratio of PND_2 was measured. Using the potentiometer setting used in the ILCE (75 or 60%) the gas analyser measured the CO concentration at the PNC_GOLD position. The CO concentration at the PNC_REF position was confirmed before the CO analyser position was moved to PNC_GOLD. Once a stable reading of the dilution ratio of PND_2 had been recorded the dilution ratio at the PNC_REF position was again confirmed to ensure the system was still stable and the gas concentration had not drifted. If any drift was observed the calibration of PND_2 was repeated until stable gas concentrations were achieved.

Results

The results of each gas calibration were compared with the most recent calibration data provided by Matter Engineering. The calibration data for PND_1 from Matter Engineering was not performed using gas but particles at one fixed diameter (91nm), using the 3 metre sampling hose and at 80°C rather than 150°C. Due to these differences in calibration methods it was anticipated that the gas calibration results would produce higher dilution ratios than the particle derived dilution ratios from Matter Engineering (due to particle losses). The calibration data from Matter Engineering has been adjusted to take into consideration the difference in temperatures between the two calibration methods, this allows a comparison to be made between the measured dilution ratios.

The dilution ratios of PND_1 measured during the four calibrations are shown in Figure 36-Figure 39.

Figure 36: Calibration of PND_1 using CO gas – January 2005

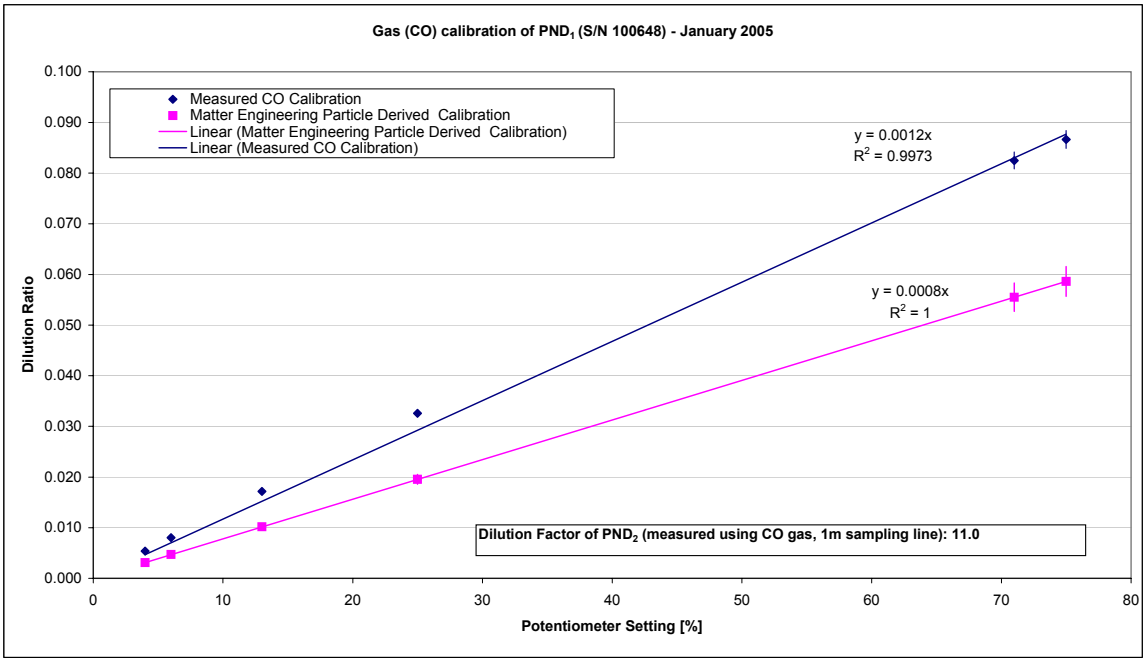


Figure 37: Calibration of PND_1 using CO gas – August 2005

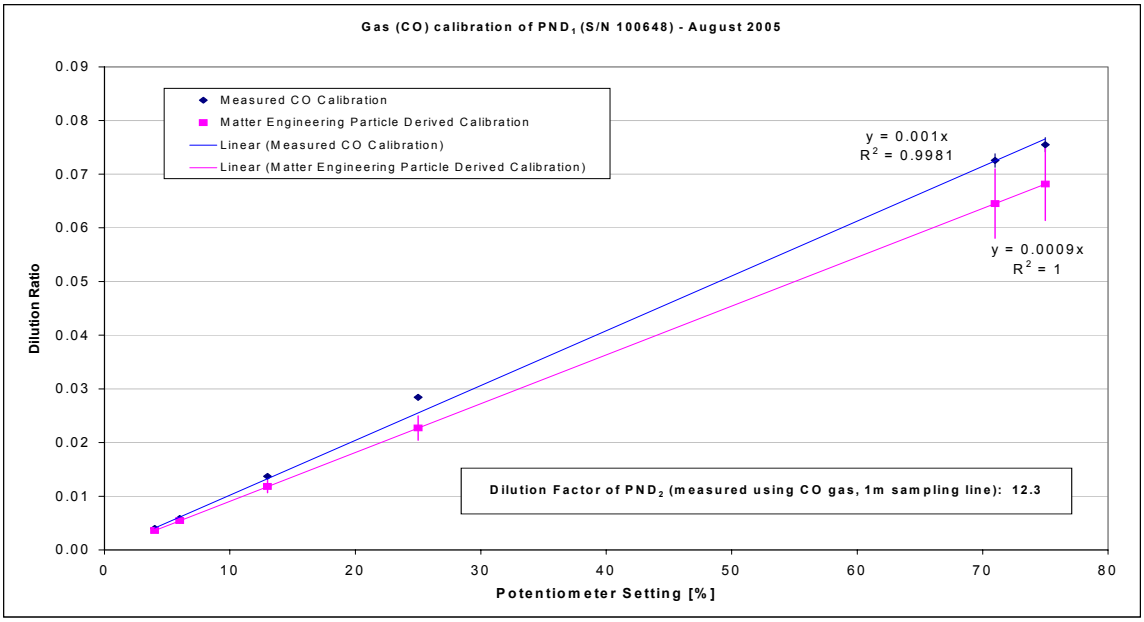
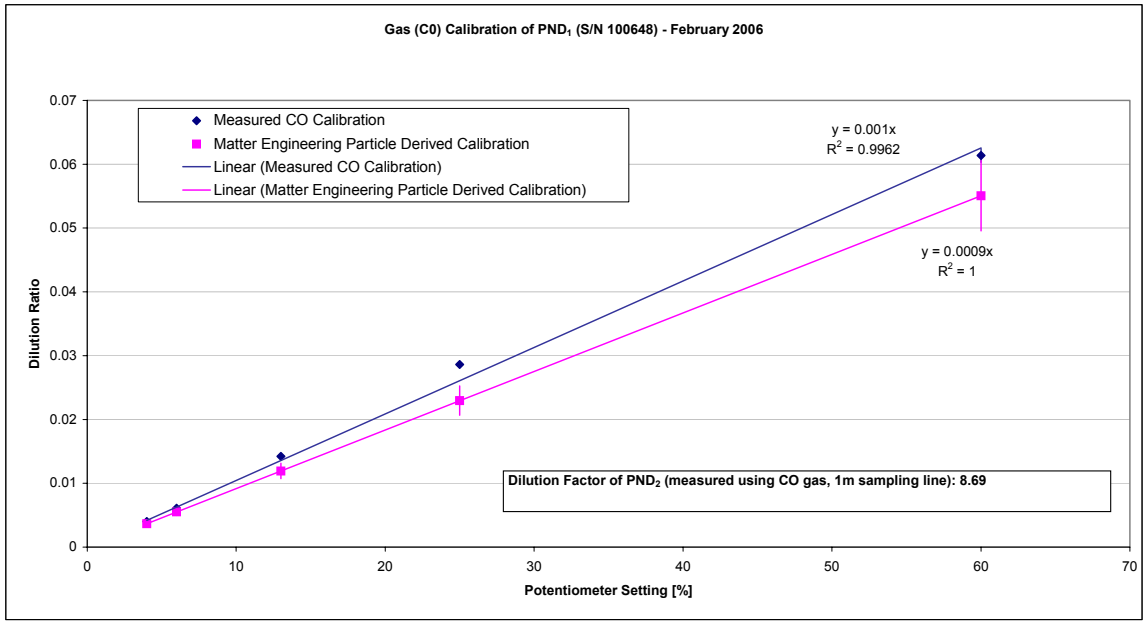


Figure 38: Calibration of PND_1 using CO gas – February 2006

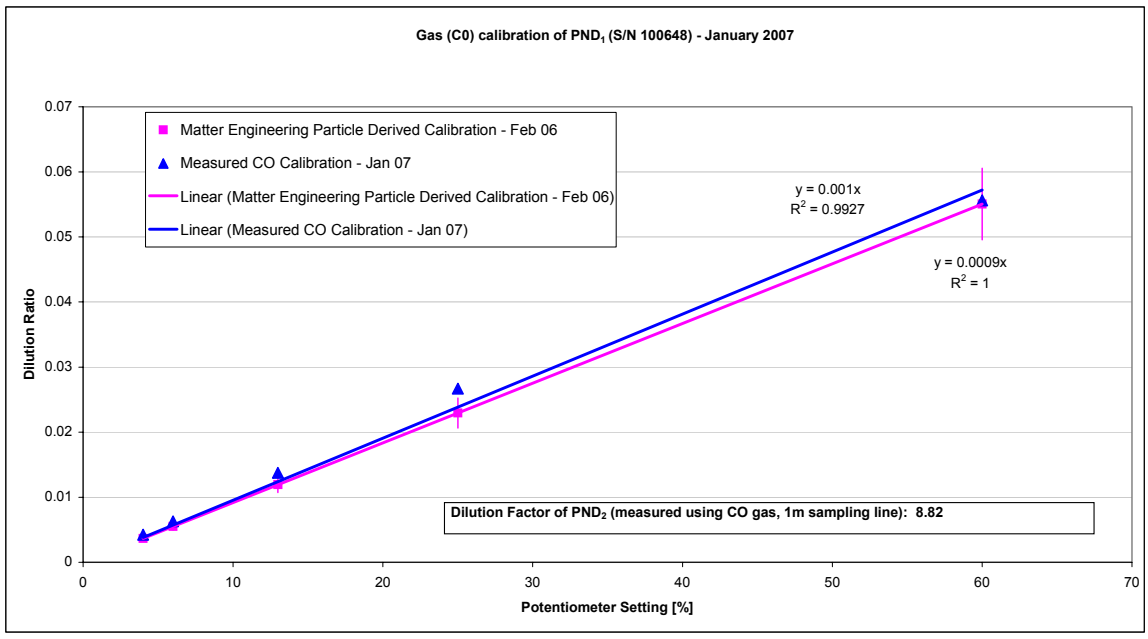


The pink line represents the particle-derived calibration from Matter Engineering and the blue line is the gas calibration performed by AEA. The accuracy of both measurements are shown using error bars. The calibration equations used to produce the Matter Engineering data (pink line) are as follows (taken from their particle calibration reports):

January 2005 calibration:	Dilution Factor = 1066 * f(temp)/Pot(%),
August 2005 calibration:	Dilution Factor = 917 * f(temp)/Pot(%),
February 2006 calibration:	Dilution Factor = 908 * f(temp)/Pot(%),
January 2007 calibration:	Dilution Factor = 908 * f(temp)/Pot(%),

where f(temp) at 150°C is 1.2 and Pot (%) is the potentiometer setting on the diluter.

Figure 39: Calibration of PND1 using CO gas – January 2007



Note: PND1 was repaired by Matter Engineering in December 2006. The dilution block and disc were replaced due to excessive wear. Matter Engineering did not perform a particle calibration after this repair work and hence the dilution factor has not changed between the February 2006 and January 2007 calibrations.

These data are summarised in Table 9, spaces in the data indicate that the potentiometer setting was not measured during the calibration.

Table 9: Calibration of PND_1: measured dilution ratios

Potentiometer Setting [%]	Measured dilution ratios			
	January 2005	August 2005	February 2006	January 2007
4	5.38×10^{-3}	4.02×10^{-3}	4.02×10^{-3}	4.24×10^{-3}
6	8.04×10^{-3}	5.88×10^{-3}	6.08×10^{-3}	6.31×10^{-3}
13	1.71×10^{-2}	1.37×10^{-2}	1.42×10^{-2}	1.38×10^{-2}
25	3.26×10^{-2}	2.84×10^{-2}	2.86×10^{-2}	2.67×10^{-2}
60	-	-	6.14×10^{-2}	5.56×10^{-2}
71	8.25×10^{-2}	7.25×10^{-2}	-	-
75	8.66×10^{-2}	7.55×10^{-2}	-	-

Table 10: PND_2 Calibration: comparison of dilution factors

Date of calibration	Dilution factors	
	Matter Engineering (from flow rates)	AEA (measured using gas dilution)
January 2005	9.465	11.0
August 2005	9.265	12.3
February 2006	8.155	8.69
January 2007	8.155	8.82

Please note that the dilution ratio = 1/dilution factor.

The Matter Engineering calibration of PND_2 was performed using flow rate measurements rather than gas or particle dilution measurements. The dilution factors measured by Matter Engineering and AEA throughout the ILCE are compared in Table 10, generally the dilution factors measured by AEA were higher than the calculated values from Matter Engineering. AEAT's measurements were performed as a developmental calibration check evaluating particle specific dilution ratios for system components. However it was considered most realistic to use the system manufacturer's (Matter Engineering) calibration for the particle number calculations throughout the inter-lab exercise. Variations in DF are an accepted source of variability from the inter-lab exercise contributing to both lab-to-lab and test-to-test variability with minor apparent impact on the overall programme results.

5.4.2 Calibration of the Volatile Particle Remover, VPR (according to 8.5.3 [7])

The VPR was calibrated using two types of particles, solid and volatile. For both sets of measurements the temperature of PND_1 was 150°C and the ET was 300°C. The potentiometer setting was 75% for the January 2005 calibration and 60% for the remaining calibrations.

Solid Particle Calibration

Solid monodisperse sodium chloride particles (produced by a condensation generator and selected with an electrostatic classifier) with diameters of 30, 50, 80 and 100nm were generated and sampled by the volatile particle remover. Number concentration measurements were made with the AEA (upstream at PND_1 inlet) and PNC_GOLD (downstream of VPR) 3010 CPC's. For the 30nm PE measurements the AEA CPC was used to measure both number concentrations (at the PND_1 inlet and the PNC_GOLD position) because the AEA CPC is unmodified and has a D_{50} of 10nm rather than 23nm that the PNC_GOLD and PNC_REF has been modified to.

The penetration efficiencies (PE) were calculated using the following equation:

$$\frac{\text{Number concentration at PNC\_GOLD location}}{(\text{Number concentration at PND1 inlet}/PND_1\text{ DF}/PND_2\text{ DF})} \times 100\% = PE$$

where DF = dilution factor.

The DF's used for this calculation were as follows:

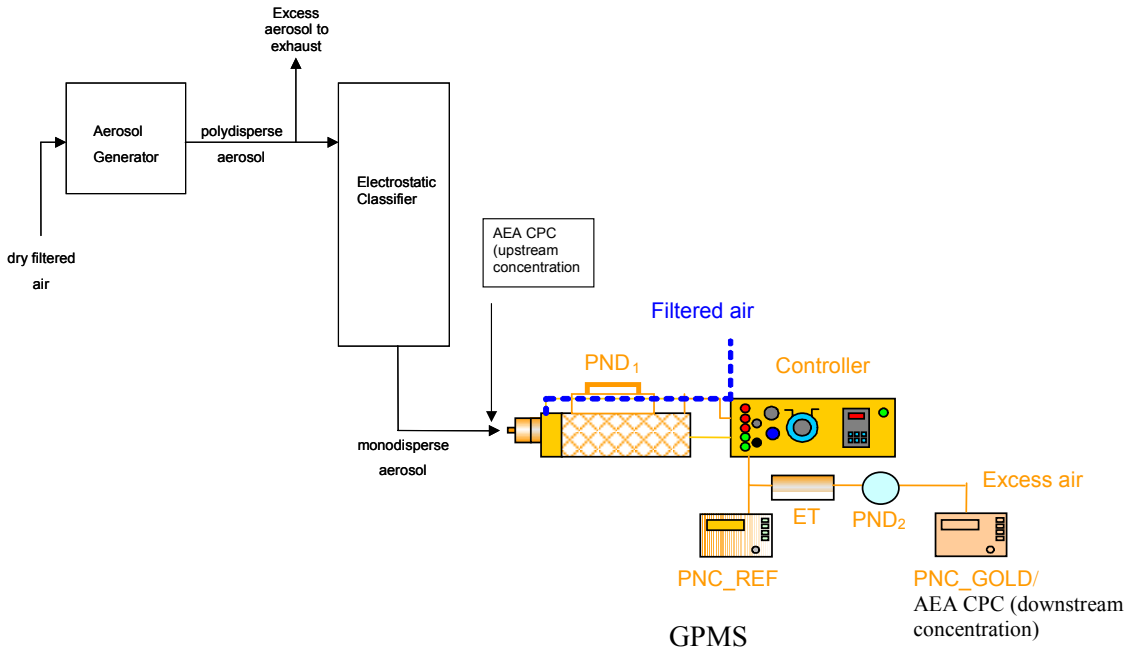
PND_1 DF = most recent DF from Matter Engineering particle calibrations (with the exception of January 2007 where particle calibration dilution factors were not available for the repaired VPR, for this calibration the AEA gas derived dilution factor was used).

PND_2 DF = most recent DF from AEA gas calibrations (rather than the Matter Engineering flow rate derived dilution factor).

Experimental Set-up

Polydisperse sodium chloride particles were produced by a condensation generator and sampled by an electrostatic classifier (TSI, Model 3080) to produce monodisperse particles. These particles were sampled by the VPR and measurements of the number concentrations were made at the inlet of PND_1 and the PNC_GOLD sampling position. Only stable concentrations above 1000 particles cm^{-3} at the PND_1 inlet were used to calculate the PE. Figure 40 describes the set-up for the measurement of the PE of the VPR and shows the sampling locations of the CPCs (the condensation aerosol generator is further described in the AEA document 'Condensation Particle Counter Calibration Procedures [15].

Figure 40: Schematic diagram of experimental set-up to measure the penetration efficiency of the VPR.



Results

The PE's measured during each calibration are shown in Figure 41-Figure 44 and the data is summarised in Table 11. The red line at 80% indicates the minimum allowable PE at 30, 50 and 100nm as originally specified in the UN-GRPE PMP Phase 3 Inter-laboratory Correlation Exercise: Framework and Laboratory Guide [7].

Figure 41: Penetration of monodisperse solid sodium chloride particles – January 2005

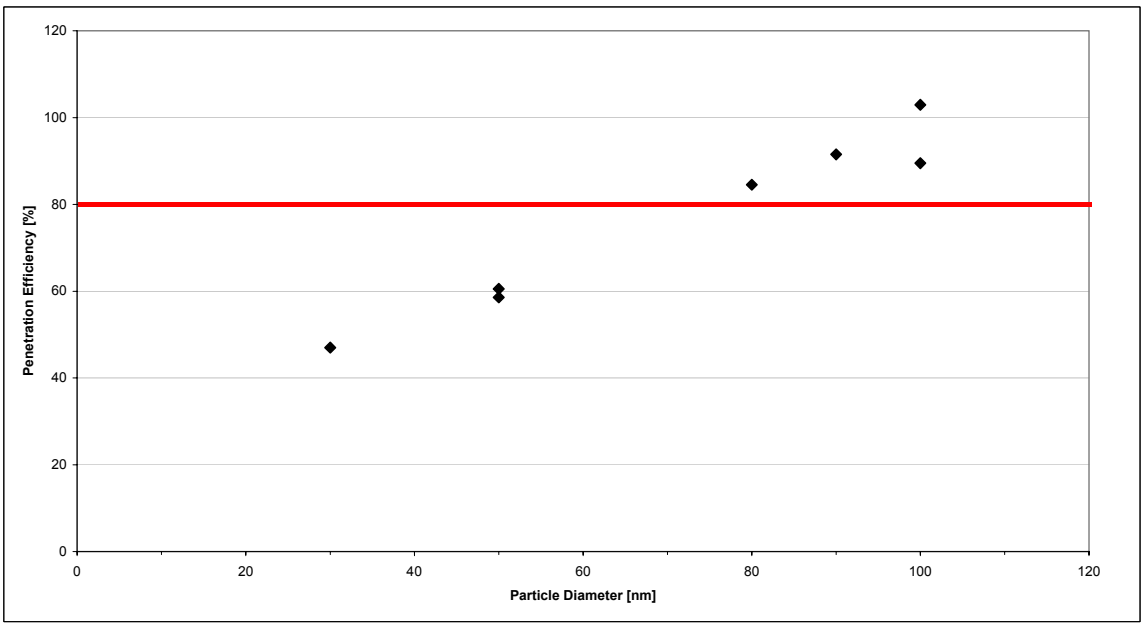


Figure 42: Penetration of monodisperse solid sodium chloride particles – August 2005

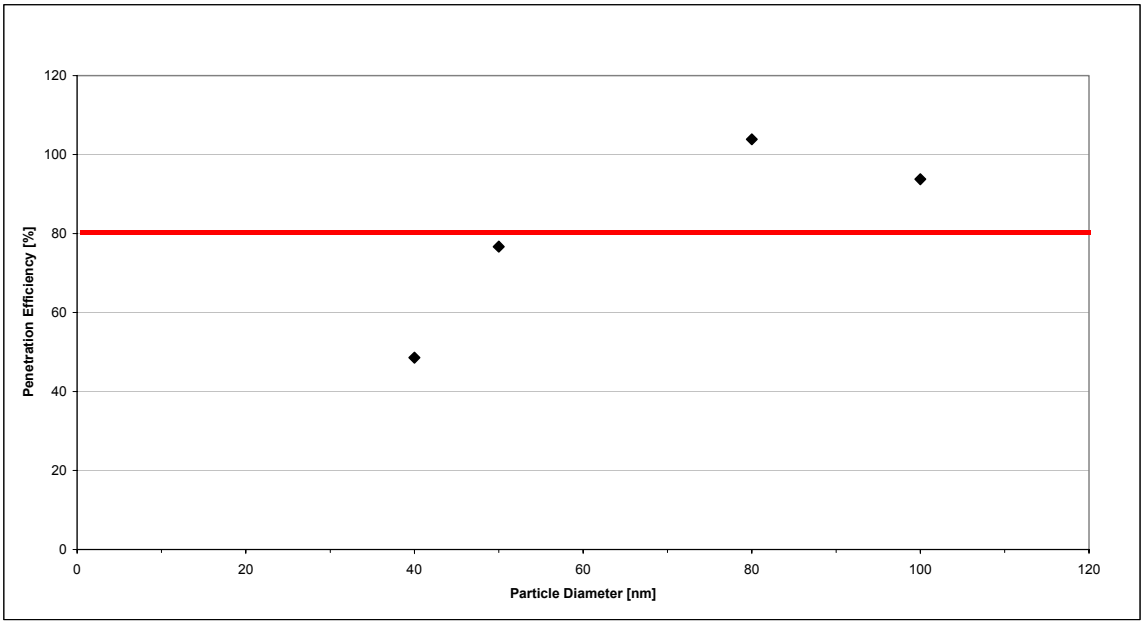


Figure 43: Penetration of monodisperse solid sodium chloride particles – February 2006

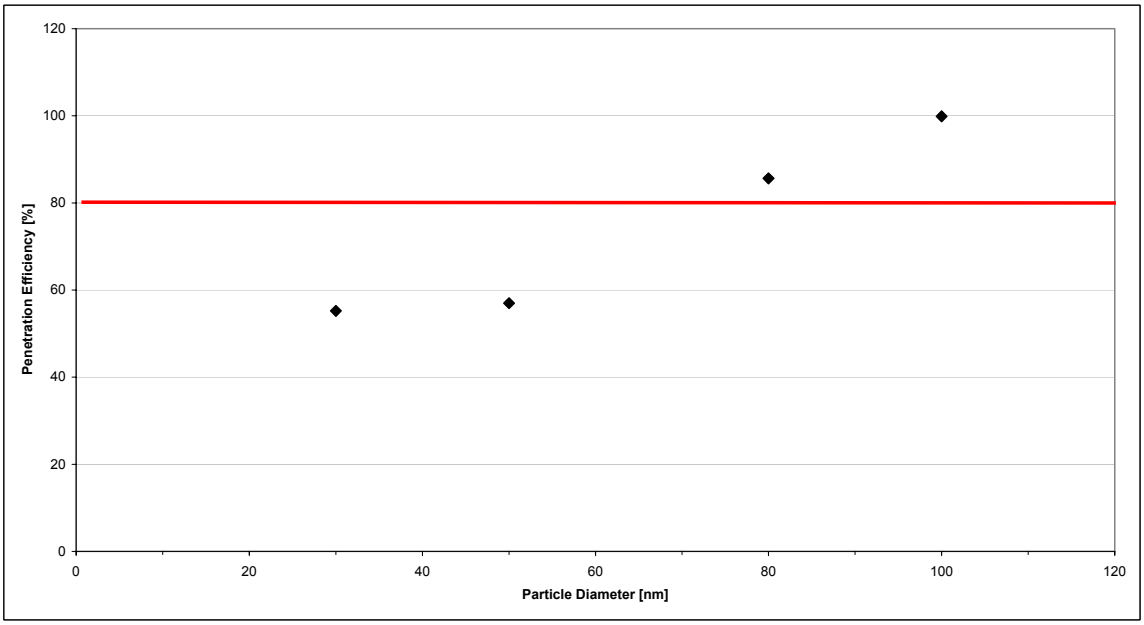


Figure 44: Penetration of monodisperse solid sodium chloride particles – January 2007

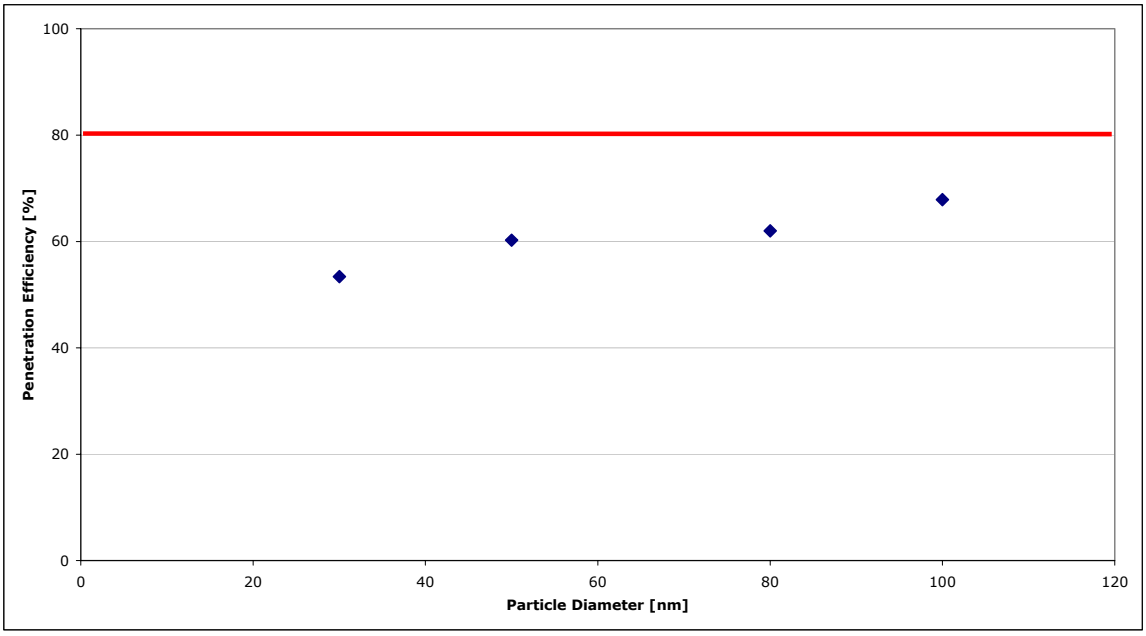


Table 11: Penetration Efficiencies of the VPR for all calibrations.

Particle Diameter [nm]	Penetration Efficiency [%]			
	January 2005	August 2005	February 2006	January 2007*
30	47.1	-	55.24	53.39
40	-	48.6	-	-
50	60.52, 50.57	76.7	57.02	60.24
80	84.53	103.9	85.67	62.00
90	91.52	-	-	-
100	89.52, 102.93	93.76	99.88	67.87

* January 2007 PE calculated using gas derived dilution factors rather than the particle derived dilution factors supplied by Matter Engineering.

Volatile Particle Calibration

The VPR was calibrated in terms of volatile particle removal efficiency. The redrafted regulation R83 [3] (Section 2.3.3) requires greater than 99% reduction of 30nm C40 (tetracontane) particles, with an upstream/inlet concentration of 10,000 particles cm^{-3}.

Experimental Set-up

Using the condensation aerosol generator tetracontane flakes were heated to produce polydisperse volatile particles. These particles were passed through an electrostatic classifier to produce monodisperse particles of 30nm diameter. Using the AEA CPC number concentrations were measured at the inlet of PND_1 and at the PNC_GOLD sampling location. The experimental set-up is described in Figure 40, the same sampling system is used for both volatile and solid particle calibrations, only the aerosol is changed in the condensation generator.

Results

The number concentrations measured at the inlet (upstream) and outlet (downstream) of the VPR for all four calibrations are summarised in Table 12. Also shown in the last row of this table is the maximum allowable downstream concentration, this is 1% of the inlet concentration, showing the maximum allowable number concentration of volatile particles at the outlet of the VPR if it is to meet the requirements of the redrafted regulation R83 [3] (Section 2.3.3).

5.4.3 Calibration of the CPC (according to 8.5.1 [7])

PNC_GOLD was calibrated according to the method described in the AEA document 'Condensation Particle Counter Calibration Procedures'.

Table 12: Number concentrations of volatile particle at the inlet and outlet of the VPR.

Sampling location	Number Concentration (particles cm^{-3})			
	January 2005	August 2005	February 2006	January 2007
Upstream (PND_1 inlet)	23,942.91	13,043.99	22,879.89	35,485.40
Downstream of VPR (PNC_GOLD position)	0.13	1.18	0.33	0.07
Maximum allowable downstream concentration (1% of upstream)	239.41	130.44	228.80	354.85

Experimental Set-up

Solid polydisperse sodium chloride particles were produced by the condensation generator and sampled using an electrostatic classifier. The PNC_GOLD and AEA reference CPC sampled direct from the electrostatic classifier and the diameter of monodisperse particles was increased from around 50 to 120nm to produce a range of number concentrations between 1 and 10,000 particles cm^{-3}.
The experimental set-up is described in Figure 45. Before the CPC calibration commenced the CPCs were checked for the following:

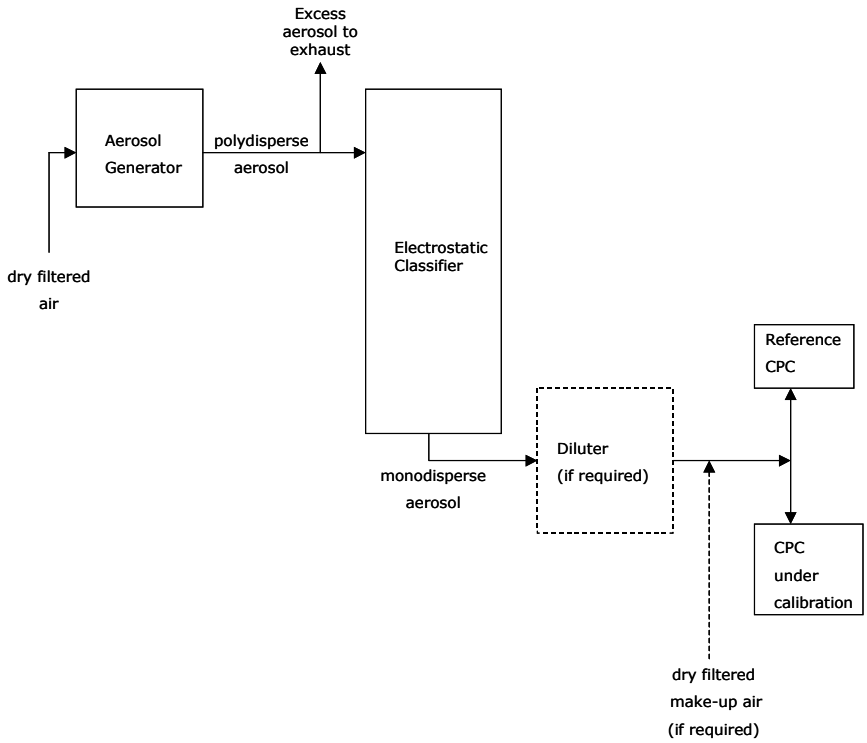
a) flow rate at the inlet of the CPCs, measured using a bubble flow meter
b) zero check on the CPCs (using a HEPA filter) and a
c) span check on the CPCs (measuring lab air).

These three checks were performed to verify that the CPCs had not been adversely affected during transport to the AEA laboratory. Calibration of the CPC did not commence until a satisfactory result was produced from these checks.
The CPC measurements were recorded simultaneously and the number concentrations were compared to produce a linearity graph.

Results

The resulting data from the calibration was analysed in terms of the correlation between the reported concentrations from both CPCs, with the AEA reference CPC on the x axis and the PNC_GOLD on the y axis, to establish the gradient and the linearity (R^2 coefficient).

Figure 45: Schematic diagram of set-up for calibration of PNC_GOLD



The linearity of response in terms of the R^2 coefficient must be greater than 0.98, else the CPC under calibration (PNC_GOLD) does not respond linearly over the measured concentration range. The gradient of the calibration plot must be within the range from 0.95 to 1.05 (unity signifies complete agreement between the two CPCs).
Figure 46-Figure 49 show the linearity of PNC_GOLD from the four calibrations. The gradient (for each graph the y=mx and m is the gradient) and R2 coefficient is shown on each graph.

Figure 46: Linearity of PNC_GOLD – January 2005

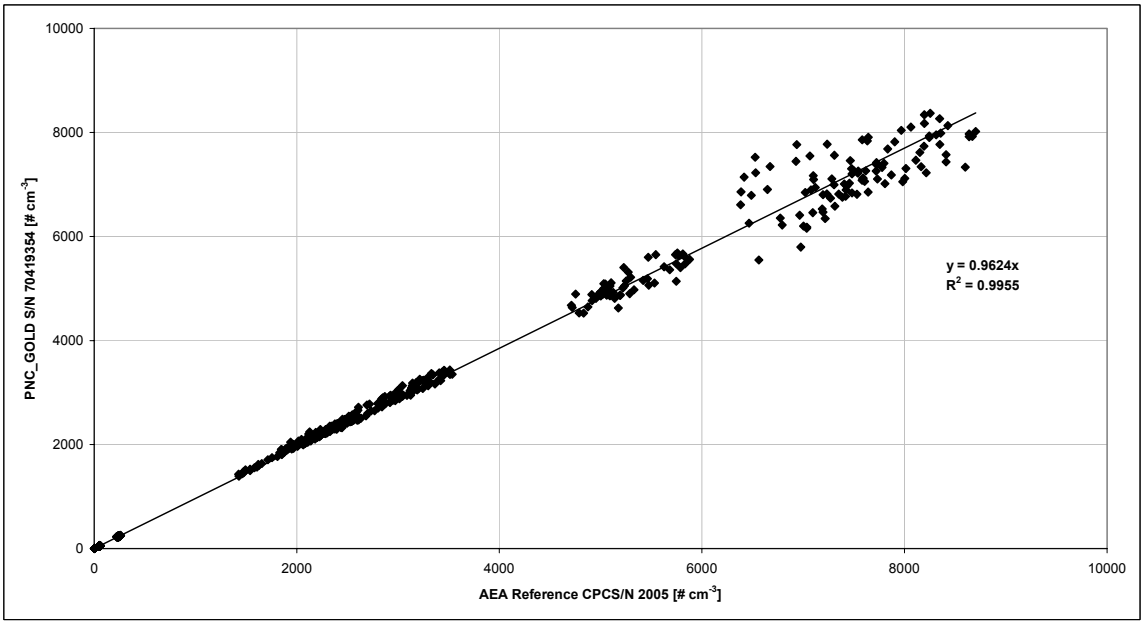


Figure 47: Linearity of PNC_GOLD – August 2005

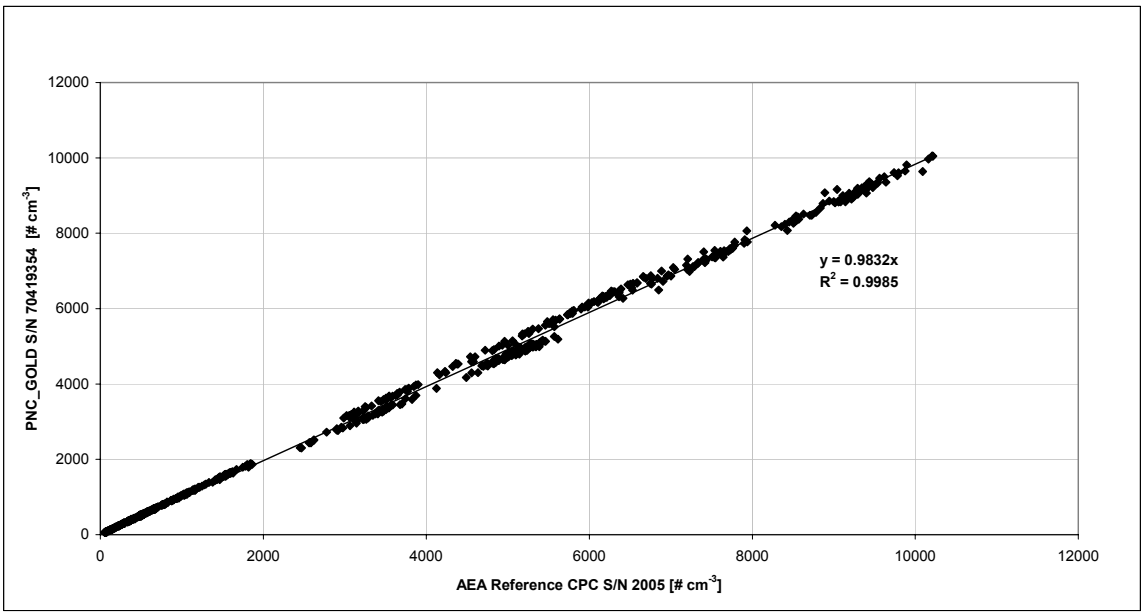


Figure 48: Linearity of PNC_GOLD – February 2006

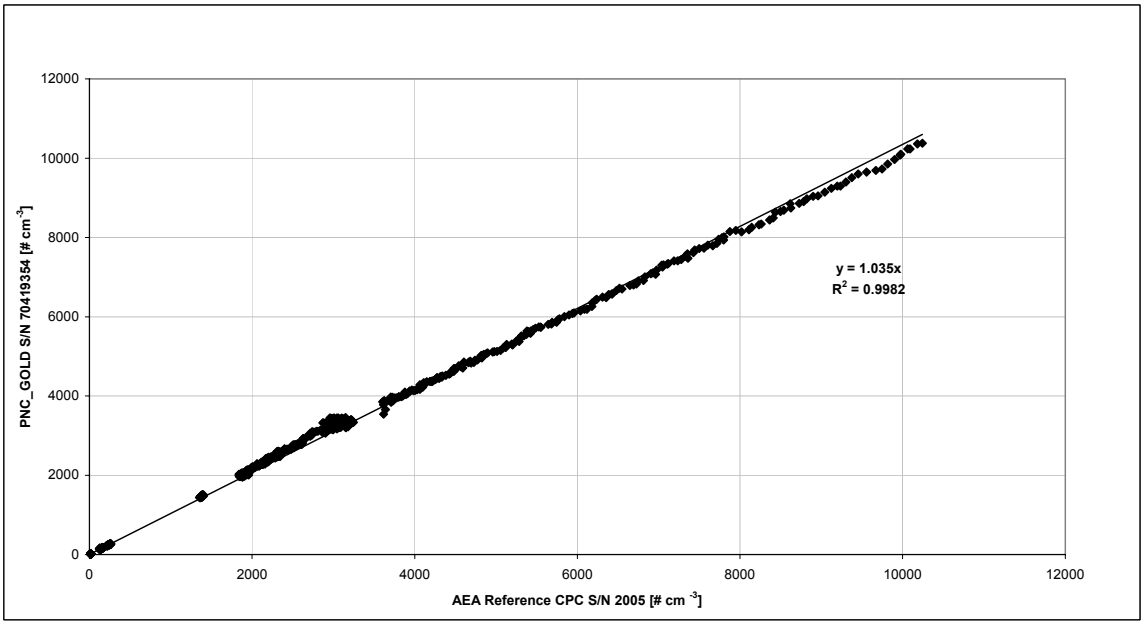
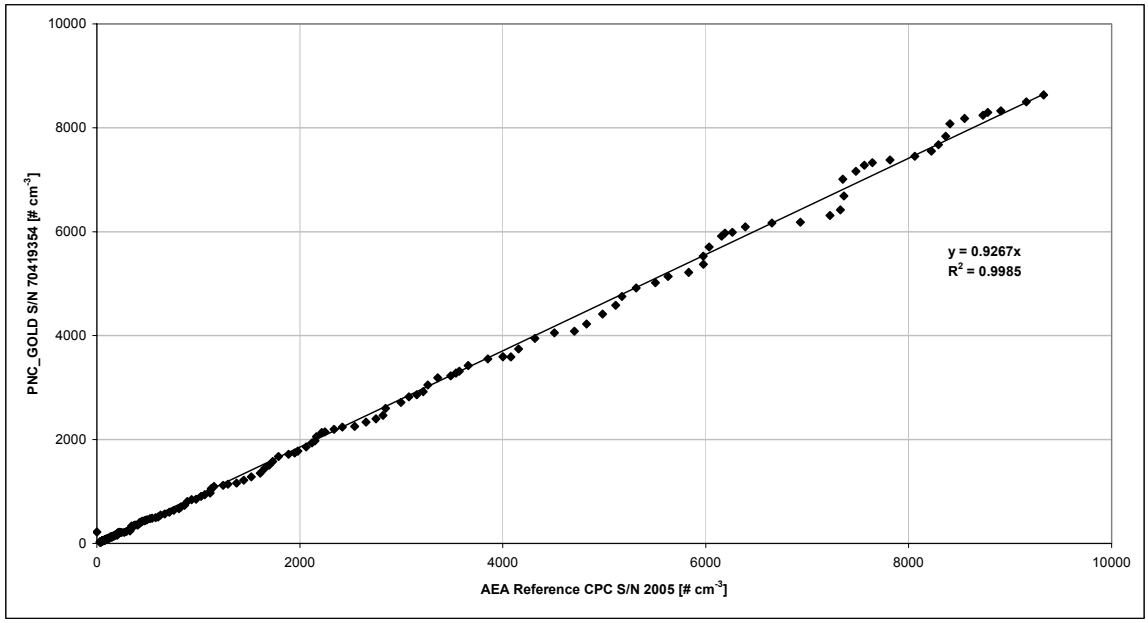


Figure 49: Linearity of PNC_GOLD – January 2007



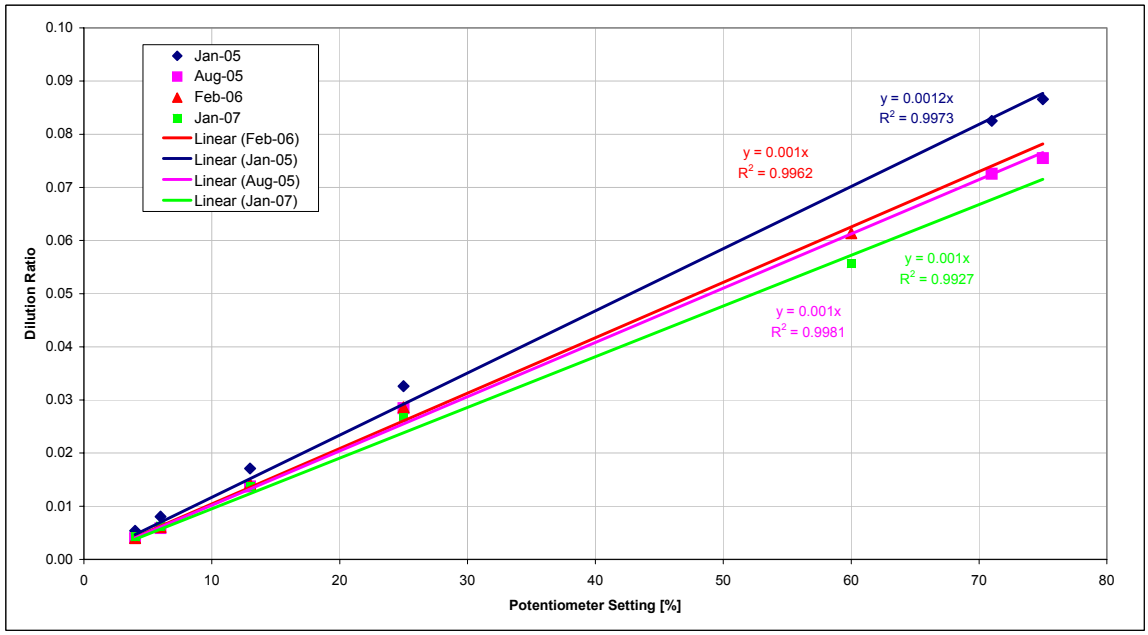
5.4.4 Summary

For each type of calibration performed during the ILCE we have summarised the key findings, comparing the results to the specifications detailed in the UNECE_GRPE PMP Phase 3 Inter-Laboratory Correlation Exercise: Framework and Laboratory Guide [7] and analysing any effects over time.

Calibration of the diluters

Figure 50 summarises the four sets of gas calibrations and illustrates the repeatability of the performance of the diluter throughout the ILCE.

Figure 50: Summary of gas calibration dilution ratios over all four calibrations.



The measured dilution ratios were just outside +/- 10% of the nominal dilution ratios (as specified in the UN-GRPE PMP Phase 3 Inter-laboratory Correlation Exercise: Framework and Laboratory Guide [7]) but this is to be expected due to the difference in calibration methods between Matter Engineering (particles) and AEA (gas).

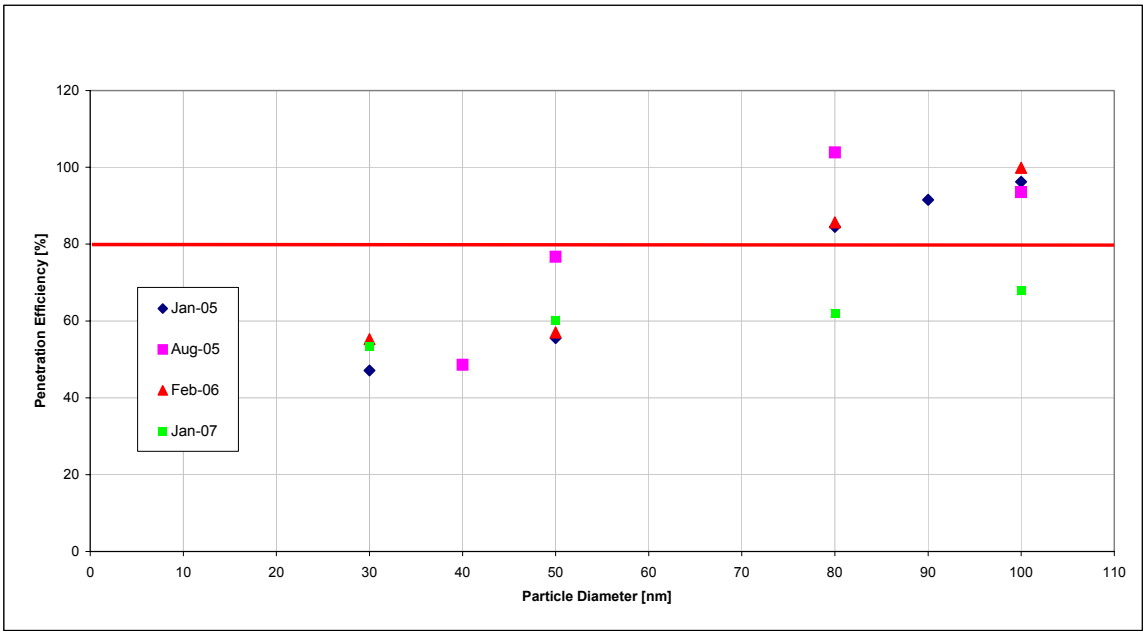
Calibration of the Volatile Particle Remover
The VPR was calibrated using two types of particles, solid and volatile, the results of which have been summarised separately.

Solid Particle Calibration
The penetration efficiencies (PE) measured during the four calibrations are reasonably consistent throughout the programme.

All VPR calibrations with solid particles show that particles below 50nm in diameter fail the 80% PE criteria (Table 11, Figure 51). This implies that particle losses of small particles (<50nm diameter) are occurring within the VPR.

The method for calculating the PE of the VPR may be performed in a number of ways depending on which set of dilution factors are used. In the results shown in Figure 51 the dilution factors for PND_1 supplied by Matter Engineering from their particle calibration work at 91nm, using the diluter heated to 80°C and using the 3 metre sampling hose were used. However in the ILCE the diluter was heated to 150°C and the 1 metre sampling hose was used, therefore it may be considered more appropriate for the PE to be calculated using the AEA gas derived dilution factors. These would represent 100% PE, and is more realistic than using the particle derived dilution factors from Matter Engineering as these will include a particle loss component. Using the gas derived dilution factors increases our confidence in the PE calculations.

Figure 51: Summary of penetration efficiency for all four calibrations



The PE data has been re-analysed using the dilution factors measured by AEA during each gas calibration. This ensures that the particle concentrations are compared with the expected concentration using a dilution factor that does not include any particle losses. This method assumes 100% of the particles entering the diluter are diluted by a known amount (using the gas dilution factor) and no particle losses occur.

Figure 52 and Table 13 show the PE measurements during the four calibrations, adjusted using the AEA gas derived dilution factors. This has not altered the general trend observed previously, whereby particle diameters of less than 50nm do not meet the requirement of 80% PE but it does reduce the overall PE values.

Further experimental work to understand and verify the particle losses within the VPR is currently being performed by AEA for the Department for Transport, using three types of aerosol at monodisperse diameters, solid sodium chloride particles, soot particles generated by a CAST (combustion aerosol standard) and exhaust from a light duty Euro 3 passenger vehicle.

Figure 52: Re-analysed penetration efficiencies, using the AEA gas dilution derived dilution factors

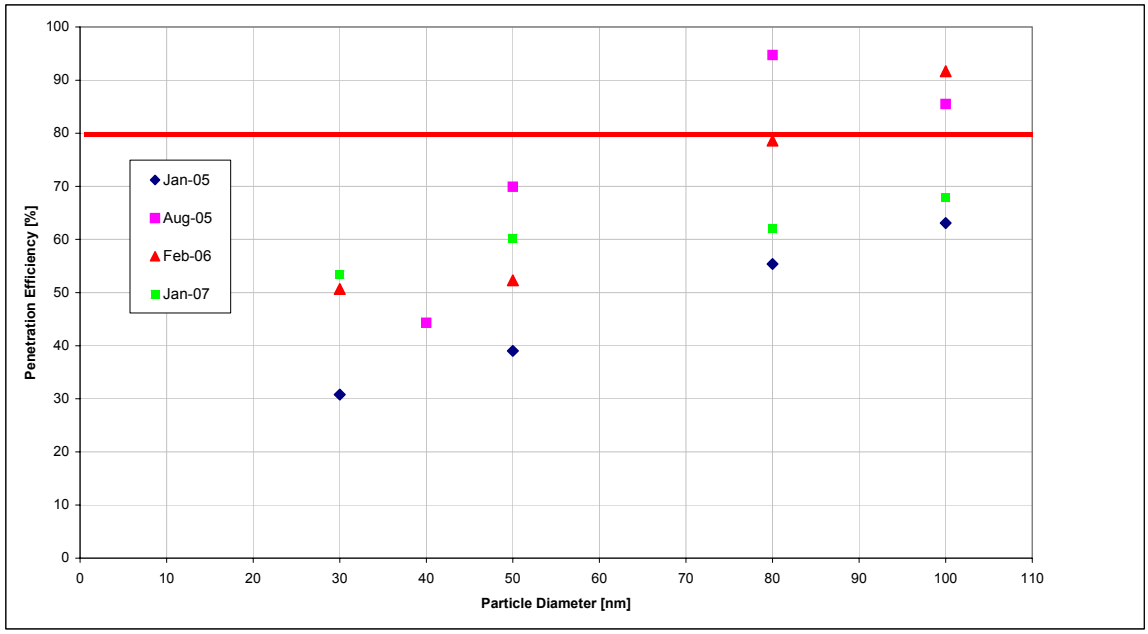


Table 13: Penetration Efficiencies of the VPR for all calibrations

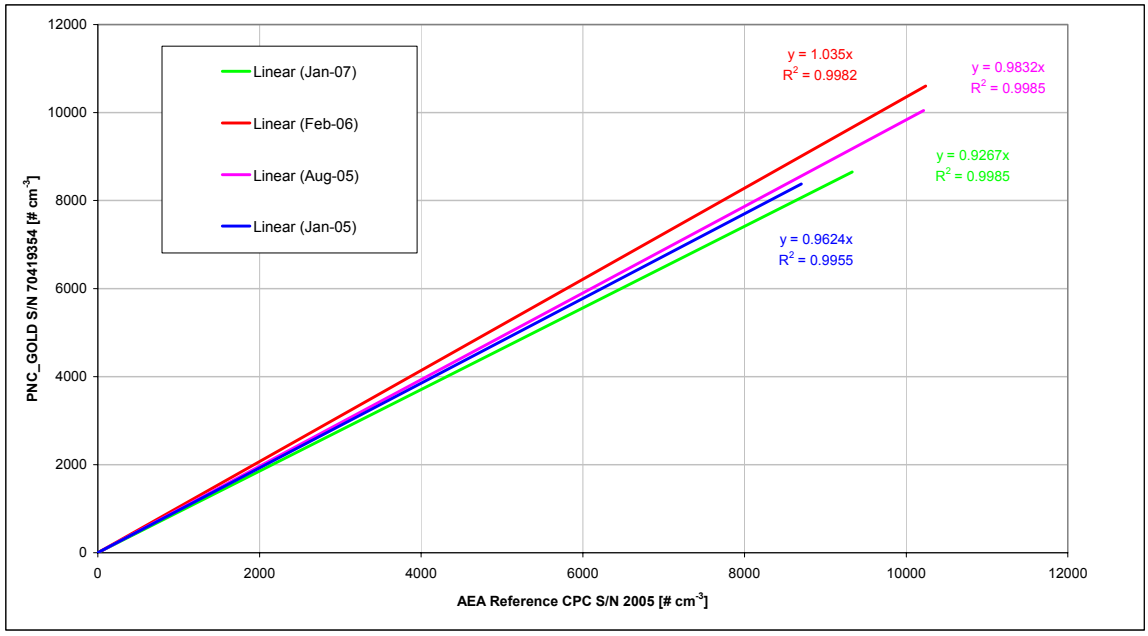
Particle Diameter [nm]	Penetration Efficiency [%]			
	January 2005	August 2005	February 2006	January 2007
30	30.80	-	50.70	53.39
40	-	44.31	-	-
50	39.02	69.99	52.33	60.24
80	55.38	94.71	78.62	62.00
100	63.09	85.48	91.66	67.87

Volatile Particle Calibration
All calibrations exceeded the requirement of >99% volatile particle removal efficiency. The VPR met this requirement with ease.

Calibration of the CPC
Three calibrations met the requirements for the R^2 coefficient (must be greater than 0.98) and the requirement that the gradient of the calibration plot must be within the range from 0.95 to 1.05. The January 2007 CPC calibration met the R^2 requirement but did not meet the requirement for the gradient to be within this range, with a value of 0.9267. Note: soon after the calibration of the CPC a serious fault occurred within the CPC, this may be the cause of the deterioration in the gradient of the linearity measurement.

The linearity of the CPCs throughout the four calibrations confirms that the performance of the PNC_GOLD was stable throughout the ILCE (Figure 53).

Figure 53: Comparison of CPC linearity over all four calibrations



5.5 GPMS Validation

In order to ensure that operation of the GPMS was consistent with the baseline calibration of the measurement system and that repeatable and valid operation could be demonstrated, regular validation exercises were performed.
The following sections illustrate results of validation exercises undertaken at Lab#3 during the ILCE_LD. These can be considered broadly representative of results acquired at all participating laboratories.
Data shown illustrate checks taken before the first test on each day, between tests on each of 3 test vehicles and at the end of each test day.

5.5.1 PNC Flow Stability

The LD_ILG states that PNC_GOLD shall report a measured flow within +/- 5% of the calibrated PNC flow. As Figure 54 and Figure 55 shows for PNC_GOLD and PNC_REF respectively, this requirement was met easily by the two TSI 3010D CPCs.

Figure 54: PNC_GOLD Flow Stability

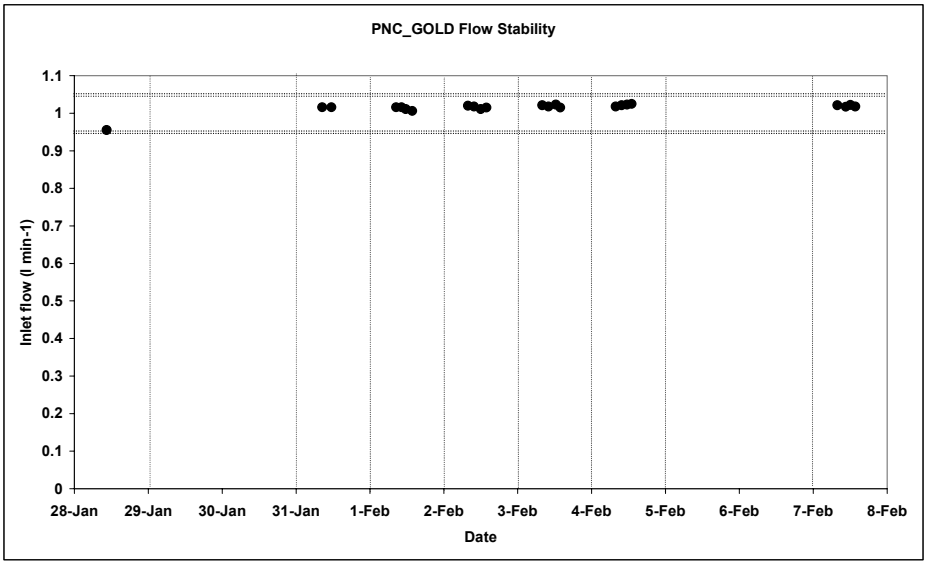
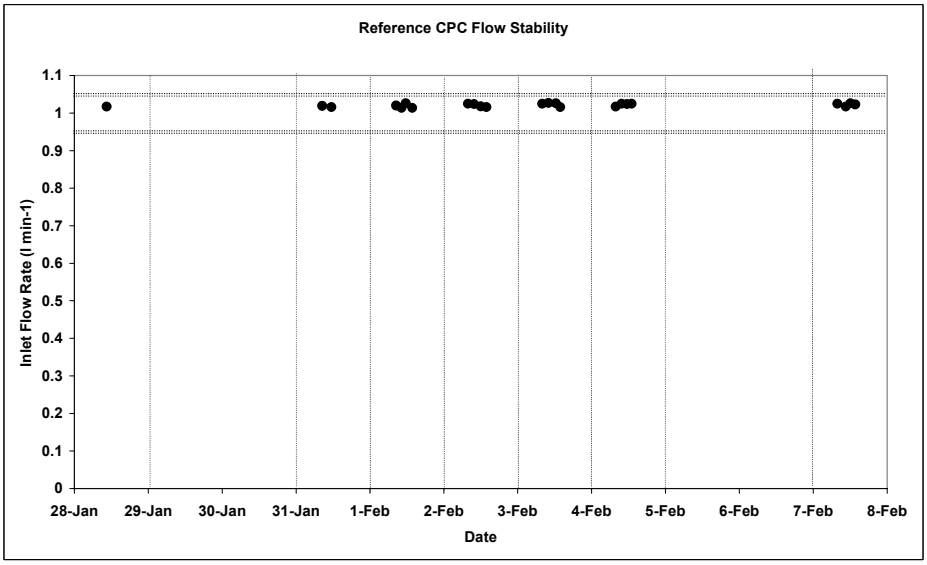


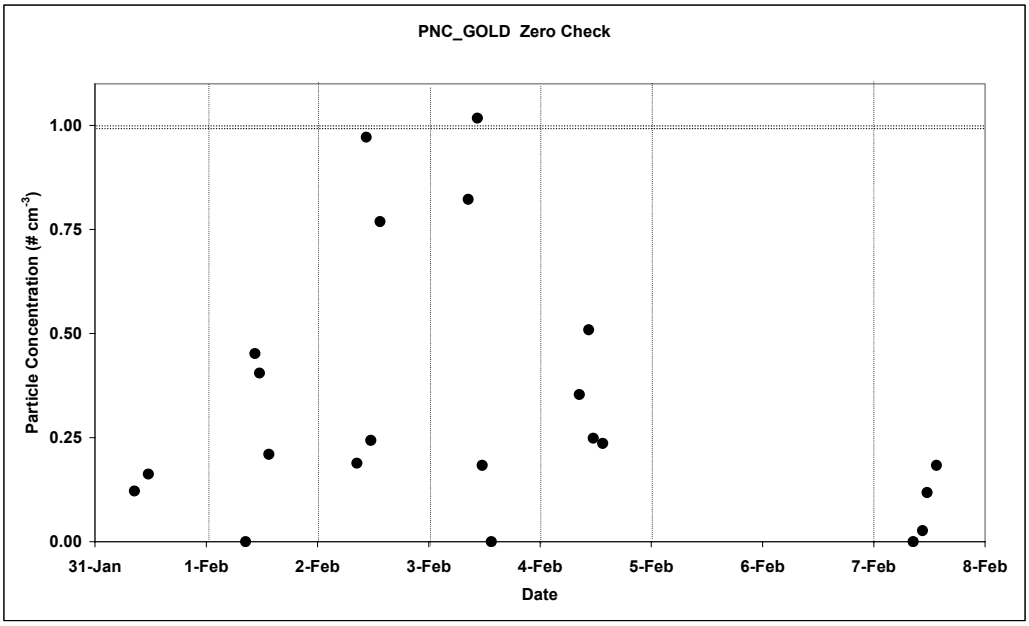
Figure 55: PNC_REF Flow Stability



5.5.2 PNC Zero Check

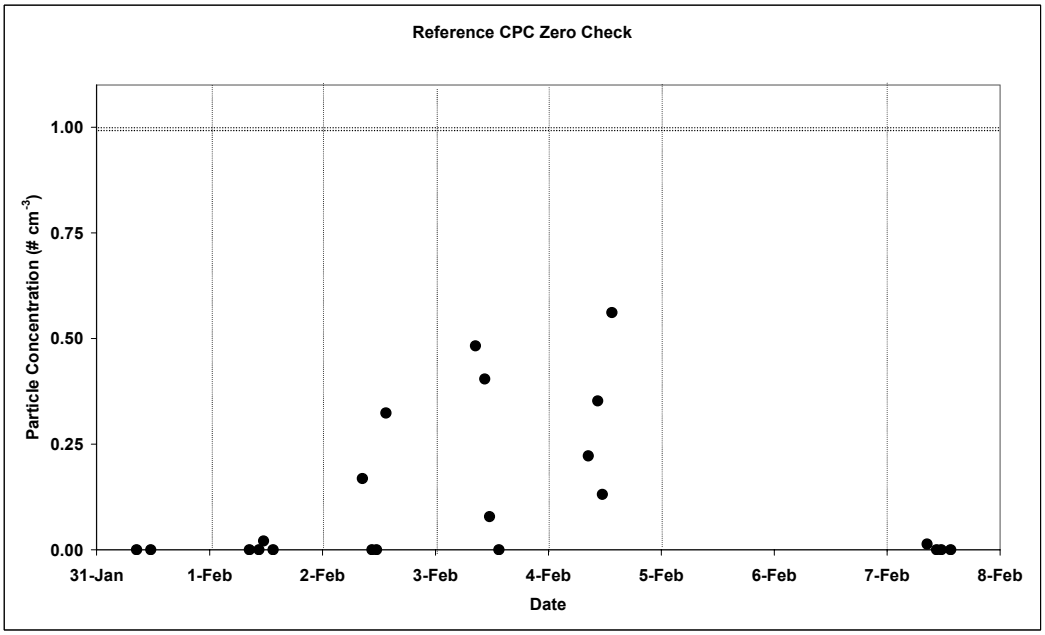
The requirement of the LD_ILG for the PNC zero check states that PNC_GOLD shall report a particle number concentration of 1cm^{-3} or less when sampling through a filter of HEPA specification.
With one marginal exception, PNC_GOLD comfortably achieved this (Figure 56) and PNC_REF always achieved this (Figure 57). The marginal failure (due to a loose connection) observed from PNC_GOLD was followed by three subsequent passes in that same day following rectification of the loose connection.

Figure 56: PNC_GOLD Zero Check



The reference CPC did not exceed the 1cm^{-3} permitted response at any time during the testing period.

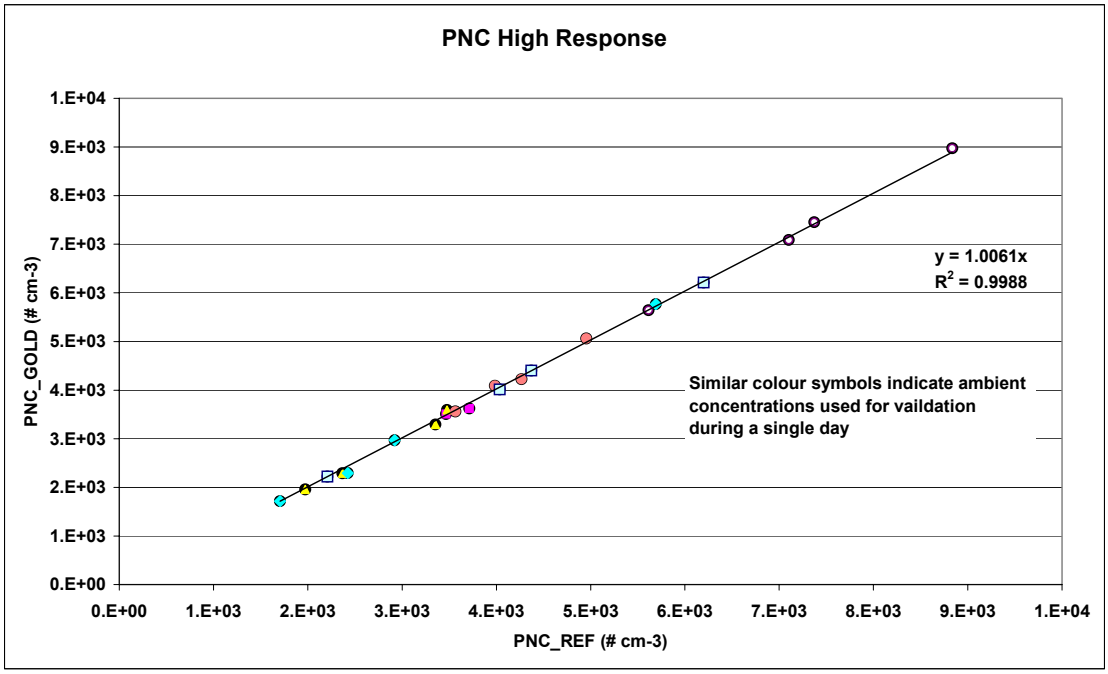
Figure 57: PNC_REF Zero Check



5.5.3 PNC High Response

The requirement of the high response check is to determine a valid response of the particle number counter at the opposite end of the linear measurement range to the zero check. At lab#3, the ambient aerosol source employed was consistently between ~1500 cm^{-3} and 9000 cm^{-3}: levels that were ideal for this check. A comparison with a simultaneous measurement from PNC_REF across several days' daily validation exercises quickly demonstrates the correlation between the two instruments and thus validates the high response of the instrument. This is illustrated in Figure 58.

Figure 58: PNC High Response



5.5.4 Leak Integrity Check

The leak integrity check ensures that the entire GPMS system shows no significant leakage of particles into the measurement system or shedding of entrained particles by sample tubing or the evaporation tube. This check is conducted by placing a HEPA filter in the sample flow upstream of PND_1, operating the measurement system as normal and acquiring data. The ILCE_LD and DR83 stipulate a maximum particle concentration in the measurement system of $5cm^{-3}$.

Figure 59 shows for PNC_GOLD that the maximum concentration observed during this test was ~2 cm^{-3}, with peak concentration observed at PNC_REF of ~1 cm^{-3} (Figure 60).

Figure 59: GPMS Leak Check – PNC_GOLD

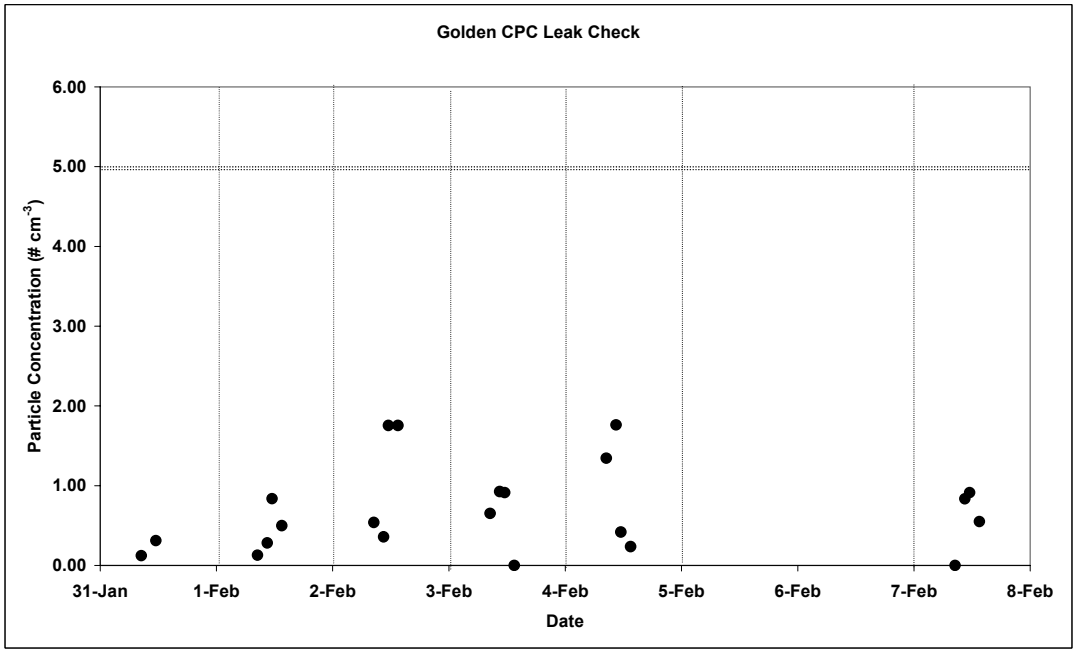
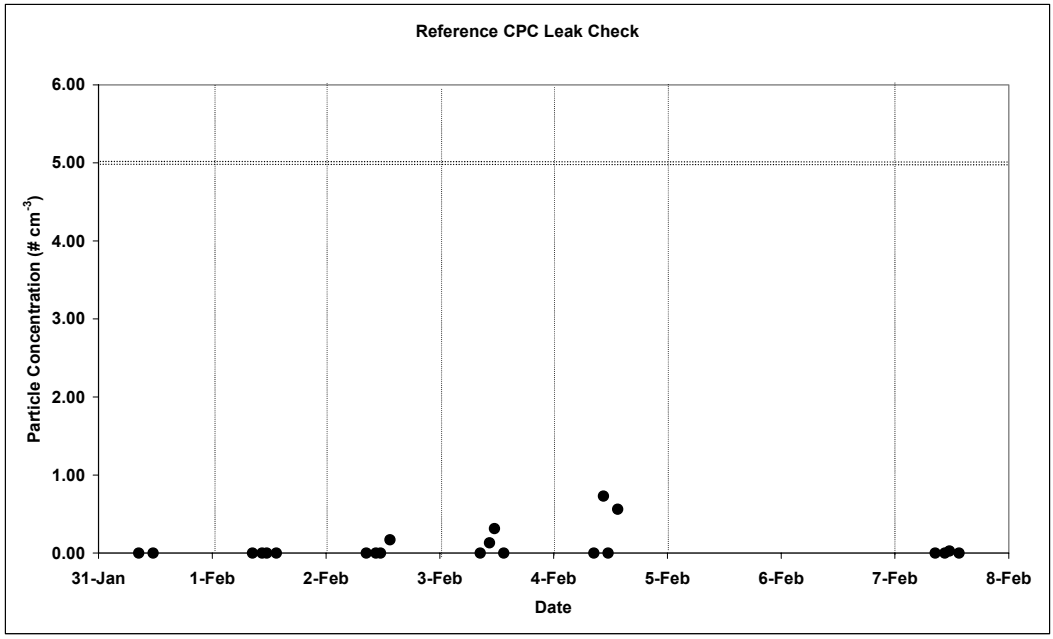


Figure 60: GPMS Leak Check – PNC_REF



The increase in particle numbers observed between the PNC_REF and PNC_GOLD occurs alongside a ~10 fold increase in dilution ratio. This suggests that a small particle contribution is present from the evaporation tube.

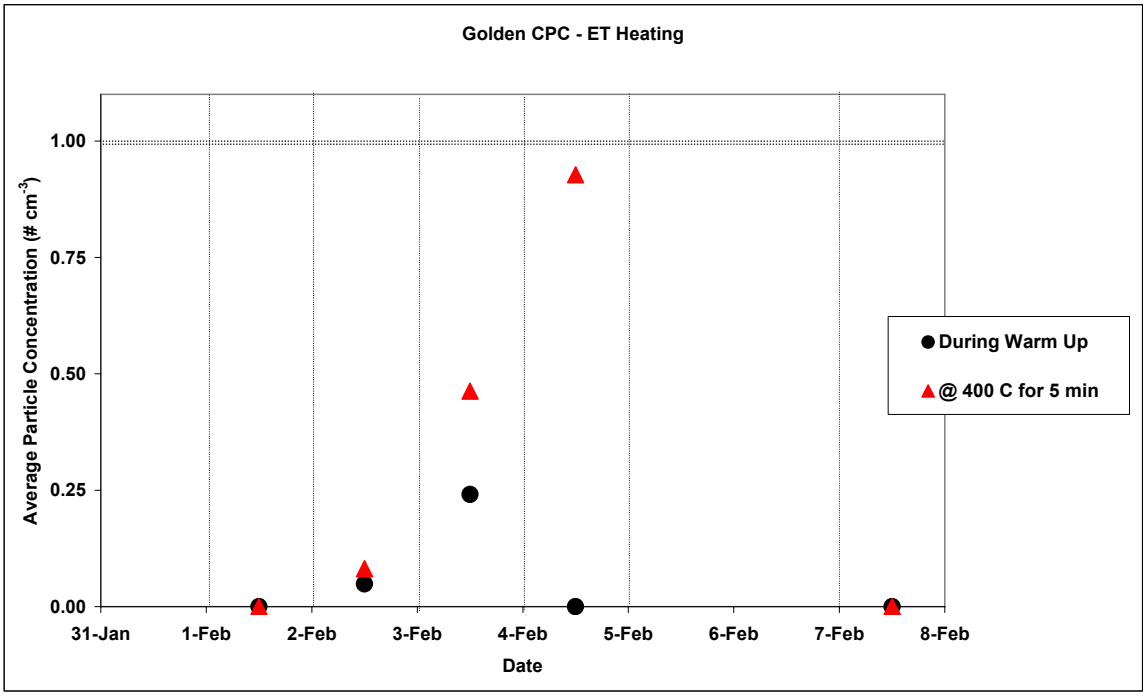
5.5.5 Particle Emissions from the ET

Particle number concentration levels were recorded from PNC_GOLD during the normal heating phase of the ET, when temperature is increased from ambient to the operational temperature of 300°C.
Measurements were also taken during a daily purge phase – when the ET was heated to 400°C in order to evaporate any low volatility materials that may have become deposited in the ET during the previous day's testing or during the cooling phase prior to shut-down.
Particle number levels (Figure 61) were higher from the purge phase than from the normal warm-up phase, but by less than $1cm^{-3}$: indicating that the contribution of particles from the ET (and thus deposition of materials in the ET during operation) was minimal.

5.5.6 Linearity Checks on the CPC

Linearity checks were not required each day, but these were undertaken daily at Lab#3. These compared PNC_GOLD with PNC_REF at several dilution ratios using ambient air as the source aerosol. An origin point was considered appropriate on the basis of the CPC zero checks and this was applied.
The required proof of linearity is an agreement between the two PNCs which shows an R^2 value greater than 0.95. To achieve this, the actual dilution ratios need not be known, but the sampling of particle numbers from the PNCs must be taken simultaneously, from the same source and with identical transport distances. However, a spread of nominal dilution ratios covering a factor of at least 20 was employed. This also included an undiluted comparison between the CPCs, which is the high point on the graphs in Figure 63.

Figure 61: Particle Emissions from the ET



The individual R^2 values obtained on each day were never lower than 0.9999 (Figure 63), demonstrating the high degree of similarity and stability of the two PNCs.
On a daily basis, the relationship between the two PNCs varied slightly: from *y=0.976x* (31st January) to *y=1.0217x* (3rd February). However, as Figure 63 shows, when all the linearity data across the test programme duration are taken as a single set, the correlation is still very strong (R^2 value =0.9997) and close to unity. These data indicate that a daily linearity check is unnecessary, and a weekly or monthly check of a test PNC against a reference PNC may be more appropriate.

Figure 62: All Linearity Check Data

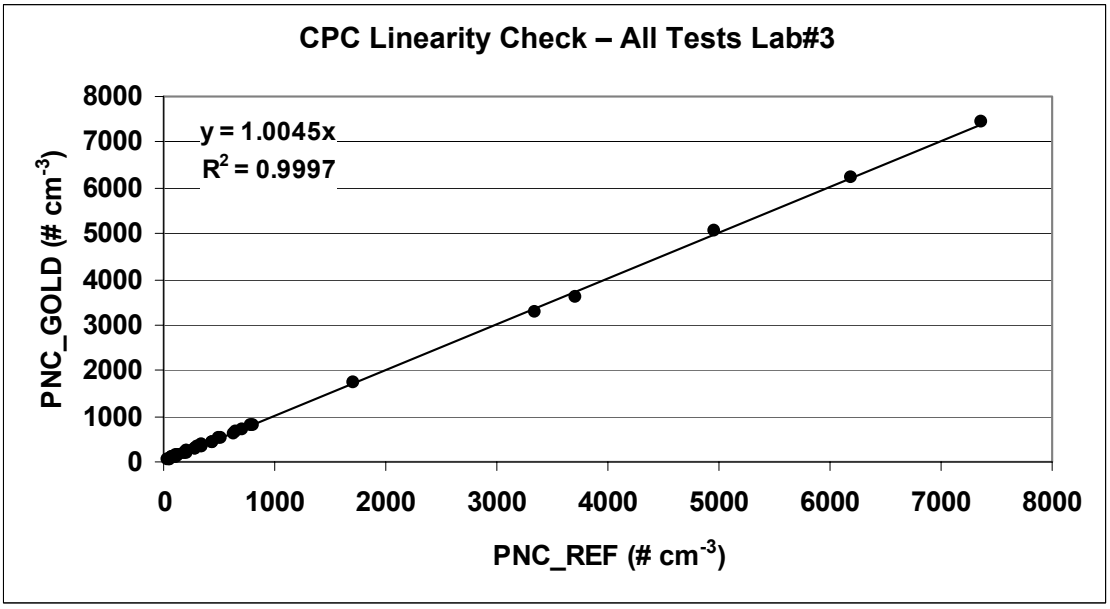
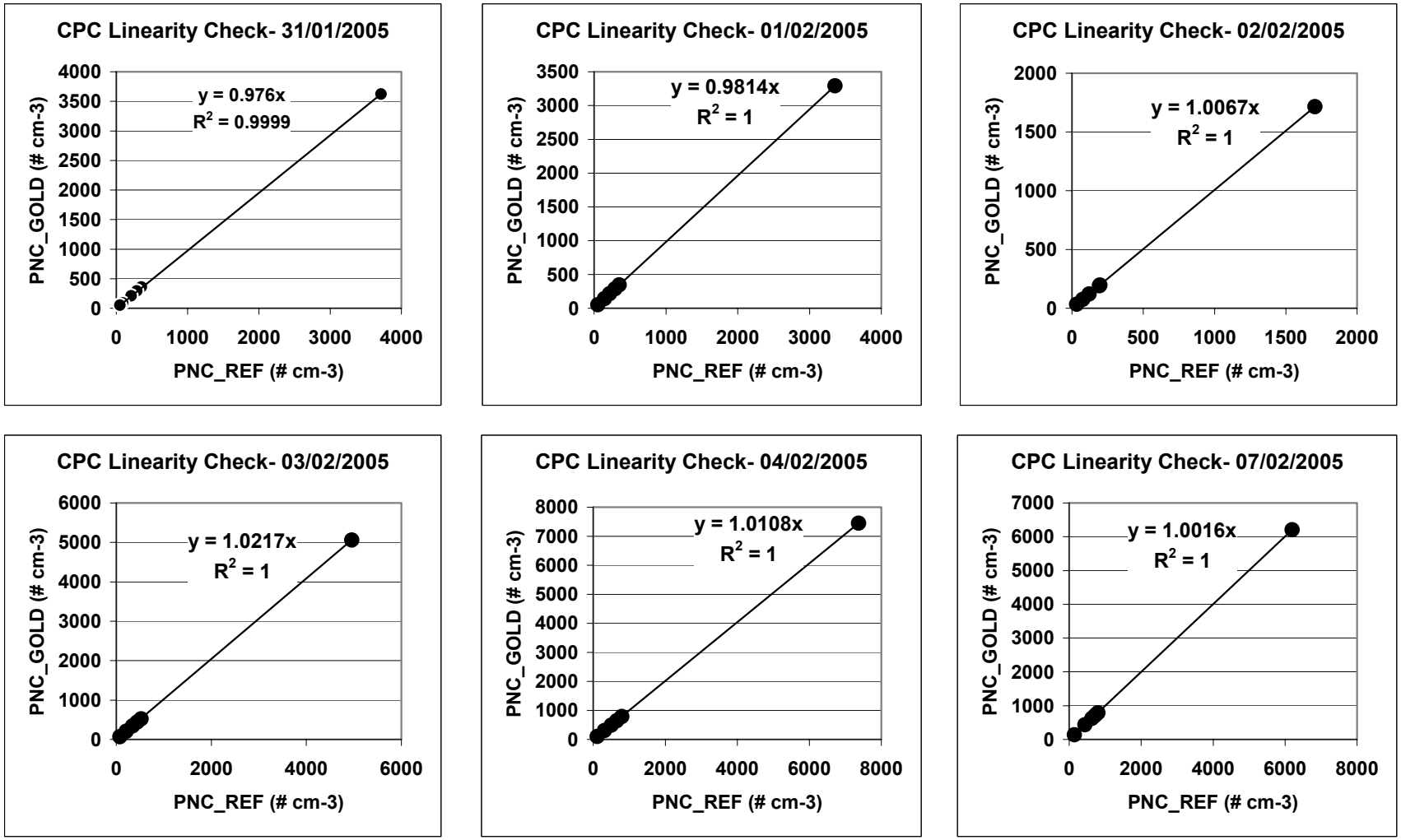


Figure 63: Daily Linearity Checks – Comparisons of PNC_REF and PNC_GOLD



5.6 Effects of GPMS Components – Real Time Data

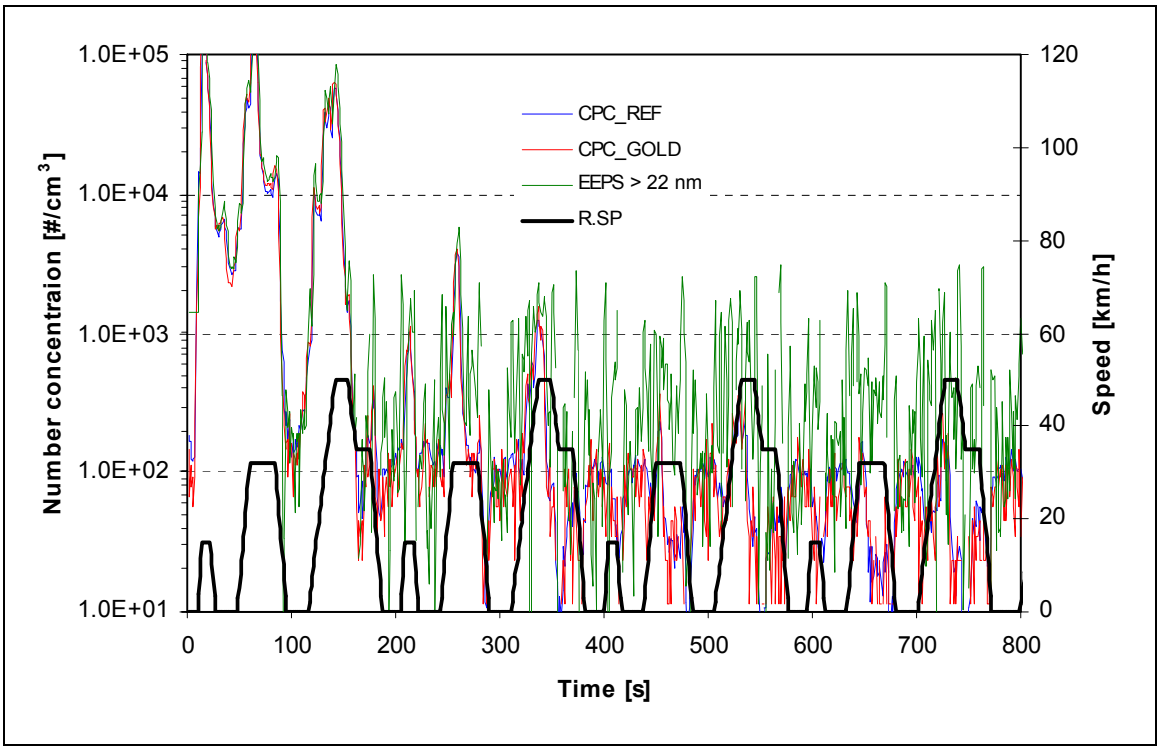
During Golden Vehicle testing at Lab#1, comparative data were acquired from PNC_REF, PNC_GOLD and from an engine exhaust particle sizer (EEPS) sampling directly from the CVS.

The EEPS determines real-time (<1Hz) size distributions of all particles – both solid and volatile - in the range 5nm to 500nm, and the data can be processed to give an integrated total that addresses a size range (>22nm) almost identical to that measured by PNC_REF and PNC_GOLD. In the following sections comparisons have been made between EEPS data restricted to this size range (EEPS) and data from PNC's REF and GOLD.

- Effects Of Hot Dilution And The Evaporation Tube

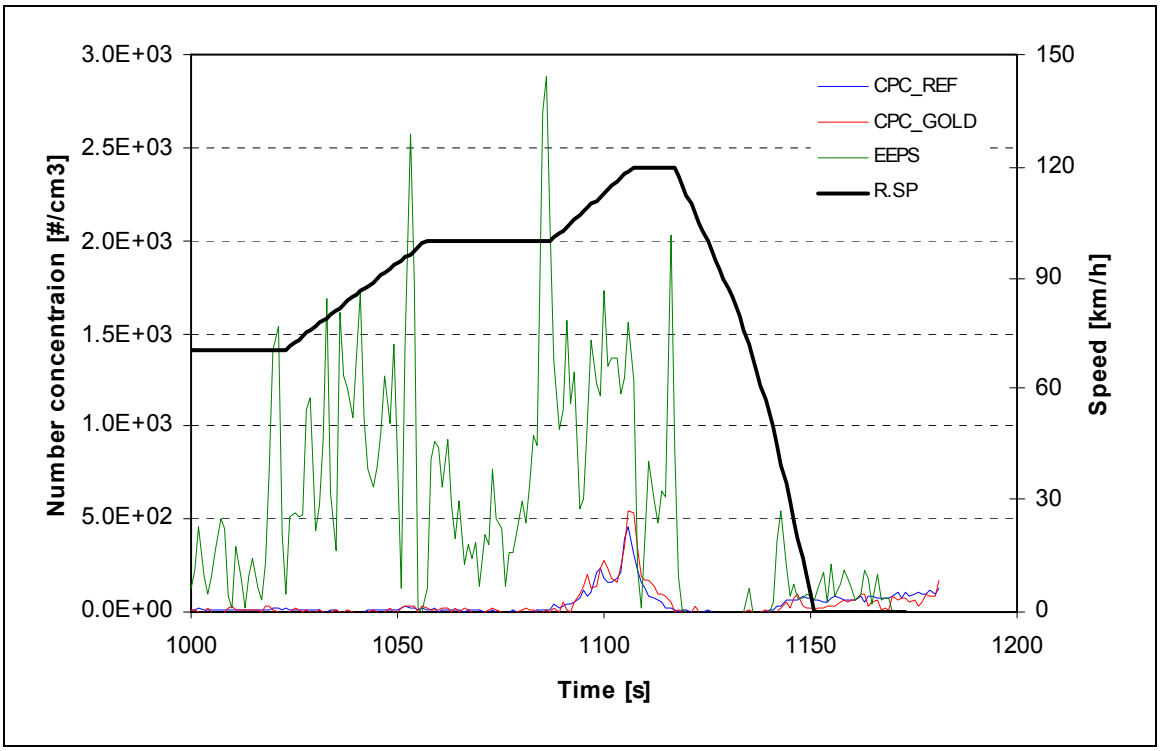
Figure 64 shows a comparison of particle number emissions from the EEPS across the urban phase of a standard cold-start NEDC test. From this test it is clear that EEPS, PNC_REF and PNC_GOLD data show very similar emissions levels over the initial 200s of the cycle. This demonstrates that in the CVS prior to entering the GPMS there are only solid particles present, and the requirement for the hot dilution (PND_1) and ET is minimal. However, later in the cycle particles are observed in the EEPS data that are not present at PNC_REF. These particles are volatile particles of >22nm in diameter that are removed by the hot dilution of PND_1.

Figure 64: Particle Number Emissions by PNCs and EEPS During ECE



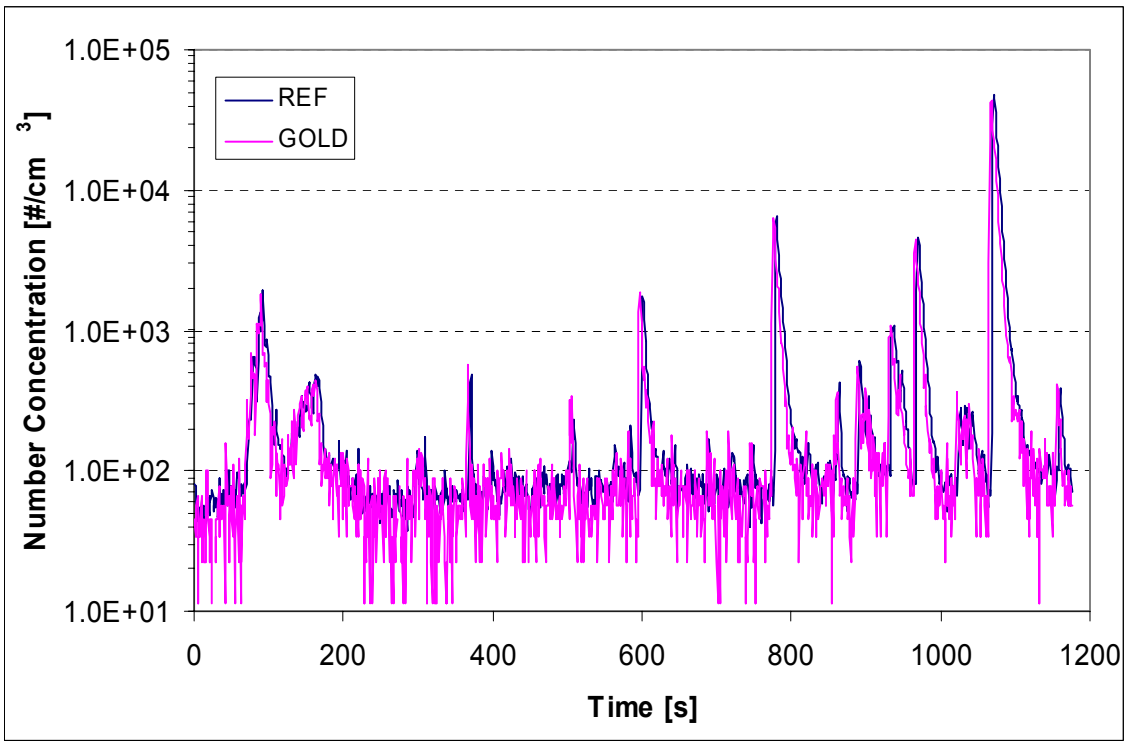
Data from the EUDC shows that volatile particles are also emitted at the end of the NEDC cycle (Figure 65) but after PND_1, only solid particles remain.

Figure 65: Particle Number Emissions by PNCs and EEPS During EUDC



Similarly, during a 120kph steady state (Figure 66) emissions levels from PNC_REF and PNC_GOLD are highly similar: no semi-volatile particles penetrate the initial hot dilution stage at this operating condition.

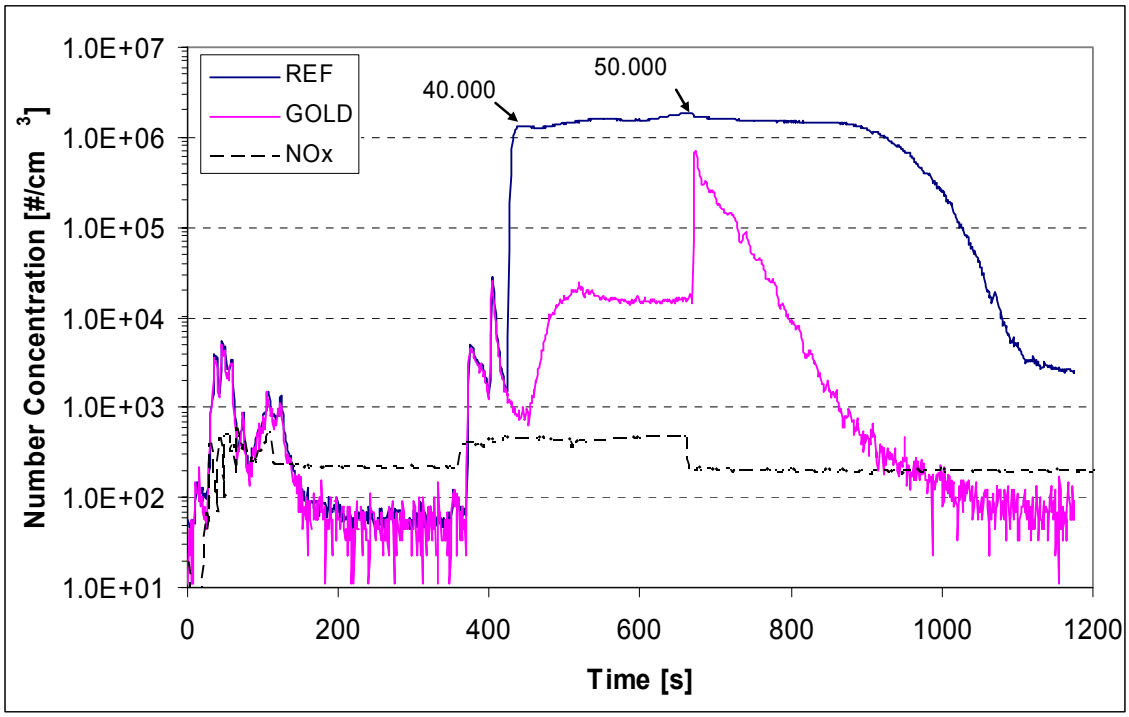
Figure 66: Particle Number Emissions by PNCs During 120kph Cruise



However, when an active regeneration is observed during a 120kph steady state (Figure 67), many volatile particles are observed and the ET is required. Of the particles that

penetrate PND_1, at least 99% are eliminated by the ET and can be considered semi-volatiles. A rapid increase in solid particle emissions occurs at the end of the regeneration (NOx emissions return to normal levels). In Figure 67 this occurred at ~670s. However particle number emissions remained elevated for more than 5 min.

Figure 67: Particle Number Emissions by PNCs During 120kph Regeneration



If regulatory procedures for particle numbers are to address regenerations, both hot dilution and an evaporation tube will be required. If an ET is required, the use of a secondary diluter (PND_2) at >10:1 dilution will also be essential – to reduce the temperature of the aerosol sample from ~300°C to <35°C prior to entering the PNC whilst avoiding thermophoretic losses.

- Effect Of 3010D Counting Efficiency

Volatile and <23nm particles are removed by the heating and size selective elements of the GPMS during NEDC tests.
During normal NEDC operation, as Figure 68 shows, EEPS particle numbers during the urban phase were relatively similar to the levels recorded by PNCs REF and GOLD irrespective of whether particles >6nm or particles >22nm were considered. This demonstrates that few <22nm particles are present.
During the EUDC, EEPS measured >22nm particle emissions were approximately twice PNC_REF levels and particles >6nm approximately 5 times PNC_REF levels: this suggests that volatile particles <22nm are released in response to the higher temperatures of this part of the NEDC.
The small and volatile particles observed from the NEDC are excluded from analysis by evaporation in PND_1 and the modified counting efficiency of PNC-GOLD can be considered unnecessary at this point.

Figure 68: Integrated Particle Numbers by PNCs and EEPS During NEDC

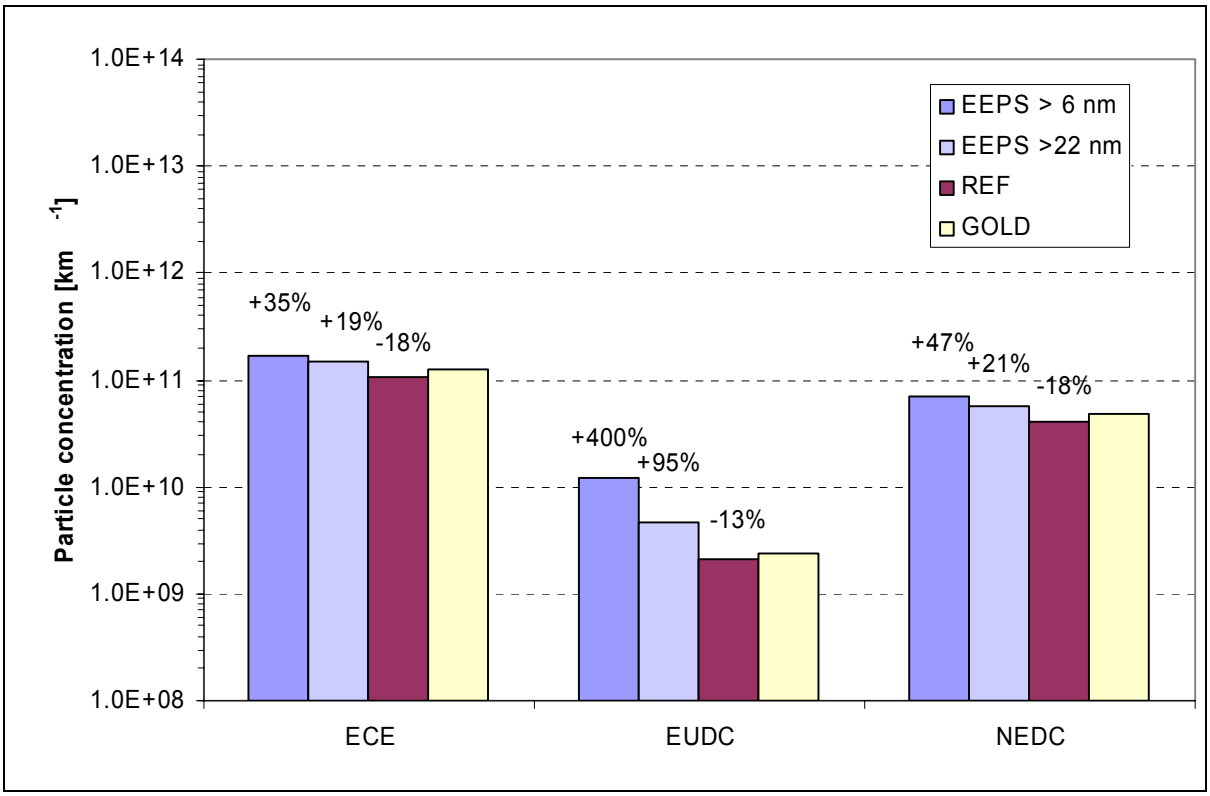
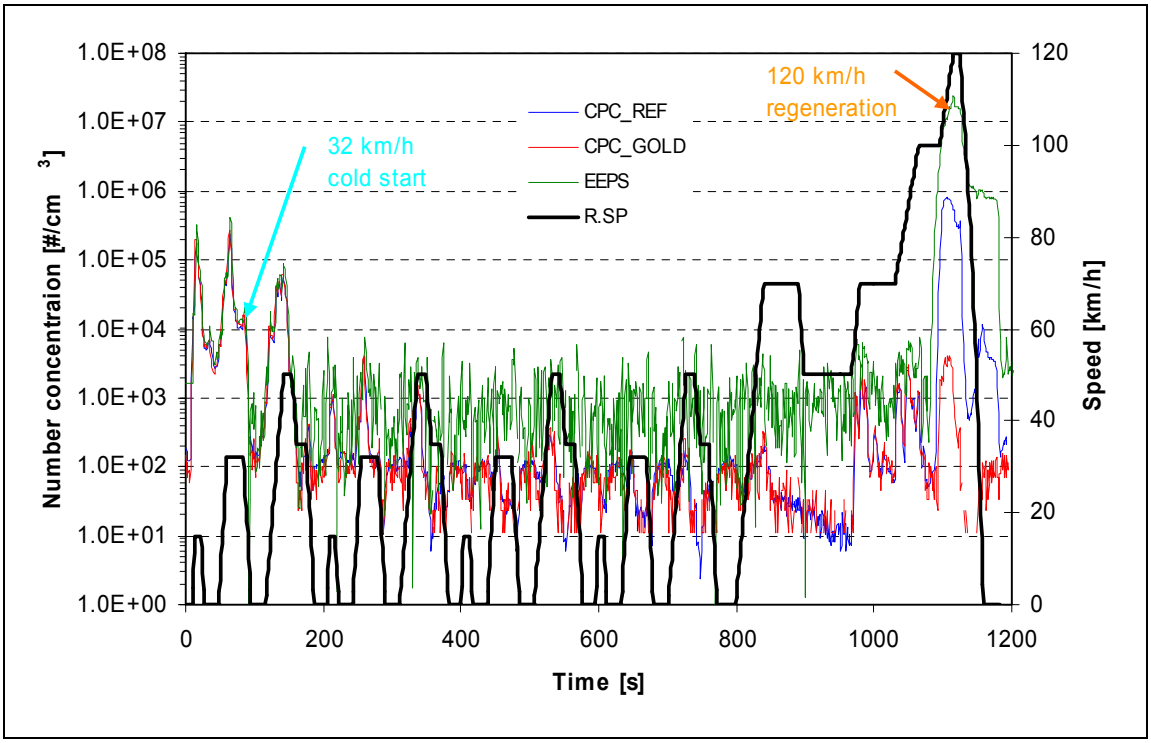


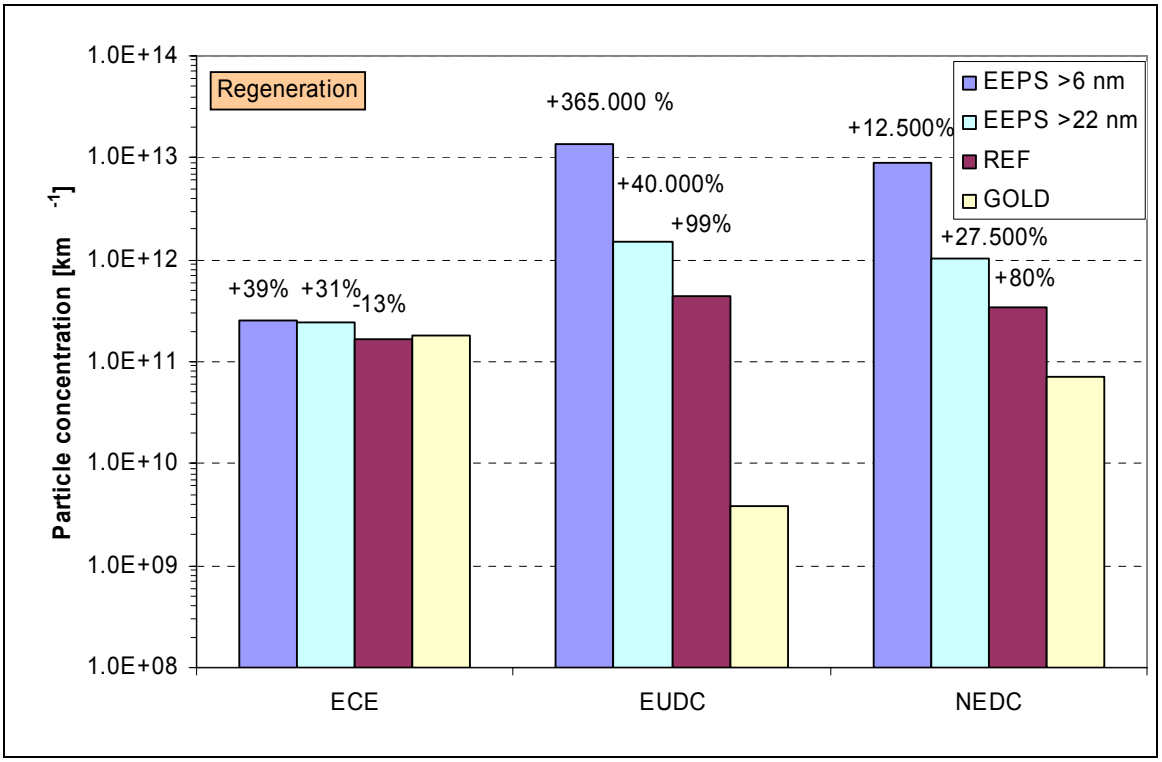
Figure 69: Particle Number Emissions, NEDC with EUDC Regeneration



However, when a regeneration is observed during the EUDC phase of an NEDC (Figure 69), elevated particle levels are seen in >6nm, >22nm EEPS data and also after PND_1 (Figure 70). In this case the very low volatility particles emitted in response to the high

temperature regeneration may be merely shrunk by passage through the ET, and it is wise to retain the modified PNC inlet characteristics to avoid counting these.

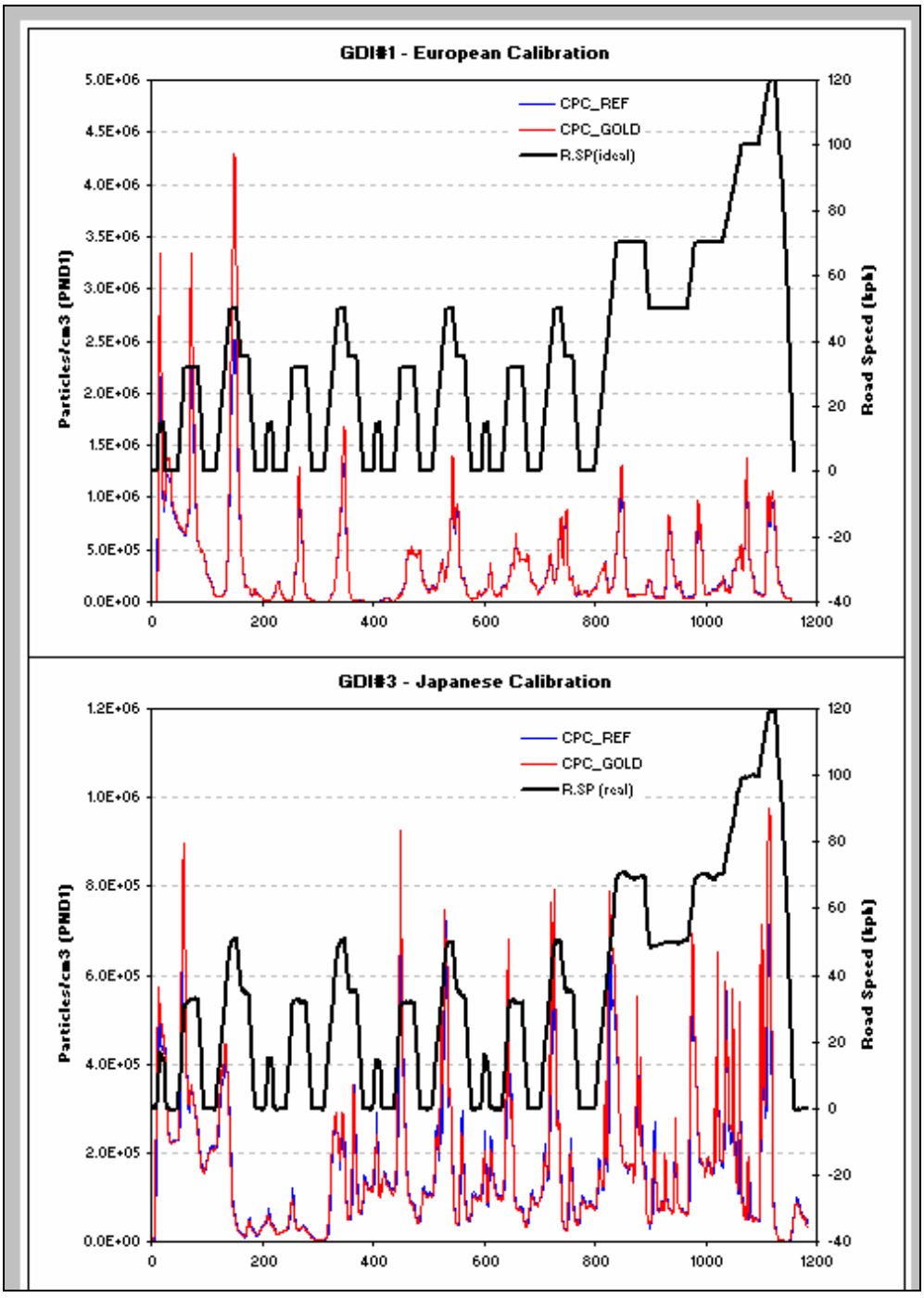
Figure 70: Integrated Particle Number Emissions, NEDC with EUDC Regeneration



- GPMS requirements for G-DI vehicles

During the ILCE_LD three G-DI vehicle types were tested. All produced particle number emissions substantially higher than those measured from the conventional gasoline and Golden Vehicles. From the real-time data collected during these tests, and as examples shown in Figure 71, neither European calibrated (G-DI#1) nor Japanese calibrated (G-DI#3) vehicles produced volatile particles that survived the initial hot dilution process in PND_1. On this basis, the ET and PND_2 would not be required for either of these vehicles. However, some G-DI vehicles may run homogeneous lean strategies which may lead to high exhaust temperatures (>600°C). Depending on duration, this kind of operation may lead to the release of low volatility species in a similar manner to that observed during active regeneration on Diesel vehicles. For this reason, it would be wise to retain the ET and PND_2 for G-DI vehicles.

Figure 71: Real-Time Particle Emissions G-DI Vehicles



5.6.1 Comparison With Alternative and Additional Systems

5.6.1.1 Golden Vehicle Testing

Particle number emissions from the Golden Vehicle were measured simultaneously from the GPMS, ALT_SYS and ADD_SYS. Figure 72 shows the correlation of GPMS with ALT and ADD systems for the average emissions over NEDC cycles for illustrative

purposes. Table 14 gives the results of the regression analysis between GPMS and ALT/ADD systems taking into account the second by second differences of the systems after they were synchronized. It can be considered that the slope indicates differences in the DR, particle losses, volatile particle efficiency removal and other minor influences. The intercept can be considered the offset and R^2 an indication of how close the systems correlate. Data generally indicate linear relationships and relatively close correlations between the GPMS results for NEDC cycles. However, as mentioned in chapter 3 this approach for method comparison should be considered as an indication of the relationship between the systems.

Alternative Systems

Data from all individual tests with ALT systems (Figure 72) sit relatively close to a diagonal line that represents the emissions from the GPMS. However, the best fit of data comes from the clone systems and the SPCS where R^2 values were typically >0.9 (Table 14). FPS based system results ranged from 0.8 to 0.9.

SPCS: SPCS data generally correlated very well with GPMS (Figure 73) (~96%).

FPS-based systems: As Table 14 shows, the FPS-based systems showed the greatest deviation from the GPMS results (27% to 47% lower). Typical real time concentrations of the FPS and the GPMS can be seen in Figure 74. It's not only the absolute value of DR that affects the differences but it seems that there is a smoothening of the particle emissions pattern with FPS. This could happen if the PNC used a high averaging time. One other explanation is the higher residence time inside the evaporation chamber (4 times higher than in the golden system). Other factors that might affect the FPS and golden system differences are:

Figure 72: Correlation Between GPMS and ALT_SYS, ADD_SYS

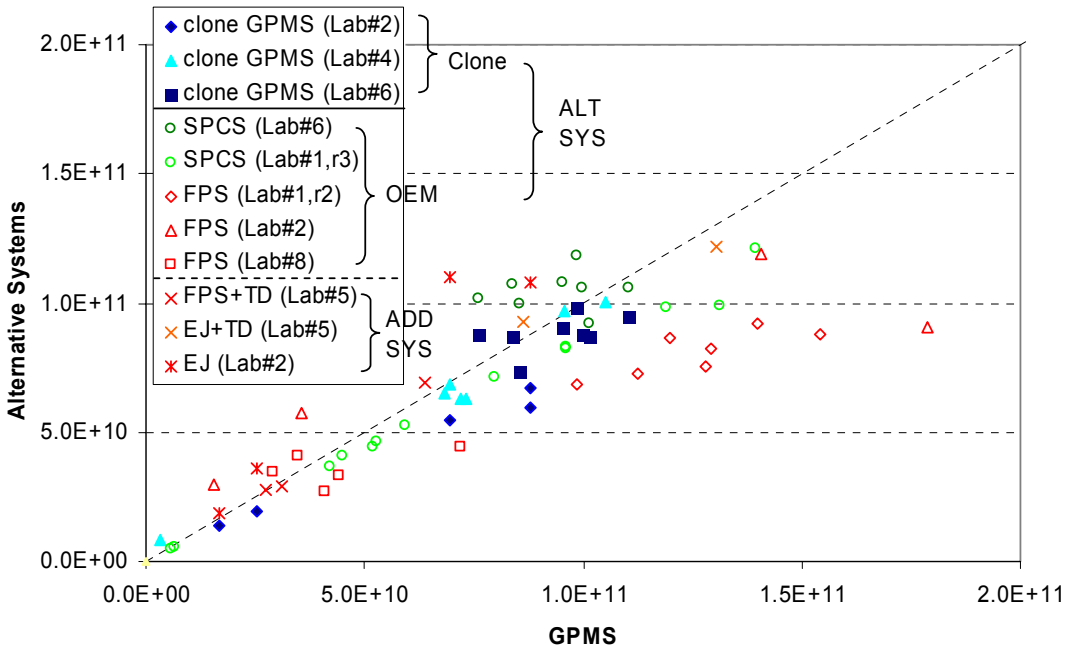
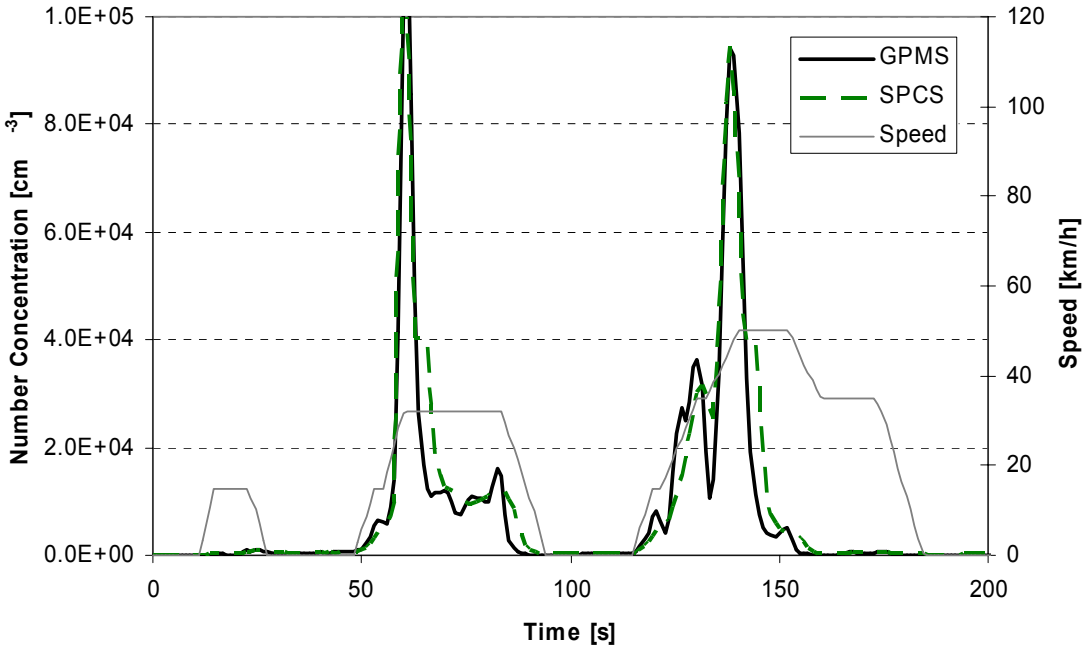


Table 14: Correlations Between GPMS and Other Systems: Golden Vehicle. The exact composition of the systems can be found in Appendix 4.

System	Linear relation with GPMS + intercept	R^2
Alternative Systems		
clone GPMS (Lab#2)	y = 1.1559x + 321	R2 = 0.9055
clone GPMS (Lab#4)	y = 0.9308x + 253.99	R2 = 0.9779
clone GPMS (Lab#6)	y = 0.7677x + 161	R2 = 0.8695
SPCS (Lab#6)	y = 0.9605x + 219	R2 = 0.9077
SPCS (Lab#1r3)	y = 0.9516x + 99	R2 = 0.9841
FPS (Lab#3)	y = 0.5342x + 1835	R2 = 0.8786
FPS (Lab#8)	y = 0.7337x + 611	R2 = 0.7873
FPS (Lab#1r2)	y = 0.5284x + 1410	R2 = 0.8698
Additional Systems		
FPS+TD (Lab#5)	y = 0.9553x + 166	R2 = 0.9686
EJ+TD (Lab#5)	y = 0.8832x + 598	R2 = 0.9768
EJ (Lab#2)	y = 0.6367x + 368	R2 = 0.9659

Figure 73: GPMS and SPCS comparison (Lab#6).



- Dilution ratio variances in the ejector diluters are affected by variable temperature and airflow at the ejector. Uncertainties in dilution ratios – especially at higher dilutions which the unit was used-will lead to larger differences between systems. It should be noted that, according to the manufacturer, at normal FPS use with not so high temperatures the accuracy of even high DRs is in the range of +/-10%.
- The PNC provided by GRIMM was used always with FPS based dilution systems, so if there are differences between the performance of this instrument and that of the TSI equipment used for PNC_REF and PNC_GOLD the influence of this will be present throughout the entire FPS dataset. In Lab#5 the linear relation between

Grimm and TSI PNCs was checked. Due to time constrains and problems with the PNC_Grimm software, the compatibility of the Grimm and the Reference PNC indications were only checked three times during their measurement period. PNC_Grimm gave 1.5 % to 9 % lower number concentrations than the PNC_REF. Figure 75 shows the results. At Lab#3, the real-time responses of the GRIMM PNC and the lab's TSI PNC (not REF or GOLD) were compared by using the two PNCs in parallel over various NEDC cycles. The results can be seen in Figure 76 and indicate similar behavior of the two PNCs taking into account a 5-10% difference between the two instruments.

Data from the FPS (indicated by the intercept term in the linear relationship) also appear to have slightly higher background levels than observed from the Clone and SPCS systems.

Clone systems: Clone systems showed good correlation with GPMS but the slope difference indicates that more calibration work needs to be done. Figure 77 shows the results of Lab#2 where the clone system overestimates particle number emissions. The good correlation of an ADD system seen in the figure will be discussed in the next section.

Figure 74: GOLD and FPS based systems correlation (Lab#3)

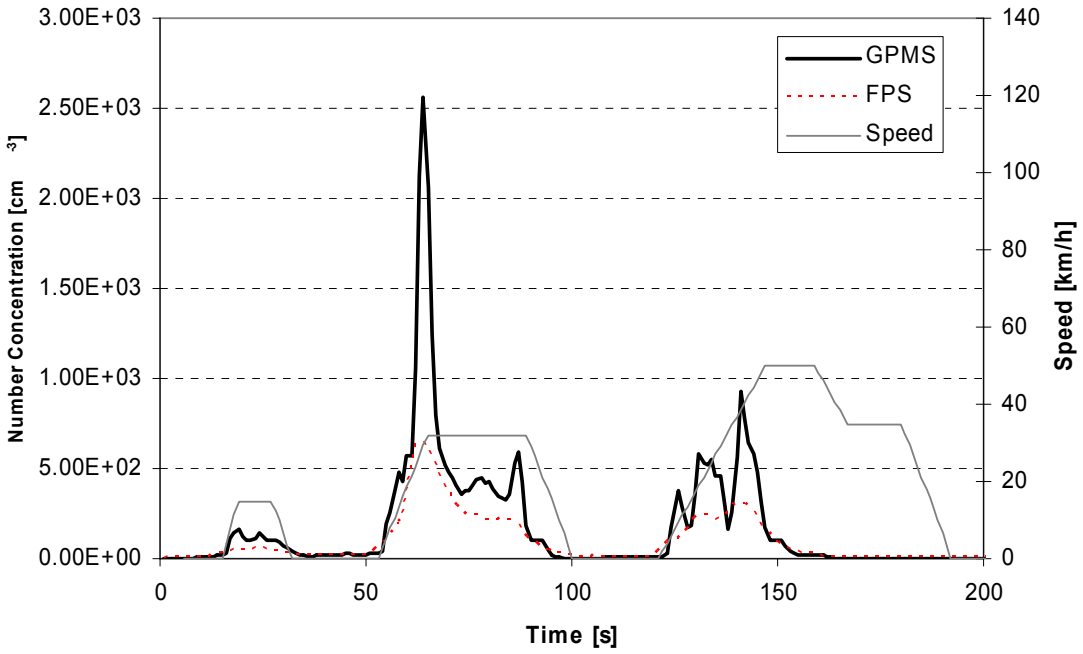


Figure 75: Correlation of the PNC_Grimm and the PNC_REF indications.

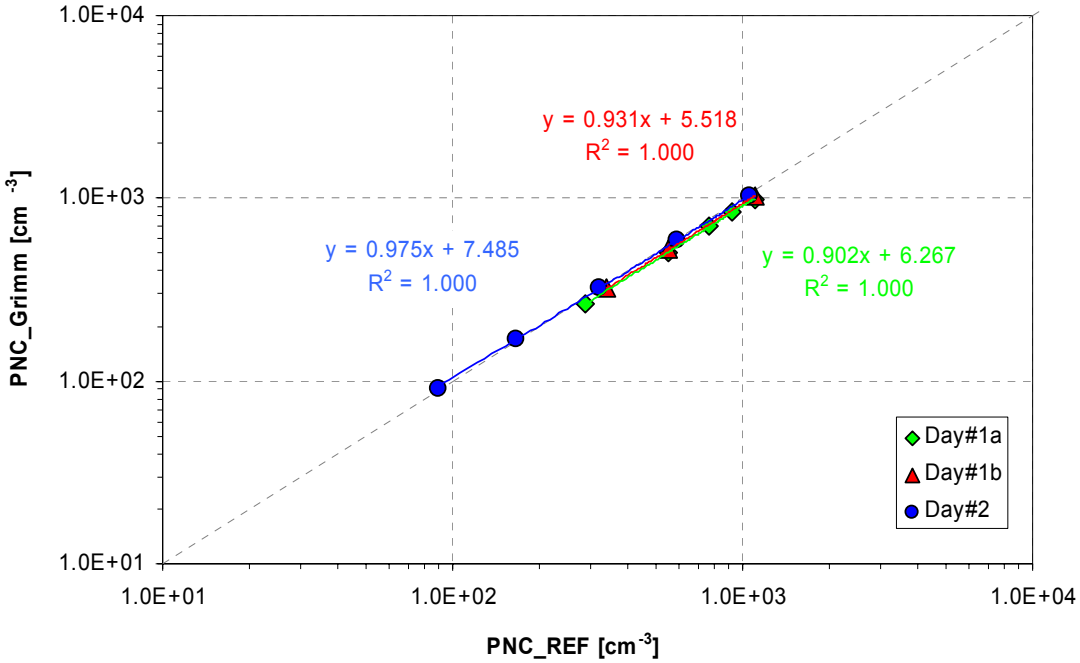
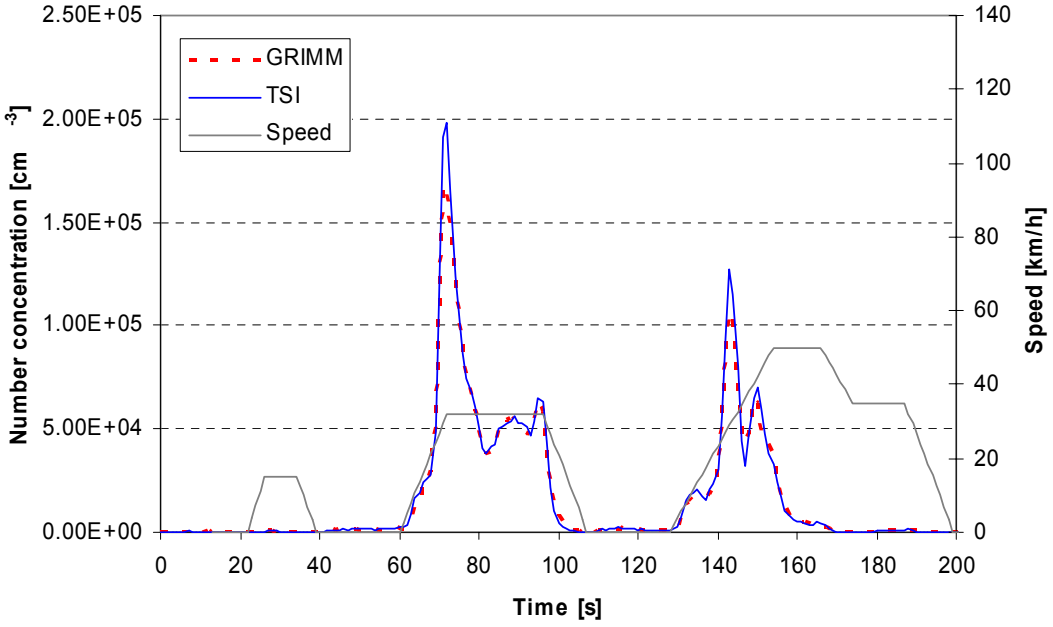


Figure 76: Real time response of Grimm and TSI PNCs.



Additional Systems

Several additional systems also demonstrated good linearity and correlation with the GPMS (e.g. Figure 77). The ejector or FPS plus thermodenuder data from Lab#5 (FPS+TD, EJ+TD; Lab#5), also showed very good agreement with the GPMS, but these data did require correction for losses in the denuder. Moreover the DR of the dilutors was externally monitored. Figure 78 shows the comparison of FPS+TD with the GPMS.

The agreement indicates that the problems observed with FPS have mainly to do with the evaporation tube of their unit and the high DRs used.

Figure 77: Comparison of an ALT (clone) and an ADD (ejector) system in Lab#2.

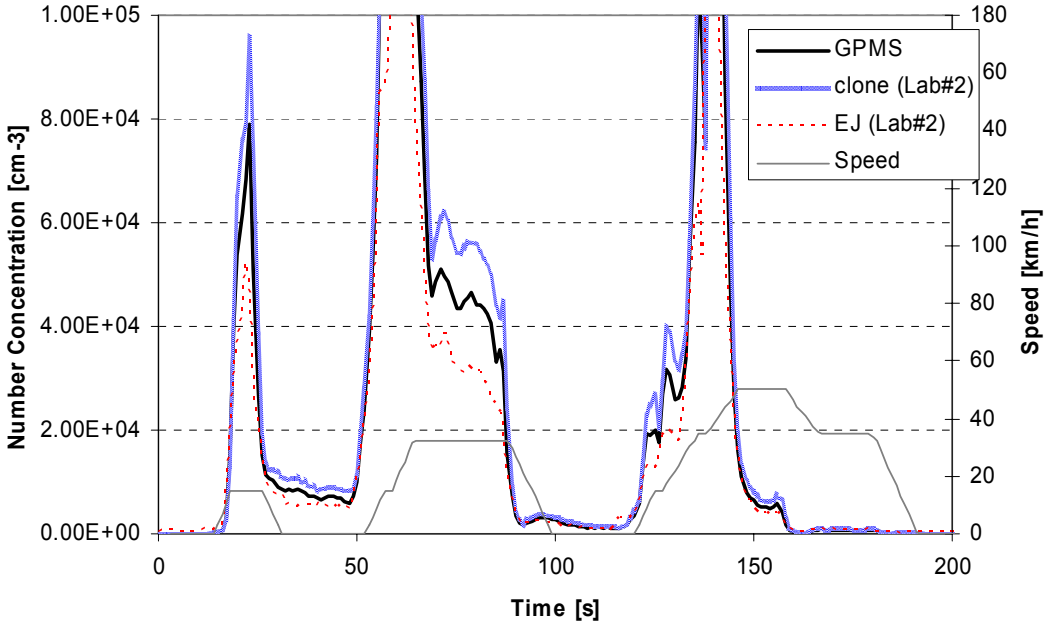
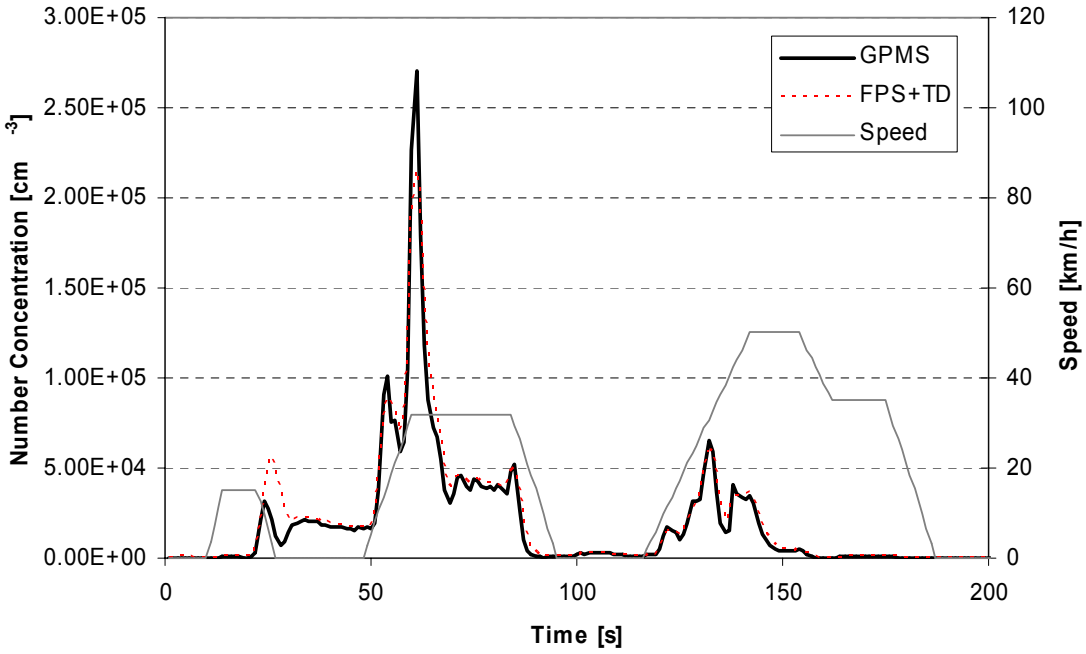


Figure 78: Comparison of GPMS system with FPS+TD (Lab#5)



5.6.1.2 Other Vehicles' Testing

These results for post-DPF particle numbers from the Golden Vehicle were replicated from the other DPF equipped and non-DPF vehicles (Figure 79a,b, Table 15) across a concentration range spanning 4 orders of magnitude (Figure 79a). Although the alternative systems deliver slightly lower results and logarithmic scale used hides some of the deviations, there is a linear response of the systems over concentrations differing by 4 orders of magnitude (note the logarithmic scale in Figure 79b).

Figure 79: GPMS and ALT_SYS, ADD_SYS Correlations – All Vehicles

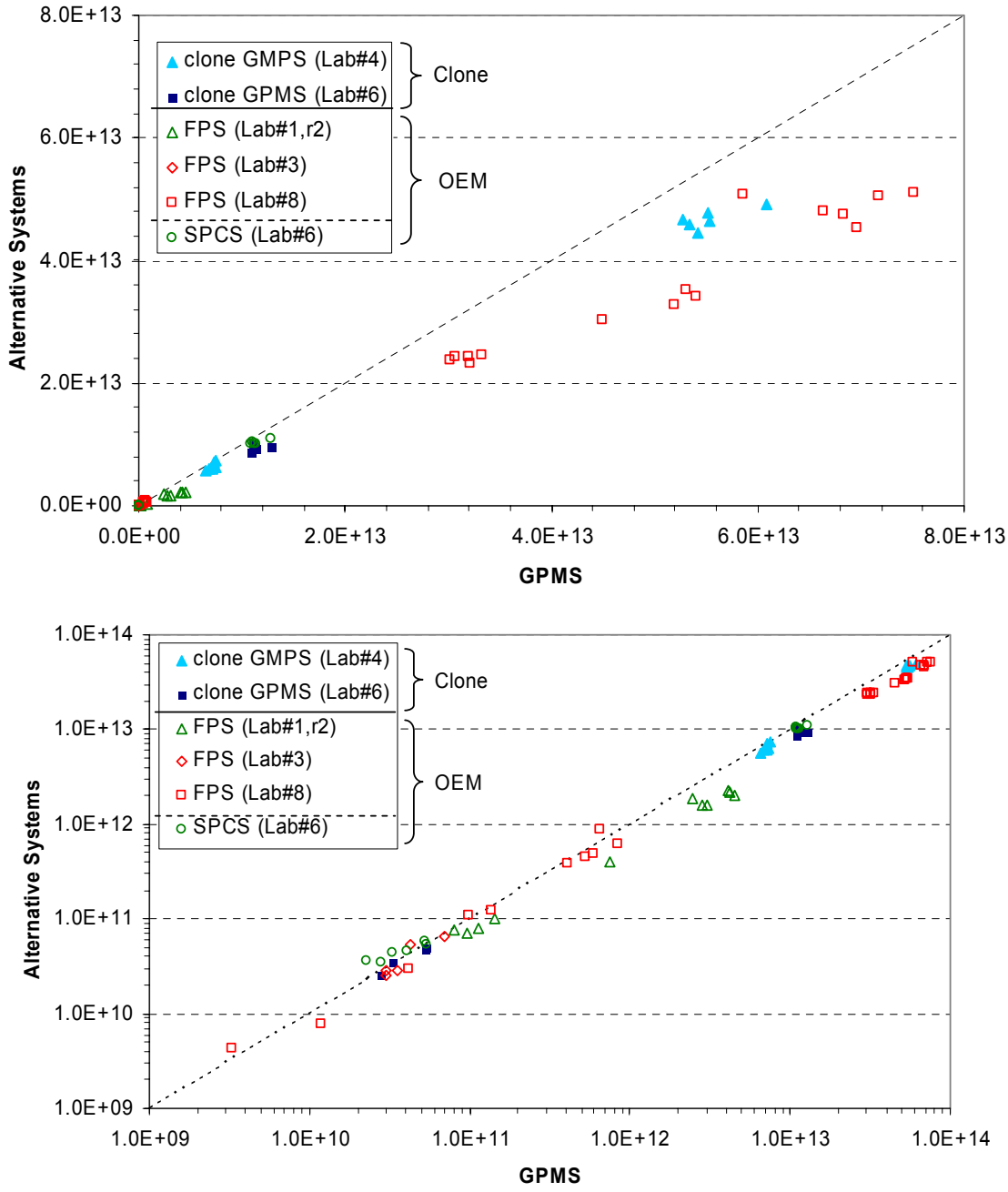


Table 15: Correlations Between GPMS and Other Systems: All Vehicles. The exact composition of the systems can be found in Appendix 4.

Alternative System	Linear relation to GPMS + intercept	R^2
clone GPMS (Lab#4)	y = 0.8352x + 32605	R2 = 0.9864
clone GPMS (Lab#6)	y = 0.826x	R2 = 0.9897
FPS (Lab#1)	y = 0.5266x + 2794	R2 = 0.8076
FPS (Lab#3)	y = 0.8609x + 4	R2 = 0.8776
FPS (Lab#8)	y = 0.5760x + 244135	R2 = 0.8889
SPCS (Lab#6)	y = 0.8742x + 2330	R2 = 0.9323

Figure 80: GPMS and SPCS comparison (Lab#6)

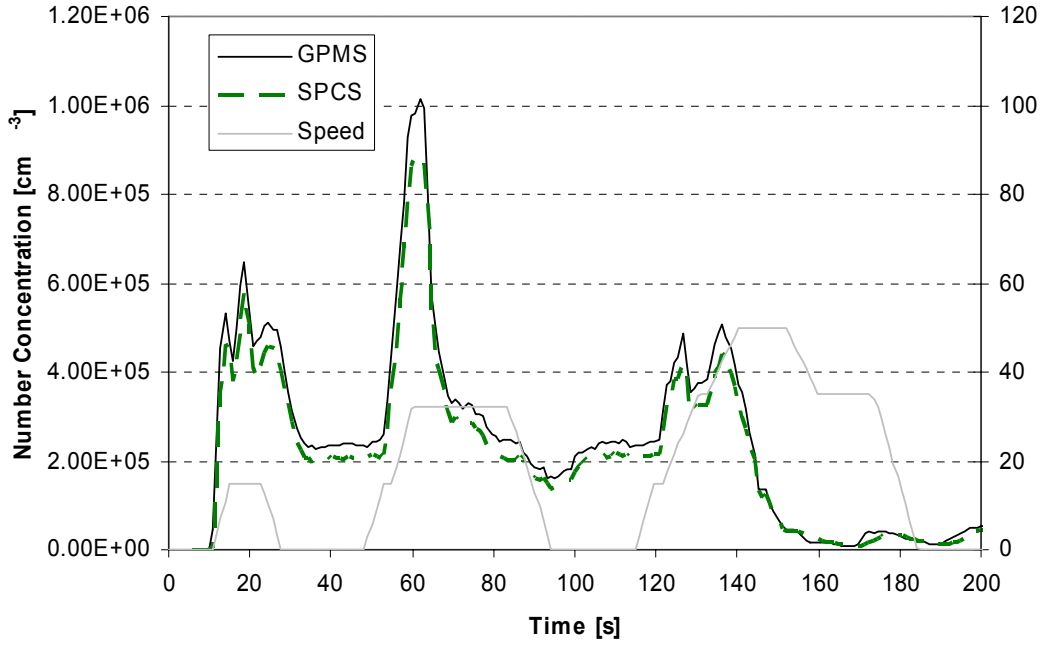
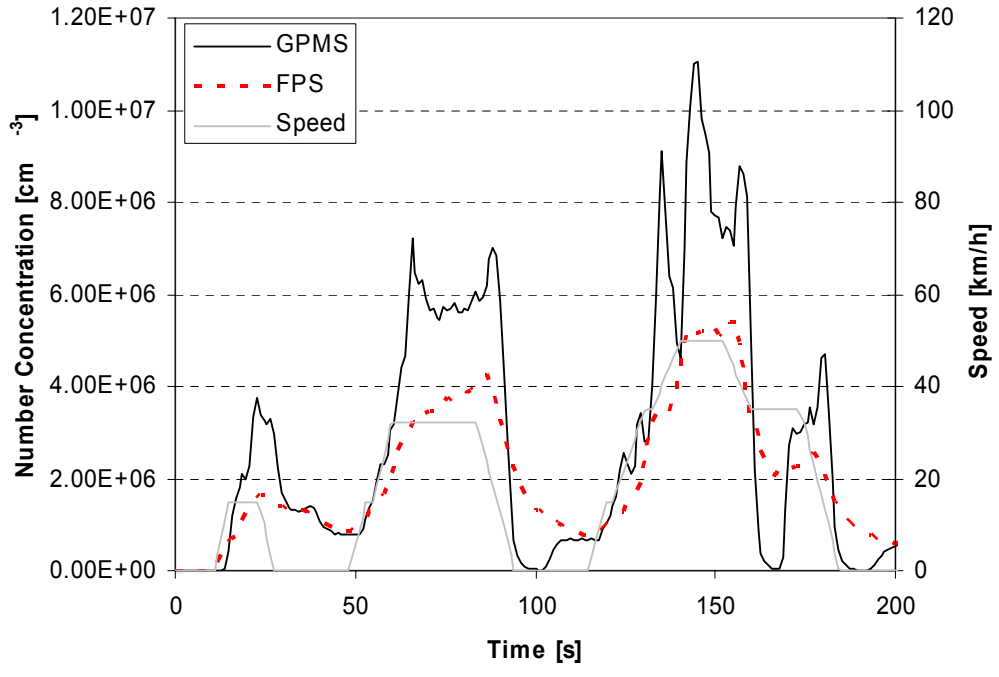


Figure 81: GPMS and FPS comparison (Lab#8)



Emissions from the Clone systems and the SPCS were typically 15% lower than the GPMS when all vehicles were considered. This was consistent with the relationships seen with the Golden Vehicle alone. Figure 80 and Figure 81 show the comparison between GPMS and SPCS and FPS respectively, which reproduce the golden vehicle's results. Background levels (intercepts) were generally higher, perhaps reflecting the contamination of the CVS with solid particles from other vehicles or previous tests but mainly due to the artefacts that regression analysis creates when many orders of magnitudes differences are examined (points with high values affect the regression coefficients more).

5.6.1.3 Compliance of ALT_SYS With The DR83 Recommended System Specifications

ALT_SYS components generally met the DR83 requirements as summarised below, and tabulated in Appendix 4.

CVS HEPA Filtration
All laboratories used HEPA filters of at least H13 of EN 1822 (99.95% efficient for 0.3µm particles). However Lab#4 initially tested using a HDD intake air filter (believed to be ~60% efficient) then switched to a HEPA filter. This resulted in a factor of three reduction in particle number emissions from ~$1.8x10^{11}$/km to ~$6.8\ x10^{10}$/km.

Sample Probe
While there was some variance in the sample probe length (both within and external to the dilution tunnel), all ALT_SYS met the maximum 1000mm pre-cyclone transfer requirement from the probe-tip.
The main variance, as seen with the GPMS, was with the probe length within the dilution tunnel (DR83 =200mm) where lengths of up to 330mm were observed.
For number measurements, in-tunnel length is not critical and this criterion can be relaxed as long as the 1000mm total distance is retained.

Pre-classifier
Most laboratories made use of the supplied URG PM2.5 cyclone, which gave a cut-point of 2.5µm at 90l/min. However, the Dekati FPS system used a PM10 cyclone with a sample flow of 10l/min.
All systems met the >2.5µm and <10µm requirement of the DR83.

Volatile Particle Remover
All individual components of the VPR should be characterised for particle penetration efficiency with solid particles of diameters 30nm, 50nm and 100nm and the overall particle penetration efficiency determined. This penetration efficiency can be calculated as the product of the penetrations of the individual components or measured as the result from the entire system. It is recommended that the penetration efficiency of the ET is established with PND2 in place and operating at a fixed dilution ratio.

First Particle Number Diluter
Three dilution approaches were employed:
- Clone Systems – variable ratio rotating disc (as the GPMS)

- Dekati FPS – variable dilution ratio perforated tube with ejector dilutor
- Horiba SPCS - variable ratio critical orifice and mass flow controller

All diluters were subject to gas calibration across the range 1 to 1000 times.
All diluters met the 150°C dilution temperature requirement, with indicator lights or software flagging deviation from the set-point.

In the ILCE_LD, PND_1 was not evaluated across its full dilution range, instead specific fixed dilution settings were employed for the different vehicle types:

- DPF Diesel and gasoline ~17
- Conventional Diesel ~250
- G-DI ~25

No data of particle size/number specific dilution factors were provided for any ALT systems.
Based upon experiences in the ILCE_LD the dilution ratio range of PND2 could be refined to 1 to 500.

Evaporation tube
The clone ALT_SYS used in the ILCE_LD met either the specification of the GPMS, or the specification of the DR83.
Investigations by Horiba have suggested that their SPCS (which was developed around the DR83 specification) meets the DR83 solid particle transfer requirement of >90% penetration of 30, 50, 100nm particles as well as the volatile particle removal criterion.
No data were supplied by Dekati or by users of GPMS clone systems regarding penetration or particle removal efficiency of the ALT_SYS, but it is understood that Clone systems used either the 350mm evaporation tube evaluated prior to the development of the GPMS or an ET identical to that in the GPMS. Clone systems ran the ET at 300°C, the Dekati system operated at 380°C at Lab#3 and 350°C at Lab#8.
Since both the SPCS and GPMS have demonstrated the volatile particle removal efficiency required, a broader performance specification for the ET can be proposed: temperature range 300°C - 400°C, residence time at temperature 0.2-0.5s, >99% n-C40 particle removal.

Second particle number diluter
The DR83 requirement for PND2 required that the product of the two dilution factors from PND_1 and PND_2 should range from 1 to 1000. The selected secondary dilution ratio must also be sufficient to reduce peak concentrations to >10,000cm^{-3} and gas temperature entering the PNC to <35°C.
Dilution ratios in the SPCS were gas calibrated and they met the requirements of the DR83. Dilution ratios in the clone GPMS systems ran at fixed secondary dilution ratios of ~10:1. The Dekati FPS system ran a gas calibrated ejector for secondary dilution – also at ~10:1.
At no time during non-regenerating NEDC cycles on DPF-equipped vehicles did particle number concentrations at the inlet to the PNC exceed 10,000cm^{-3}
No issues with CPC inlet temperature exceeding 35°C were observed.
Based upon experiences in the ILCE_LD the dilution of PND_2 could be fixed at between 10 and 30 with a recommendation for flexibility between these points.

Particle number counter with modified counting efficiency
Particle number counters used with ALT_SYS in the ILCE_LD were either 3010D instruments, standard 3010 systems that were modified to give 9K temperature

differences between the saturation and condensation chambers or GRIMM 5.403/5.404 CPCs. These led to specific counting efficiency characteristics: the lower particle size limit characteristics of the PNC shall be such that the 10% (D10), 25% (D25), 50% (D50) and 90% (D90) inlet efficiencies of the instrument correspond to the particle sizes 16nm (+/-nm), 18nm (+/-2nm), 23nm (+/-3nm and 37nm (+/-4nm)) respectively.
The 3010D systems were all validated individually to meet the DR83 criteria (which in turn is based upon a number of 3010D's characterised by TSI)
The modified 3010s were not experimentally validated, but were assumed to be similar to the 3010Ds
It was claimed by the manufacturers that the GRIMM CPCs met the counting efficiency requirements. Limited measurements in Lab#5 showed that the CPC_Grimm reports lower particle number concentrations relative to 3010Ds (1-9%). Further data are being collected in order to validate the performance of the GRIMM system used in the ILCE_LD.
Other PNC requirements were met by the 3010D, 3010 and GRIMM systems:

- Full flow operation only – no flow splitting which might partition the particles by size and lead to counting inaccuracies
- A counting accuracy of ± 10% across the range $10^2 cm^{-3}$ to $10^4 cm^{-3}$ and +/- $10 cm^{-3}$ below this concentration against a traceable standard.
- A readability of 0.1 particles/cm^3.
- A linear response to particle concentration over 1 to 10,000 particles/cm^3.
- A data logging frequency of equal to or less than 0.5 Hz.
- A T90 response time of between 5s and 15s
- A data-averaging period of between 1 and 6s.

The DR83 explicitly prohibits automatic data manipulation functions. However it is considered wise to permit a coincidence correction for higher concentrations (>1000cm^{-3}), but no other manipulation.

5.6.1.4 Overview

From the ALT_SYS tested in this programme it seems clear that systems which were specifically designed for the PMP programme show close correlation to the GPMS, while the adapting of existing measurement systems to PMP purposes has so far proven less successful. It would be wise to consider only measurement systems that comprise compatible components (from one or more manufacturers) that have been fully validated and integrated for future heavy-duty PMP work.
Between the GPMS and other systems there may be offsets in particle numbers related to small levels of internal losses, particle background differences and dilution ratio uncertainties. However, the SPCS agreed closely in both number and background levels with the GPMS, and from both this and the Clone systems absolute particle number agreement was typically within 15% and at worst 25%.
Some additional systems also agree well with the GPMS. On this basis, and as previously discussed in Section 5.6, certain system components such as the evaporation tube could be omitted from the PMP's particle measurement system if extreme emissions events such as high temperature operation and regenerations are never to be considered in a regulatory framework.

6 MEASUREMENT SYSTEM INVESTIGATIONS

This section presents results and discussions of experiments investigating the effects of engine operation and sampling on particle number emissions from the Golden Vehicle. The differences between mass calculated from particle size and number and the filter method are also discussed.

6.1 DPF Stabilisation and Regeneration

In previous sections, data has been shown that demonstrates immediate increases in particle number emissions following a complete DPF regeneration on the Golden Vehicle (Figure 26, Section 5.1.1) followed by progressive decreases in particle numbers from subsequent tests. This effect of steadily decreasing emissions with accumulated post-regeneration mileage was also seen on another DPF-equipped vehicle (Figure 28) and was briefly discussed in Section 5.3.1.

The immediate effects of regenerations on emissions of particle numbers have also been presented (Section 5.6): from steady state operation at 120kph (Figure 67) and during an NEDC cycle (Figure 69, Figure 70).

In these previous data it was demonstrated that elevated levels of both semi-volatile particles (those which survive the first stage of dilution but not the evaporation tube) and solid particles appear during regenerations.

To further explore the emissions of solid and volatile particle emissions during regenerations and DPF-fill effects on particle number emissions, additional experiments were conducted at Lab#1 following the 3rd set of repeat measurements. These experiments are described below.

A sequence of NEDC cycles was driven on the chassis dynamometer. Using the GPMS and an EEPS on selected tests, solid particle numbers and number weighted particle size distribution data were acquired during each cycle.

6.1.1 DPF Stabilisation Experiments

Once the DPF had regenerated, cold NEDCs with the standard PMP preconditioning (120kph; 20mins + 3 x EUDC) were driven each day (some days these were followed by hot NEDCs) until DPF regeneration was observed. Further NEDCs were undertaken following the first regeneration. Particle numbers were recorded through each Cold NEDC cycle using the GPMS to observe effects on solid particle emissions following regenerations. These and similar data from regenerations observed at Lab#3, Lab#4 and in earlier testing at Lab#1r2 are shown in Figure 82.

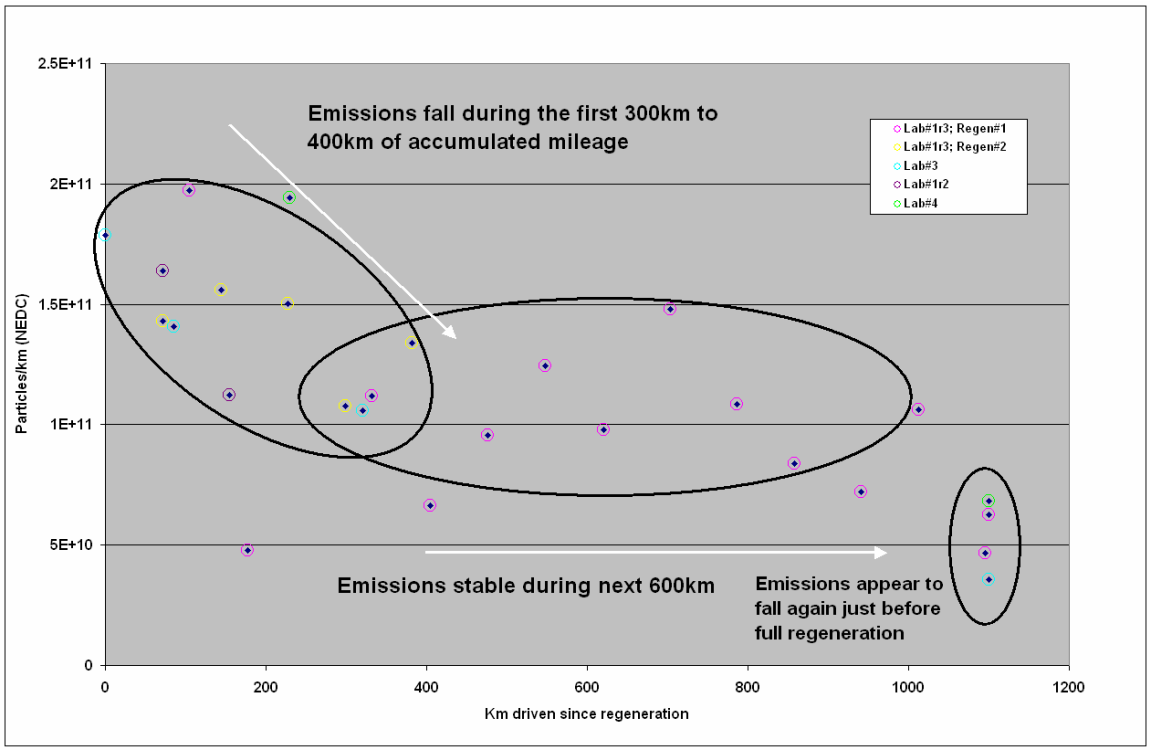
It is clear that during the first 300 to 400km following DPF regeneration the emissions of solid particles reduce. This is believed to be related to the progressive filling of the DPF and increase in filtration efficiency as mileage is accumulated.

Interestingly, particle numbers appear to drop immediately before a scheduled regeneration is due. This may be due to partial regeneration during EUDC cycles or

preconditioning leading to a change in PM characteristics on the DPF which in turn affects filtration efficiency.

For most consistent particle number results it is advised to avoid testing the initial DPF loading phase since this may lead to elevated particle numbers and increased test-to-test variability. On this basis, and since on the fuel tested the regeneration periodicity of the DPF was ~1100km, it is recommended to perform particle number measurements after at least 35% of the DPF regeneration period has elapsed, or 35% of the DPF mass loading has been reached.

Figure 82: Golden Vehicle Particle Number Emissions Reduce As Mileage Increases



6.1.2 Regeneration Effects on Particle Emissions During Steady State Operation

This section describes the effects of regenerations on solid and volatile particle emissions during steady state testing.

During PMP preconditioning of the vehicle for cold start NEDC cycles, an active DPF regeneration was observed during the 20 minute duration 120kph steady state (Figure 67). This type of regeneration throttles the engine, shuts down EGR and injects fuel very late in the engine cycle (post-injection). This results in elevated exhaust temperatures and a substantial level of fuel surviving to combust across the oxidation catalyst but limits the level of oxygen. Soot on the DPF, which incorporates cerium, as a catalyst, combusts emitting CO2. Ultimately this led to exhaust temperatures ~100°C higher than from a non-regenerating 120kph steady state.

Solid particle per km emissions (Figure 83) measured by PNC_GOLD rose by a factor of ~60: from 2.56×10^{9}/km to 1.52×10^{11}/km between the non-regenerating and regenerating steady states (Figure 66), but semi-volatile particles measured upstream of

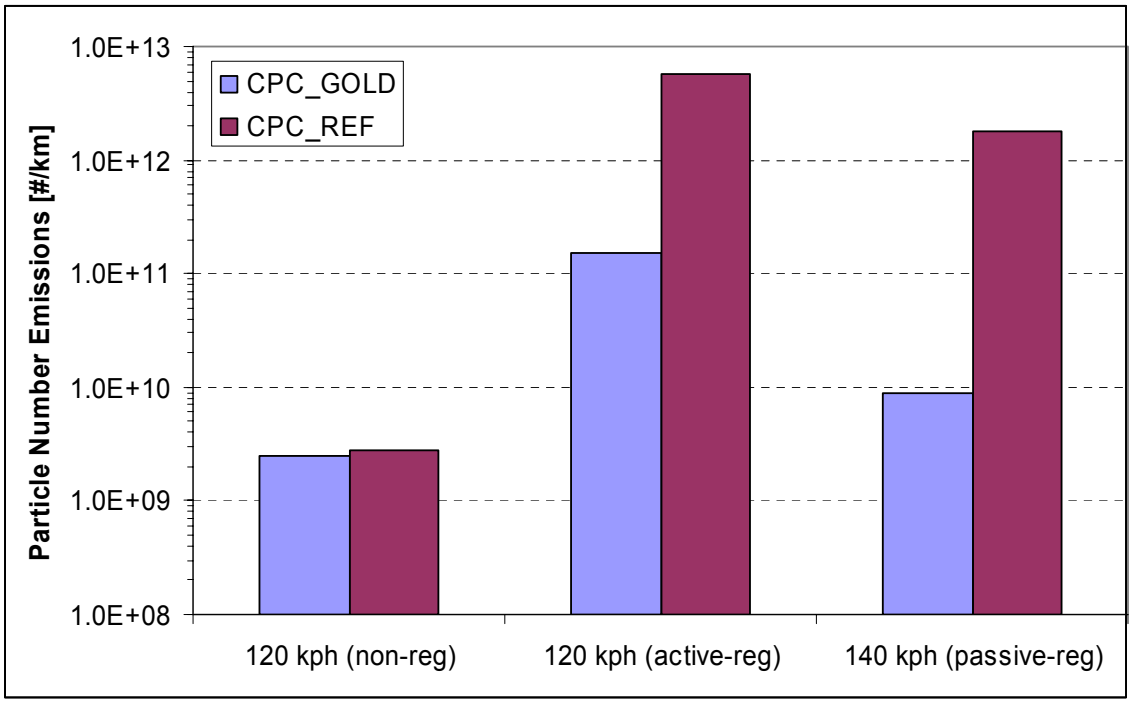
the evaporation tube by PNC_REF showed a more than ~2000 times increase ($2.78x10^{9}$/km to $5.60x10^{12}$/km). Solid particles emitted are believed to be comprised of both elemental carbon from particulate which is incompletely oxidised and very low volatility hydrocarbons. The low volatility HCs may be lubricant derived species that are either stored on the DPF through adsorption with carbon and evaporate during regeneration, or are materials that slip through the DPF when filtration efficiency and exhaust temperatures are low and condense in the exhaust system. These are then released in response to high thermal temperatures in the exhaust [16].

Comparing the PNC_REF particle number measurements with the PNC_GOLD measurements allows the proportions particles removed by the evaporation tube (i.e. those that are semi-volatile) to be determined. For the non-regenerating 120kph steady state these were 8% and for the regenerating more than 97%. As the CPC_REF was saturated for many seconds the exact concentration of the semi-volatiles couldn't be calculated.

In addition, a passive DPF regeneration – where exhaust temperatures and oxygen levels are sufficiently high to enable cerium doped carbon to combust without any additional thermal assistance from engine changes – was observed during a steady state cruise at 140kph (87mph). Particle emissions (Figure 84) measured by PNC_REF increased by ~475x and PNC_GOLD by ~2.5x in response to the regeneration, in each case by substantially less than from the active regeneration at 120kph (Figure 83).

In this case the evaporation tube eliminated more than 99% of the particles recorded by PNC_REF.

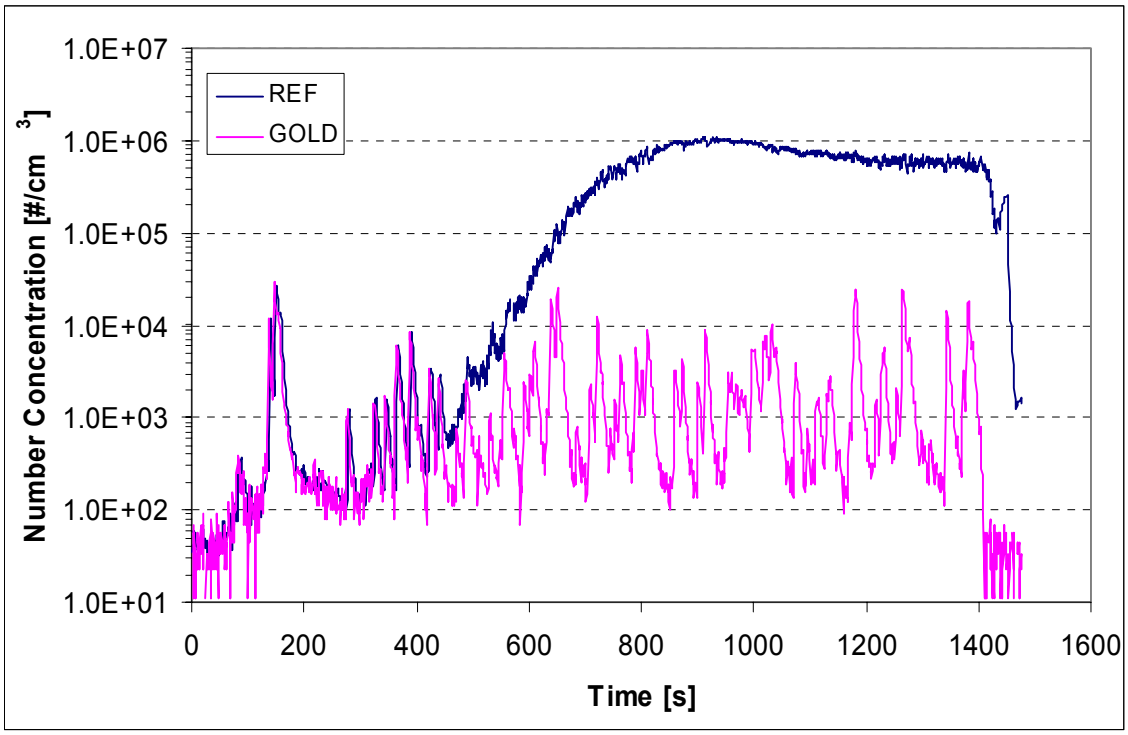
Figure 83: Particle Emissions During Steady State Regenerations



During the passive regeneration soot oxidation may be more efficient than from the active regeneration due to a surplus of oxygen, and exhaust temperatures will be lower:

the former leading to reduced carbon particle emissions and the latter to reduced volatile particle emissions.

Figure 84: Particle Emissions During Passive Regeneration (140 km/h)



6.1.3 Regeneration Effects on Particle Emissions During Transient Cycles

This section describes the effects on solid (from PNC_GOLD), semi-volatile (from PNC_REF) and volatile (from EEPS) particle emissions of regenerations observed during the sequence of transient drive cycles. Initially repeated NEDC cycles were driven with the aim of loading the DPF to regeneration point. This included both cold start and hot start NEDCs with few intermediate preconditionings (Table 16). After each NEDC test, the vehicle was brought to rest and switched off. The CVS flow was also stopped until just prior to commencement of the next NEDC.

During the sequence of NEDC tests, regeneration activity was initially observed to commence during the EUDC phase of NEDC#3. this was a hot start NEDC – and after approximately 1100km total mileage. This regeneration paused when the vehicle was stopped at the end of the cycle and then reactivated during the EUDC of the next cycle when exhaust temperatures were appropriate. This series of events occurred for a total of 8 consecutive NEDCs. During these EUDC phase regeneration events, both solid and volatile particle emissions were observed: Figure 85 illustrates the following:

- Emissions of solid particles (from PNC_GOLD)
- Emissions of semi –volatiles + solids (from PNC_REF)
- Emissions of volatiles, semi –volatiles + solids (>22nm from EEPS)
- Emissions of volatiles, semi –volatiles + solids (>5nm from EEPS)

The >22nm EEPS data approximates the size range measured by PNC_GOLD and PNC_REF.

Table 16: Sequence of NEDC Tests Including Regenerations

NEDC	Hot/cold	Precon	Soak	Start of Regen
				(s into test)
1	cold	None	>6h, night	n/a
2	hot	None	10-20min	n/a
3	hot	None	10-20min	1044
4	'cold'	None	~4h, day	1096
5	hot	None	10-20min	1096
6	cold	None	>6h, night	1094
7	hot	None	10-20min	1088
8	hot	None	10-20min	1083
9	cold	None	>6h, night	1039
10	hot	None	10-20min	1039
11	'cold'	None	~5h, day	n/a
12	cold	120, 3EUDC	>6h, night	n/a
13	cold	120, 3EUDC	>6h, night	n/a

Emissions of solid particles (measured by PNC_GOLD) increased by a maximum of ~77 (to $2.2x10^{10}$/km) and an average of ~22 times during the sequence of regenerations when compared to the initial emissions from the EUDC of cold start NEDC#1 ($2.85x10^{8}$/km).

Emissions of semi-volatile particles (PNC_REF measurements) increased by a maximum of ~6500 (to $2x10^{12}$) and an average of ~680, indicating a strong release of materials that survive hot dilution in PND_1 but are subsequently eliminated by the ET. PNC_REF EUDC#1 emissions were ~$3.1x10^{8}$/km.

EEPS data (>22nm) from the initial cold start test ($5.7x10^{9}$/km) showed emissions levels ~20 times those of PNC_GOLD – indicating that about 5% of total particle emissions in the size range measured by the PNCs could be considered solids. During regenerations, EEPS levels ranged from ~30x to 2300x ($1.54x10^{13}$) greater those from PNC_GOLD indicating significant releases of particles >22nm.

EEPS data (>5nm) from the initial cold start test showed emissions levels ~40 times those of PNC_GOLD – showing that about 98% of total particle emissions were volatiles and that half of these were smaller than ~22nm. During regenerations, EEPS levels ranged from ~730x to 7000x (max $3.2x10^{13}$/km) those from PNC_GOLD indicating releases of particles between 5nm and 22nm that were 3x to 24x the total number of particles emitted in the size range above 22nm.

EEPS particle size distribution data (Figure 86) shows that the majority of particles emitted during the sequence of NEDC tests were nanoparticles in modes that show peaks between 10 and 20nm. An exception was seen from the initial regeneration (EUDC#3) where the mode appeared at ~35nm. This is believed to be due to the purging of volatile materials stored in the exhaust system that combine with the unburned fuel and lubricant HCs to form larger droplets under initial regeneration conditions.

Figure 85: Solid and Volatile Particle Emissions During the NEDC Cycle Sequence

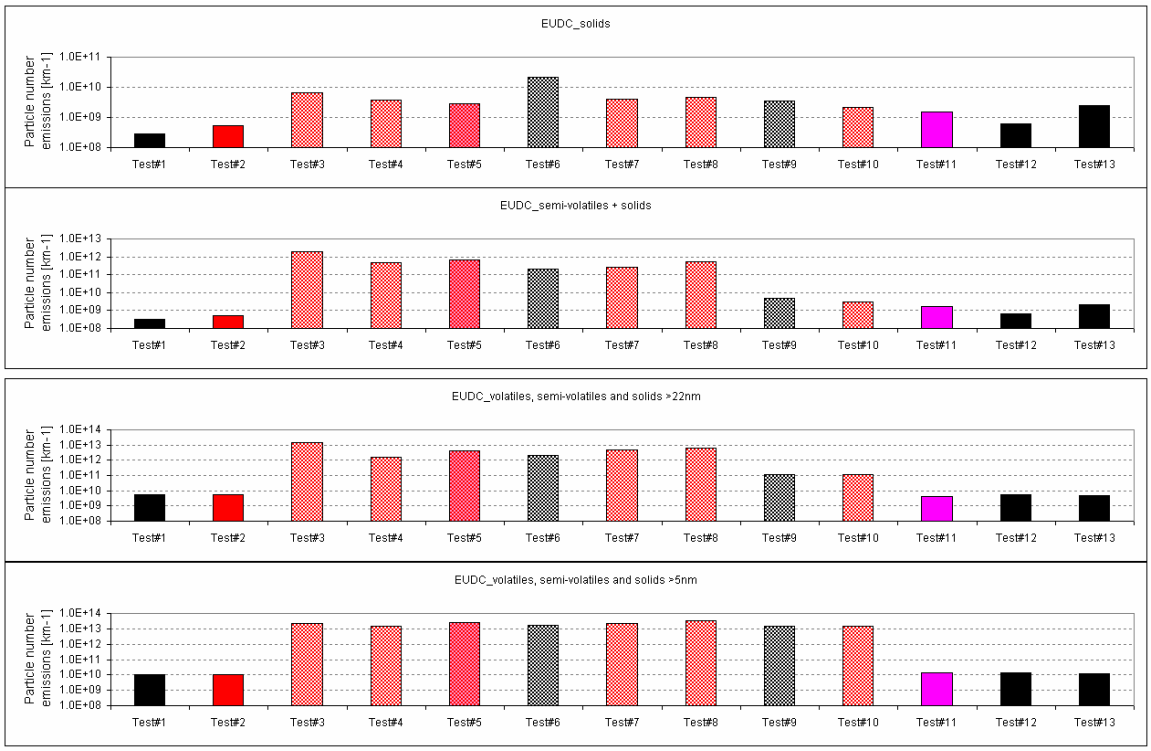
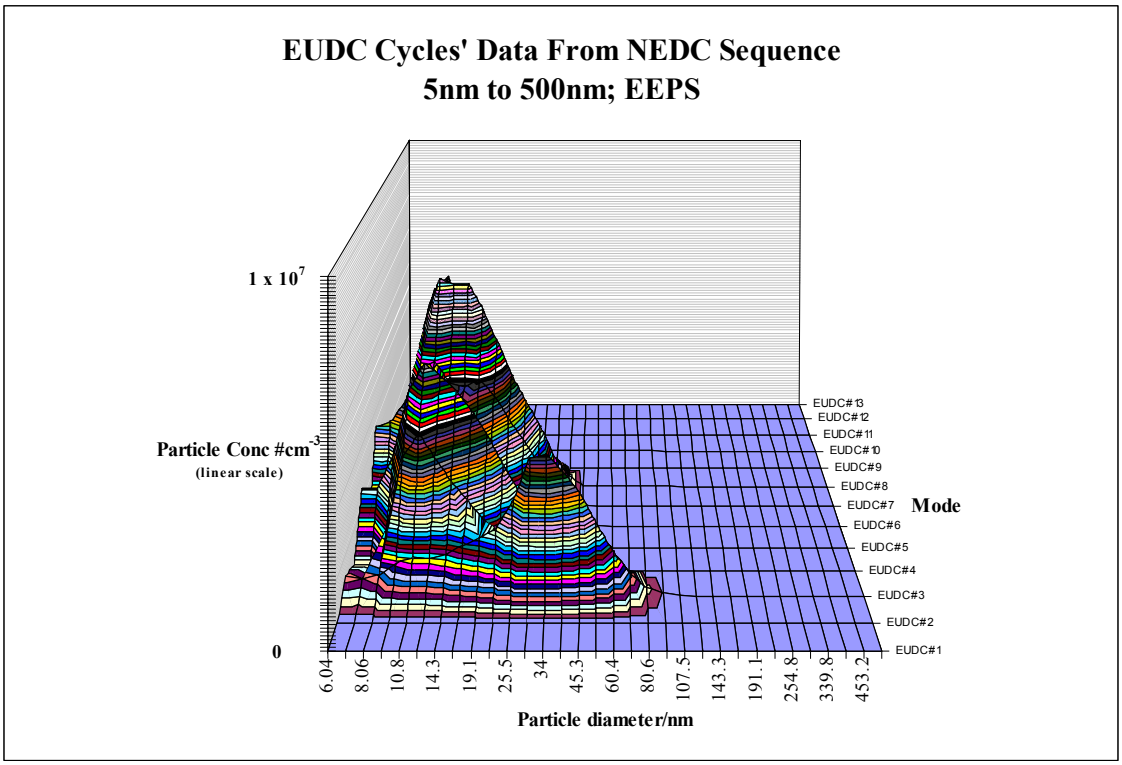


Figure 86: Particle Size Distributions From The EEPS During Regenerations



6.2 Preconditioning and Cold Start Effects

During the ILCE_LD, a number of experiments were conducted in order to establish any effects of different vehicle preconditioning on particle number emissions from the Golden Vehicle. The various preconditionings considered are listed in Table 8.

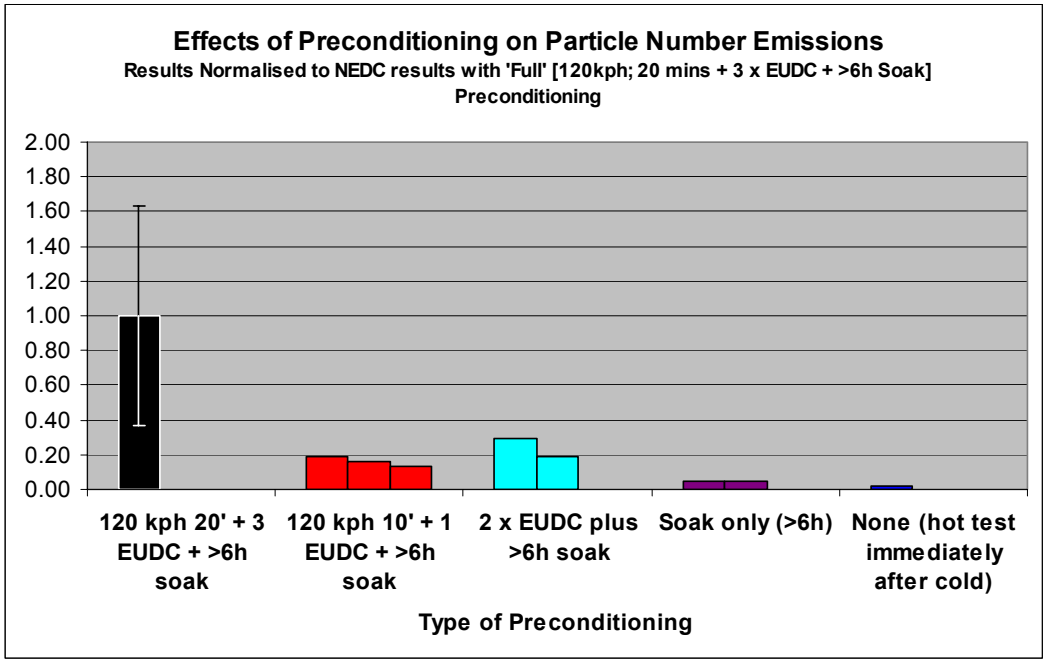
Table 8: Various Vehicle Preconditionings

First Precon	Second Precon	Soak
120kph; 20 mins	3 x EUDC	>6h
120kph; 10 mins	1 x EUDC	~6h
None	2 x EUDC	~6h
None	None	>6h
None	None	None

Figure 87 compares emissions from NEDC tests following the various preconditionings. In each case, the emissions level is normalised to an NEDC result from a cold start test conducted with the full PMP preconditioning procedure (120kph; 20 minutes + 3 x EUDC + >6h soak). Prior NEDCs were undertaken earlier on the same day or on the previous day.

Each result is also compared with mean Golden Vehicle NEDC particle number result (+/- 2*S*) from the entire ILCE_LD. All data are drawn from tests undertaken with a partially filled DPF to avoid fill-any effects of fill-state on results.

Figure 87: Effects of Vehicle Preconditioning on Particle Number Emissions



Experiments investigating preconditioning effects on particulate mass emissions showed no obvious effects (Figure 22, Section 4.3.6). This was not the case with particle number measurements: there were clear effects. In general, particle numbers from NEDC cycles decreased as the severity (in terms of speed and load) of the preconditioning decreased (Figure 87).

The differences between the cycles' particle emissions occur in the first ~3 minutes of the NEDC cycle (Figure 88) and on this basis might appear to be a cold start effect (Figure 89).

Figure 88: Apparent Cold Start Effect on Particle Numbers

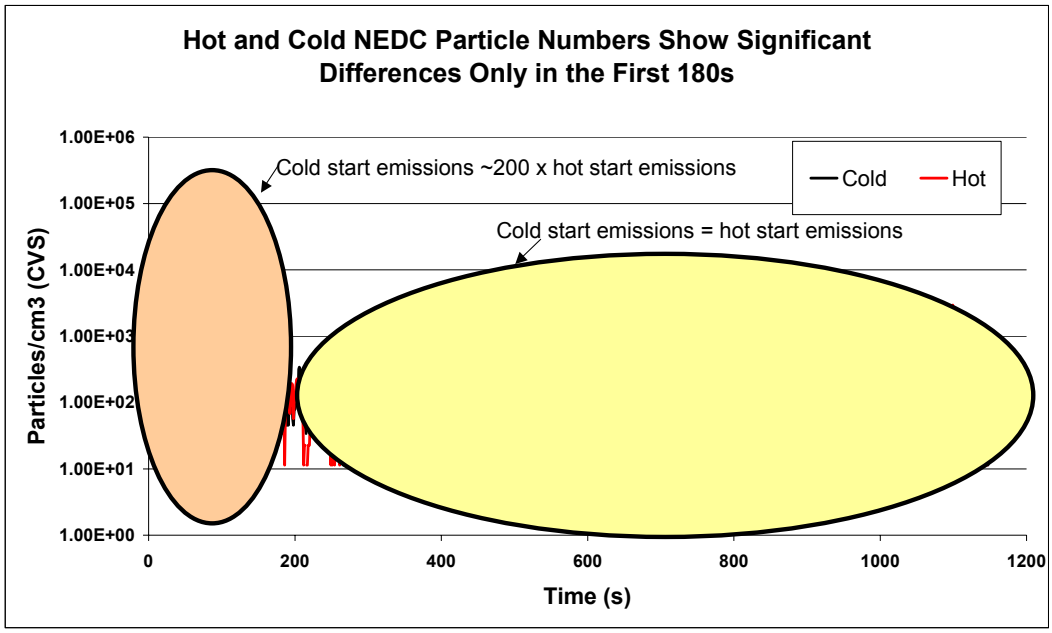
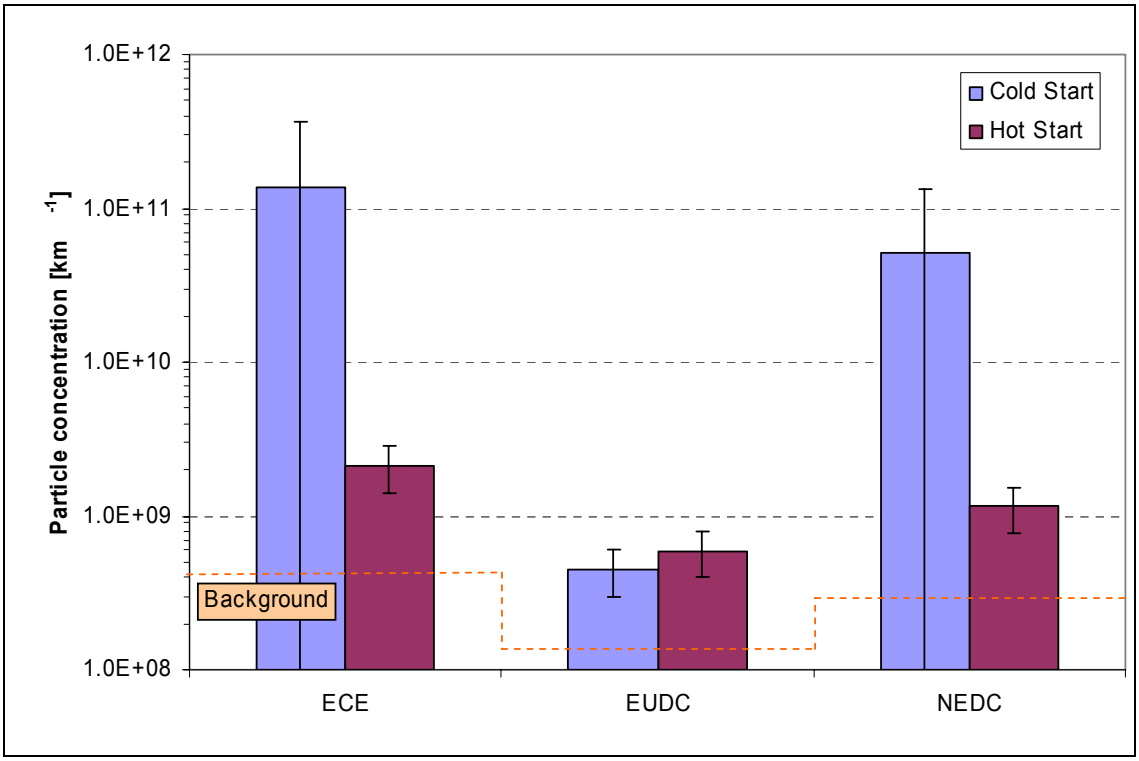


Figure 89: Comparative Cold and Hot NEDC, ECE & EUDC Particle Number Emissions

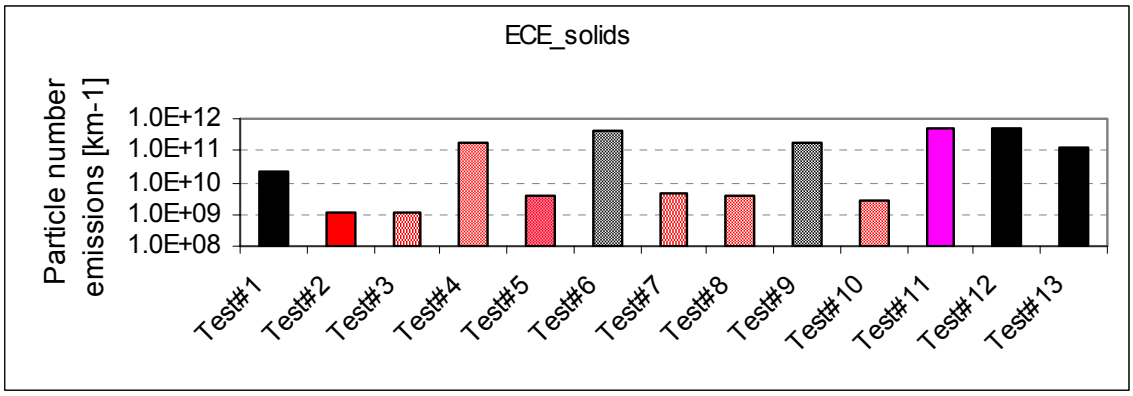


However, it is hypothesised that with the Golden Vehicle and its own particular DPF, the preconditioning process loads the interstitial voids of the DPF with carbon particles during high exhaust flows and increased engine-out carbon levels. These particles settle

during soak periods are then emitted from the DPF under start-up in response to pressure changes in the particle filter. Thus elevated emissions are always seen with cold start tests relative to hot, because cold start tests have a preconditioning. There is no substantial difference between emissions from (non-regenerating) EUDC cycles irrespective of preconditioning.

These hypotheses are supported by ECE phase data generated during the series of NEDC regeneration tests discussed in the previous section and listed in Table 16. As Figure 90 shows, elevated emissions levels are observed from Tests 1, 4, 6, 9, 11, 12 and 13.

Figure 90: Solid Particle Emissions from a Series of NEDC Cycles' ECE Phases



Differences in emissions during ECE cycles can be attributed to types of preconditioning, effects of soak period, hot and cold starts, DPF filtration efficiencies and regeneration influences (Table 17:).

Figure 91: ECE Cycles' Particle Size Distributions

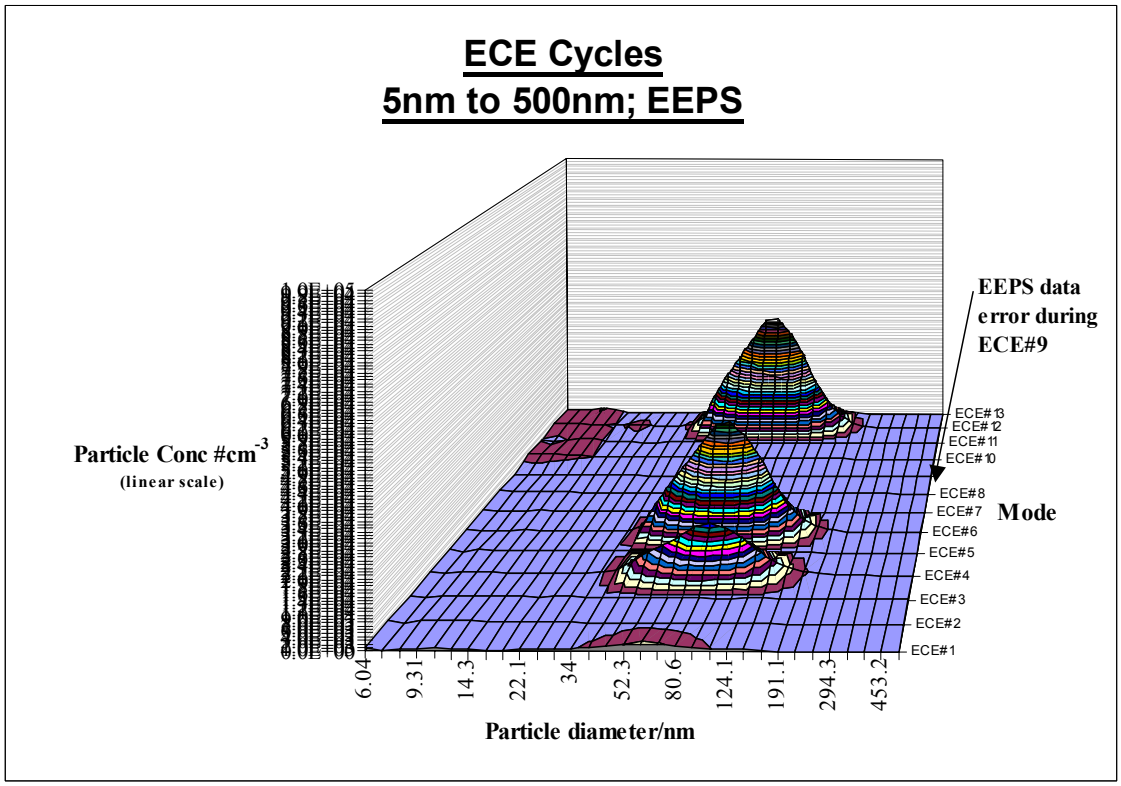


Table 17: Influences on ECE Cycle Particle Number Emissions

NEDC	Preconditioning, DPF fill state, hot or cold test, comments
	No preconditioning DPF to be almost full)
NEDC#1	Cold start following soak. No regeneration, DPF continues to fill
	Short hot soak with CVS running, no particles settle
NEDC#2	Hot start test - low emissions, no regeneration, DPF fill continues
	Short hot soak, no particles settle
NEDC#3	Hot start test - low emissions on ECE, partial regeneration on EUDC - some soot regenerated, some solids thermally released
	4h soak, no flow through exhaust, soot settles
NEDC#4	'Cold' start (not allowed without 3xEUDC) following soak. ECE emissions elevated: soot from poor filtration, soot released from DPF interstices. EUDC partial regeneration
	Short hot soak, no particles settle
NEDC#5	Hot start test - low emissions on ECE, partial regeneration on EUDC - some soot regenerated, some solids thermally released
	Overnight soak, no flow through exhaust, soot settles
NEDC#6	True cold start following soak. ECE emissions: soot from poor filtration, soot from DPF interstices. EUDC partial regeneration.
	Short hot soak, no particles settle
NEDC#7	Hot start test - low emissions on ECE, partial regeneration on EUDC - some soot regenerated, some solids thermally released
	Short hot soak, no particles settle
NEDC#8	Hot start test - low emissions on ECE, partial regeneration on EUDC - some soot regenerated, some solids thermally released
	Overnight soak, no flow through exhaust, soot settles
NEDC#9	True cold start following soak. ECE emissions: soot from poor filtration, soot from DPF interstices. EUDC partial regeneration.
	Short hot soak, no particles settle
NEDC#10	Hot start test - low emissions on ECE, EMS completes regeneration on EUDC - some soot regenerated, some solids thermally released
	5h soak, no flow through exhaust, soot settles
NEDC#11	'Cold' start following soak. ECE emissions: soot from poor filtration, soot from DPF interstices.
	Hard preconditioning (120/3xEUDC), overnight soak, no regeneration expected, no flow through exhaust, soot loads DPF and interstices
NEDC#12	True cold start following soak. ECE emissions: high soot from poor filtration, high soot from DPF interstices. EUDC emissions low
	Hard preconditioning (120/3xEUDC), overnight soak, no regeneration expected, no flow through exhaust, soot loads DPF and interstices
NEDC#13	True cold start following overnight soak. ECE emissions: high soot from poor filtration but reduced from NEDC#12, high soot from DPF interstices. EUDC emissions low

The influences on ECE cycle emissions can be summarised as follows:

- A full DPF leads to lower particle number emissions since filtration is most efficient
- The more vigorous a preconditioning phase, the higher the solid particle number emissions since particles are forced into the walls of the DPF and released during the next cold start test.
- Hot start tests immediately following cold tests release virtually no solid particles
- Longer soak periods (hours) allow particles to settle within the DPF interstices and lead to higher solid emissions than short soak periods (minutes)
- Full regenerations (as observed under steady state operation) empty the DPF and lead to increased emissions levels through reduced filtration efficiency

- Partial regenerations (as observed during the sequence of NEDCs) partially empty the DPF and lead to smaller increases in solid particle numbers.

It is clear that a number of these effects may combine to give the observed particle number emission level from any given test. However, as Figure 91 shows, particle size distributions are unaffected. This observation can be interpreted as evidence that while the magnitude of emissions changes, the chemistry of the particles – almost certainly soot – does not.

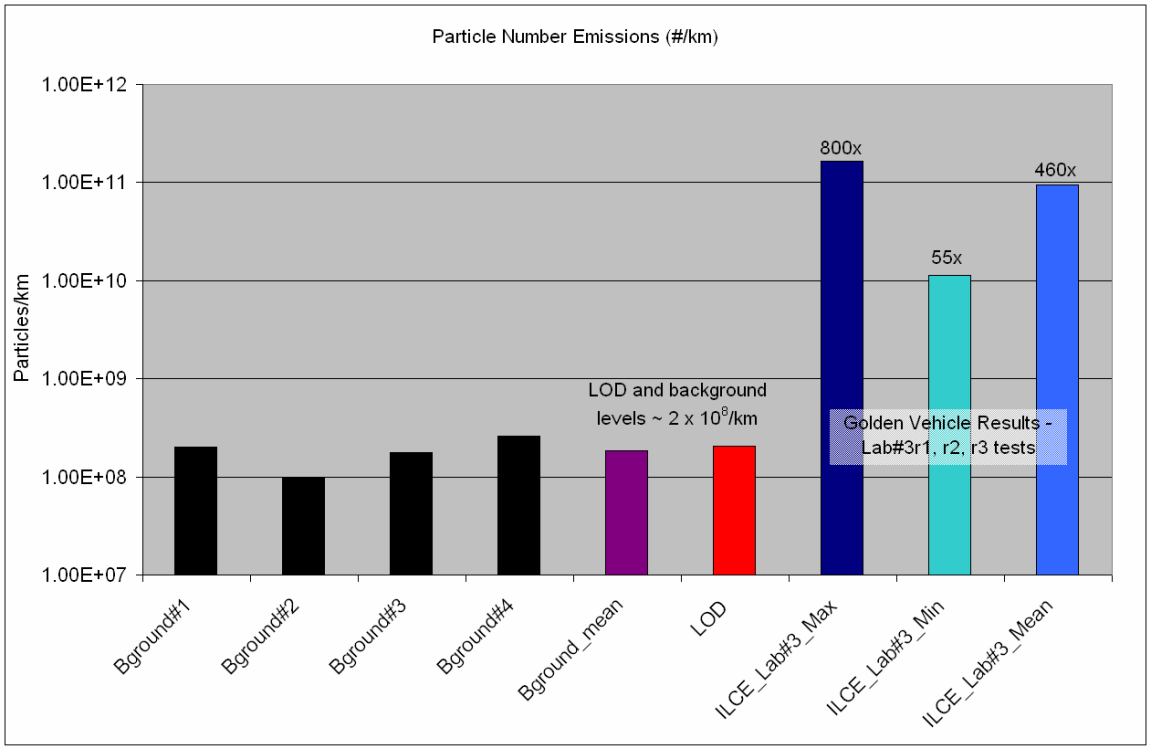
6.3 Particle Number Background and Limit of Detection

In Section 4.3.7, the LOD and background levels for particulate mass were shown to be of the same order as the Golden Vehicle's emissions rate. When the same comparative process is performed with particle number measurements, the following observations can be made (Figure 92):

- Both LOD and background levels for particle numbers are of the order ~2 x 10^8 particles/km
- Particle number LOD is 55 times lower than the lowest NEDC emissions measurement made from a cold start NEDC at Lab#1,R3
- Particle number LOD is 800 times lower than the highest NEDC emissions measurement made from a cold start NEDC at Lab#1,R3

From these data it is clear that the number measurement method can easily discriminate between vehicle emissions and background level. However, it is also apparent that the difference between background levels and vehicle emissions levels is so great (460 times for the average NEDC emission) that it is unnecessary to subtract the background.

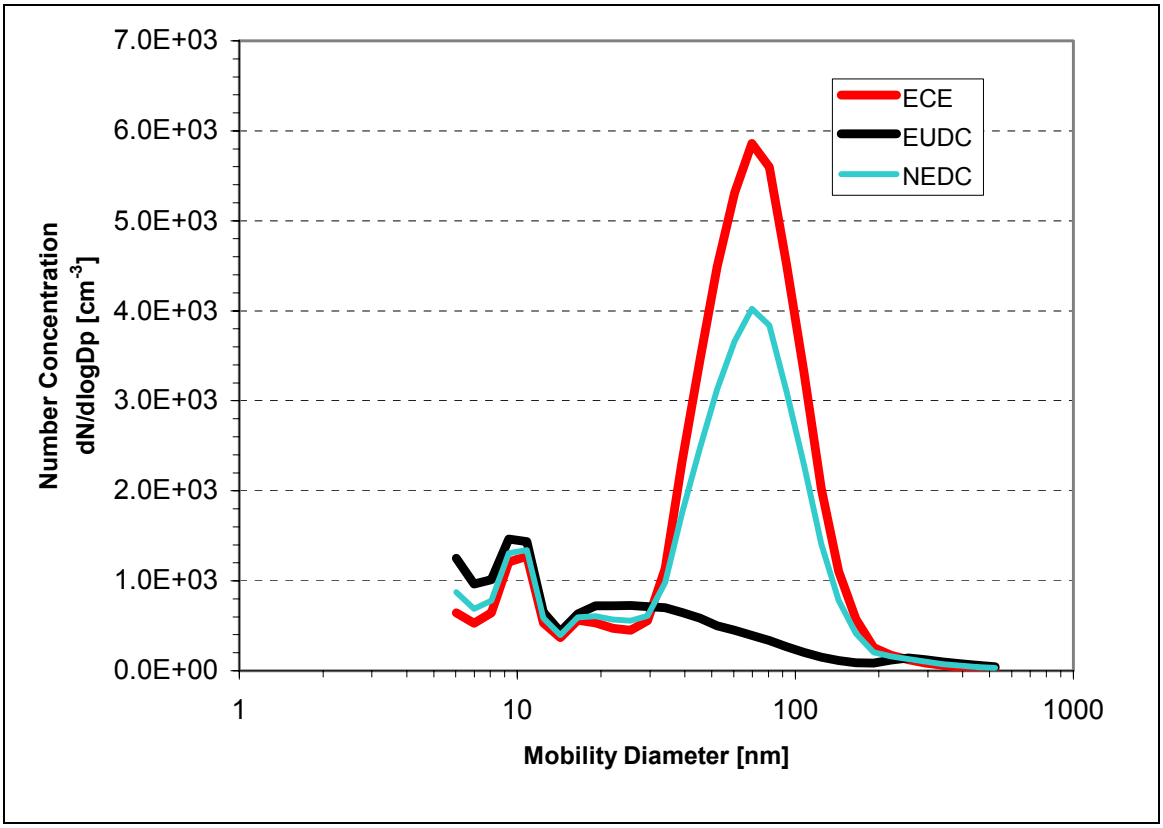
Figure 92: Comparison of Background Particle Number and LOD with Lab#3 Data



6.4 Particle Size Distributions From ECE, EUDC and NEDC Cycles

Figure 86 showed particle size distributions from regenerating EUDC cycles to be predominantly nucleation modes, these in turn dominating the overall particle number emissions of respective NEDC cycles. However during non-regenerating EUDCs, particle emissions are very low and the contribution to the NEDC cycle is minimal (Figure 93). In this case the ECE phase emissions, dominated by the carbonaceous accumulation mode (30 to 200nm) dictate the form of the overall NEDC cycle distribution.

Figure 93: Particle Size Distributions from an NEDC Cycle



6.5 Implications of Regenerations on Particle Number Emissions

In European regulatory procedures, an increase in emissions from periodically regenerating emissions control devices such as actively regenerated DPFs must be factored in to a vehicle's emissions.

During this work, it was observed that the Golden Vehicle regenerated at intervals of ~1100km, or once every 98 NEDC cycles. The precise periodicity is also dependent on the drive cycles used and the fuel type. On this basis, to establish the particle number emissions contribution from regenerating tests, the weighting for regeneration to non regenerating tests would be: (1/98 x regenerating contribution) + (97/98 x non-regenerating contribution).

The regenerating contribution was determined by assuming that at least two NEDCs driven back to back would be required for full regeneration: one hot and one cold. The emissions from each of these were determined from averaging the regenerating-cold and regenerating-hot cycles' data shown in Figure 94. These two results were then averaged.

In Figure 94, cold start tests are shown in black, hot starts in red. Tests that showed regenerations during the EUDC phases show 'hatched' shading.
The average regeneration result was then proportioned as described above, to determine the weighted NEDC cycle emission. Data are shown in Figure 95.

Figure 94: Solid Particles From Regenerating And Non-Regenerating NEDC Tests

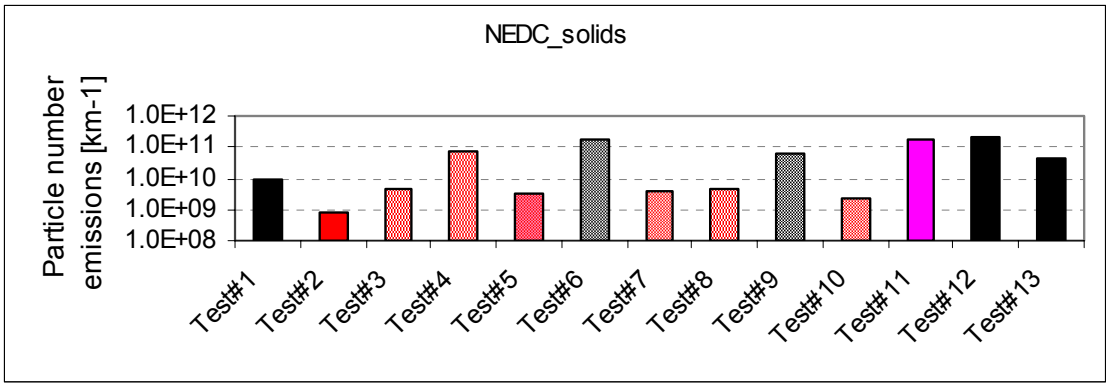
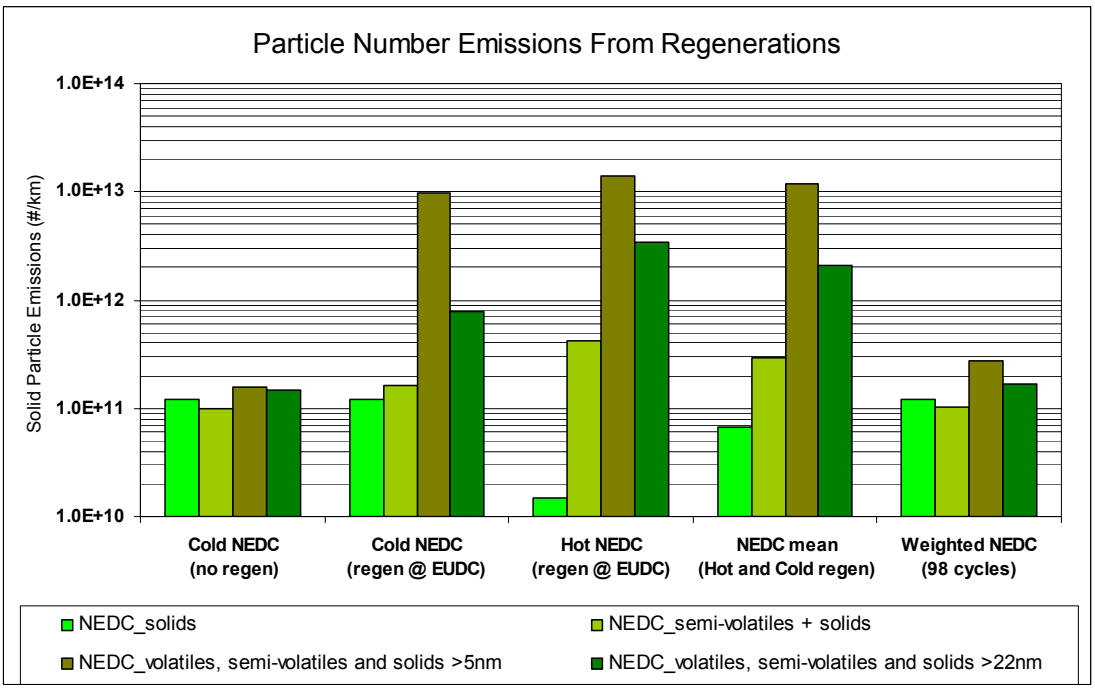


Figure 95: Effects of Regenerations on NEDC Cycle Emissions



Interestingly, from this series of regenerations, it was calculated that an NEDC cycle containing a complete regeneration would produce solid particle emissions similar to a non-regenerating test and when this contribution is divided across 98 tests, there is no effect on the weighted emissions rate.

Under steady state regeneration, the worst case for solid particles was observed with the active regeneration at 120kph where solid particles were increased by ~60 times. Even the effect of this is to increase weighted cycle particle numbers by <0.5%.

In general, for this vehicle with this DPF, it would not be necessary to include regenerations in the regulatory assessment for solid particles. However, other vehicles

and emissions control systems may perform differently and it may be wise to consider monitoring particle numbers during regenerations.

It should also be noted that volatile particle emissions were observed to increase by >5000 times in certain cases, this would be sufficient to increase NEDC cycle emissions by a factor of ~10 if included in the weighted NEDC result.

6.6 Mass Estimates from EEPS compared with Filter Masses from the PMP Method

An estimate of mass concentrations can be calculated from particle size distributions measured by the EEPS. These are calculated using the particle size and number concentration by converting the size to volume and then to mass using an assumed particle density.

From the EEPS manual[1]: mass concentration may be calculated from the following equation:

$$dM = dN \,.\, (\pi/6) \,.\, Dp^3 \cdot \rho$$

where Dp is the geometric midpoint of the particle size channel and ρ is the density. This quantity is related to Volume concentration by the simple factor ρ.

In the following comparison, the density factor is taken to be unity. However, research has shown that the real density of particle agglomerates tends to decrease as mobility size increases [17]: from ~1g/cm^3 at 50nm to ~0.4g/cm^3 at 200nm. This may be engine and operating condition dependent, but assuming a particle density of 1g/cm^3 across the size range will certainly over-estimate the particulate mass contribution from the measured size distribution. On this basis, the masses calculated from the EEPS data should be considered theoretical maxima, with actual masses up to 70% lower based upon the densities described above.

Figure 96 shows measured filter masses (mg/km) compared with calculated EEPS masses. These tests include non-regenerating cold start NEDC cycles and several hot and cold NEDCs from the series of regeneration tests described in previous sections, Table 16 and Table 17. There is also one test (the last bar) included that was conducted with full preconditioning (120kph+3xEUDCs). EEPS data can be considered as the mass emitted by the engine as volatile or solid particles in the size range ~5nm to ~500nm.

6.6.1 NEDCs

From standard start NEDCs (the first 5 columns of Figure 96), EEPS masses comprise between 3% and 5.5% of the corresponding filter masses. As discussed in previous sections, this mass is virtually all solid particles and probably elemental carbon. The much higher filter mass probably reflects the sum of the small elemental carbon particles emission and gaseous volatiles collected by the sample filter.

[1] http://www.tsi.com/documents/1980494E-3090_EEPS.pdf

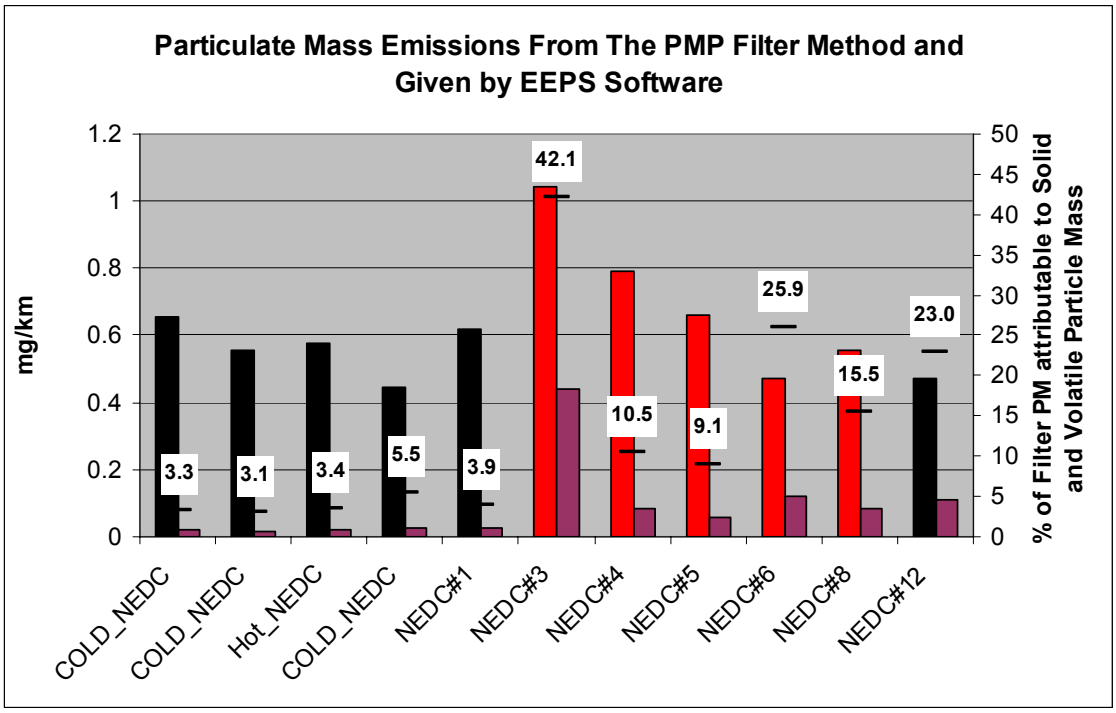
6.6.2 NEDCs with Partial Regenerations During EUDC Phase

The next column, labeled NEDC#3, is the first cycle in which an EUDC phase regeneration occurred. This shows EEPS masses at ~42% of the filter masses. This can be explained by the emission, in response to the regeneration, of hydrocarbons of various volatilities including low volatility materials that condense on the sample filter. These particles are seen as a nanoparticle mode with a peak at ~35nm in Figure 86 which has sufficient total volume to substantially impact calculated mass. The four subsequent NEDCs: #4, #5, #6 and #8 all contained EUDC phase regenerations during which unburned fuel HCs were emitted. These generated large nucleation modes which contribute to EEPS mass and also adsorbed to the filter paper. EEPS contributions to filter PM ranged from 9% to 26%.

6.6.3 Cold Start Test Following Regeneration and Preconditioning

The final column (NEDC#12) shows a 23% contribution of EEPS mass to the filter mass from a cold start NEDC. In this case, the DPF has just completed regeneration and is relatively empty, and a 120kph + 3xEUDC was performed prior to the test. Together these lead to high levels of particle emissions through low DPF filtration efficiency and through interstitial particle release as the vehicle starts. PM filter mass was broadly similar to that from the earlier cold start tests. It is likely that solid particle emissions were increased in response to higher penetration through the 'empty' DPF, but this contribution to total mass is small compared with the volatiles collected. The PM method is incapable of discriminating this effect and consequently the mass reported is similar to the results from the earlier NEDCs.

Figure 96: PM and EEPS Mass Emissions From Selected Tests



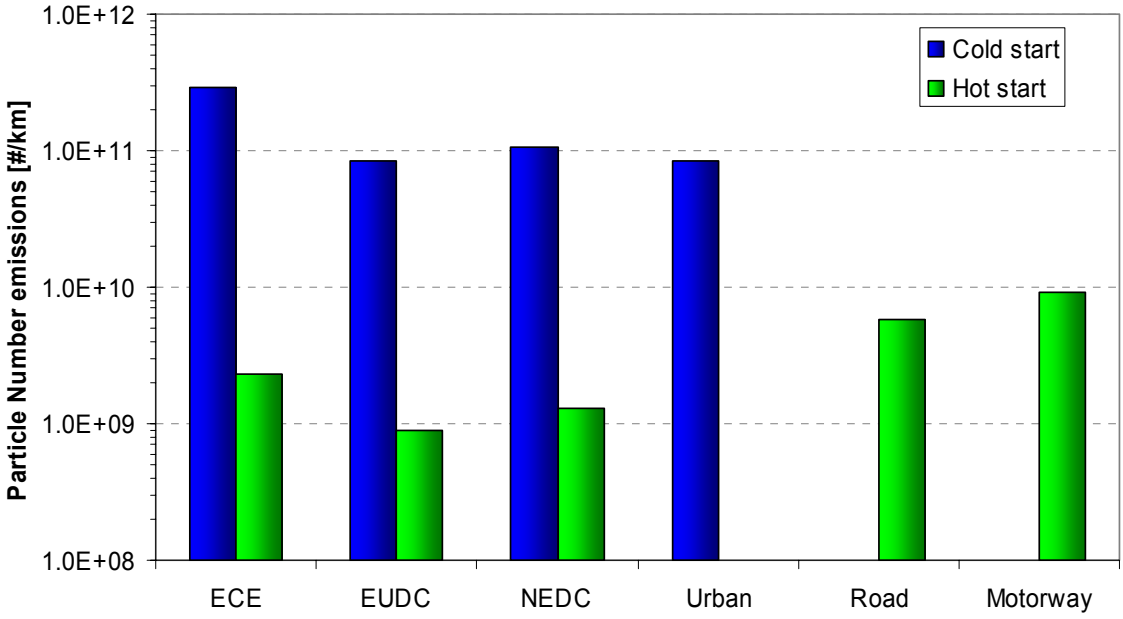
It is clear from these tests that the filter method collects elemental carbon, solid 'low volatility' hydrocarbon particles and non-particle volatiles. Agreement between number calculated mass emissions and filter measurements improves as the volatility of the exhaust hydrocarbon species reduces. It is possible that the heavier hydrocarbons displace the lighter ones within the filter medium.

Under normal engine operation the non-particle volatiles dominate the measured mass, comprising ≥ 95% of the total filter mass. This is broadly consistent with Laser Induced Incandescence analyses (Section 8.2, Figure 115) that showed that typically ~2% of filter mass from cold start tests was elemental carbon.

6.7 Particle Emissions from Other Drive Cycles

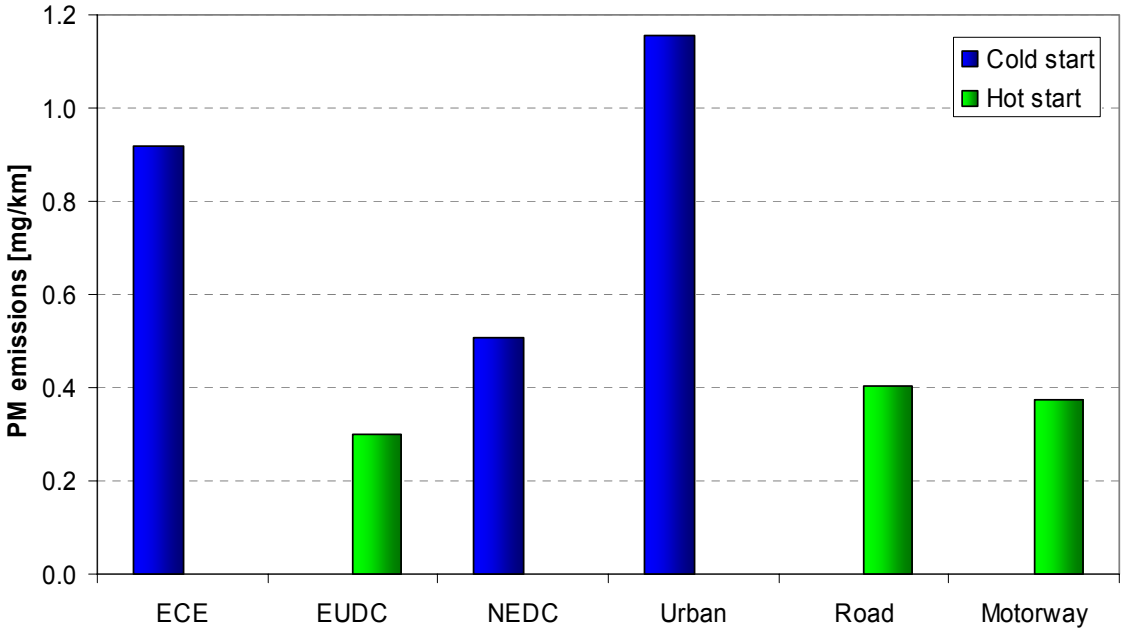
Also during tests at Lab#1r3, a limited number of additional drive cycles were driven on the Golden Vehicle. These included the ARTEMIS 'real-world' urban, rural and motorway cycles [18].
Particle number emissions from these tests (Figure 97) showed similar trends and magnitudes to the NEDC cycle. Cold start tests (following a soak period and driven preconditioning: in these experiments an EUDC was also treated as a cold start cycle) irrespective of cycle always gave emissions in the region of 10^{11}/km, while hot start tests gave emissions at least a factor of 10 lower. Highest emissions were seen from the shorter cycles, with lowest emissions from the longer cycles.
From these data it is hypothesised that the particle number emissions of the vehicle are dependent primarily on the preconditioning and the filtration characteristics of the DPF. After the initial emission of carbon from the DPF – which is closely related to preconditioning- subsequent emissions are related to DPF fill (and filtration) and DPF substrate porosity. Thus emissions appear to almost independent of drive cycle: per km emissions only elevated from drive cycles that divide by small distances.
It is possible that contributions of solid non carbonaceous particles might be elevated in response to very high load and speed conditions in real-world drive cycles. However, as passive regeneration data showed (Figure 84), the contribution of solid particles is expected to be small.

Figure 97: Particle Number Emissions – Various Emissions Cycles (NEDC and ARTEMIS cycle parts: a) Urban b) Road and c) Motorway)



As Figure 98 shows, particulate mass emissions from cold start tests tended to be higher than those from hot start tests, but most results were in the region of 1mg/km. When the typical variability of PM emissions in the ILCE_LD is considered (+/- 60% a 2-sigma) this appears to be a real trend: with hot start emissions levels at perhaps 50% of those from cold tests. This may be a through a reduced level of volatile hydrocarbons available for absorption by the filter from hot tests as the oxidation catalyst is more efficient. However, any differences between different cold tests' emissions would not be significant.

Figure 98: Particulate Mass Emissions Different Cycles



7 EMISSIONS RESULTS: GASES

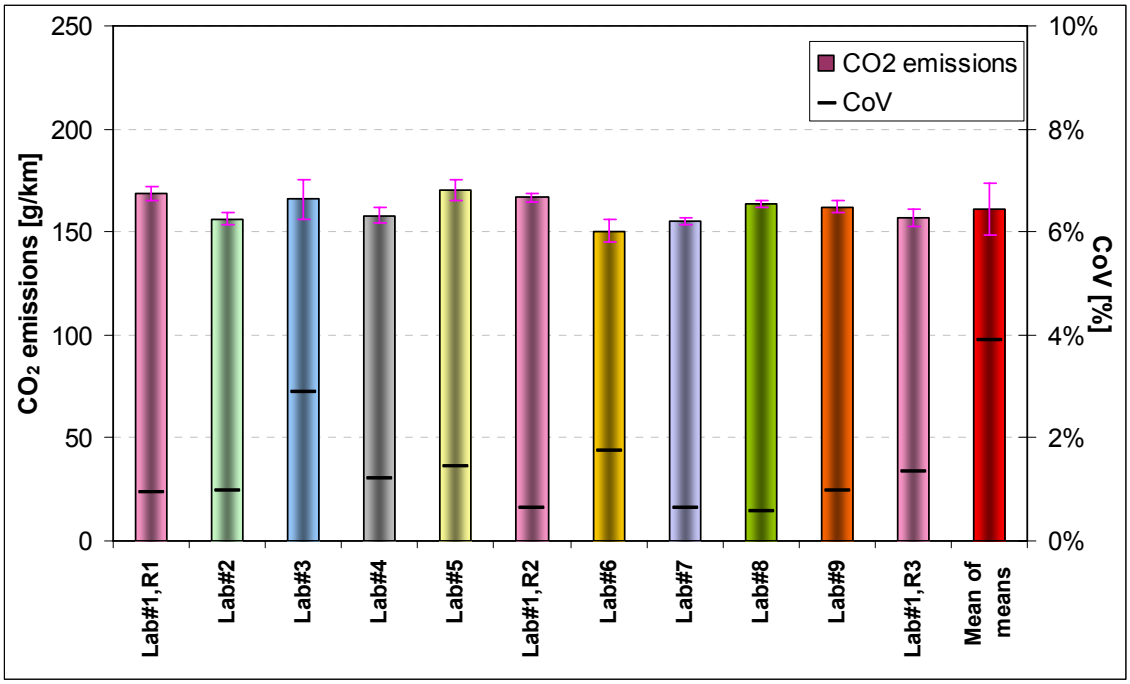
The results of gaseous emissions from valid NEDC tests are presented in this section. Data that are excluded were identified using conventional R83 criteria and the mass criterion described in Section 3.

7.1 Valid Test Results From The Test Programme

7.1.1 Intra-Lab And Inter-Lab Variability: Golden Vehicle

In the following sections, charts are presented of NEDC cycle mean data with 2-*S* repeatability bands from all individual laboratories, along with the 2-*S* reproducibility bands around the mean of the individual laboratories results. All data are used to calculate the mean emissions, excluding mass based and R83 criteria outliers.
Gaseous emissions data from the Golden Vehicle were consistent with the expected levels of CO_2 (155g/km), CO (0.031g/km), HC+NOx (0.182 g/km) and NOx (0.166 g/km) quoted for the test vehicle by the UK Vehicle Certification Agency[2].
Mean carbon dioxide emissions (Figure 99) from the Golden Vehicle ranged from 150g/km to 170g/km with a mean value of 161g/km. Repeatability was generally good, with *CoV*s generally below 3% and the reproducibility level at <4%.

Figure 99: Carbon Dioxide Emissions Repeatability and Reproducibility, Au-DV1



As expected from a Diesel vehicle equipped with an oxidation catalyst, carbon monoxide emissions (Figure 100) were low: always below 100mg/km with a mean emission of 56mg/km. There were some significant differences between laboratories but these are unlikely to be indicative of any substantive shift in engine operation.

[2] www.vca.gov.uk

Figure 100: Carbon Monoxide Emissions Repeatability and Reproducibility, Au-DV1

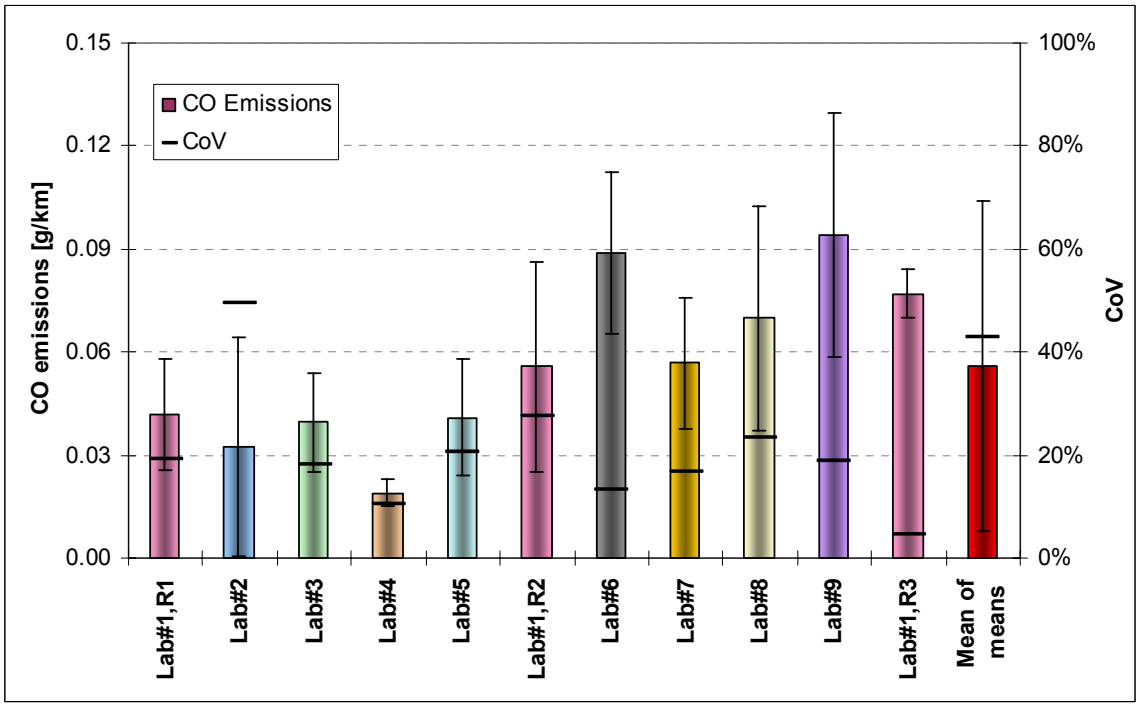
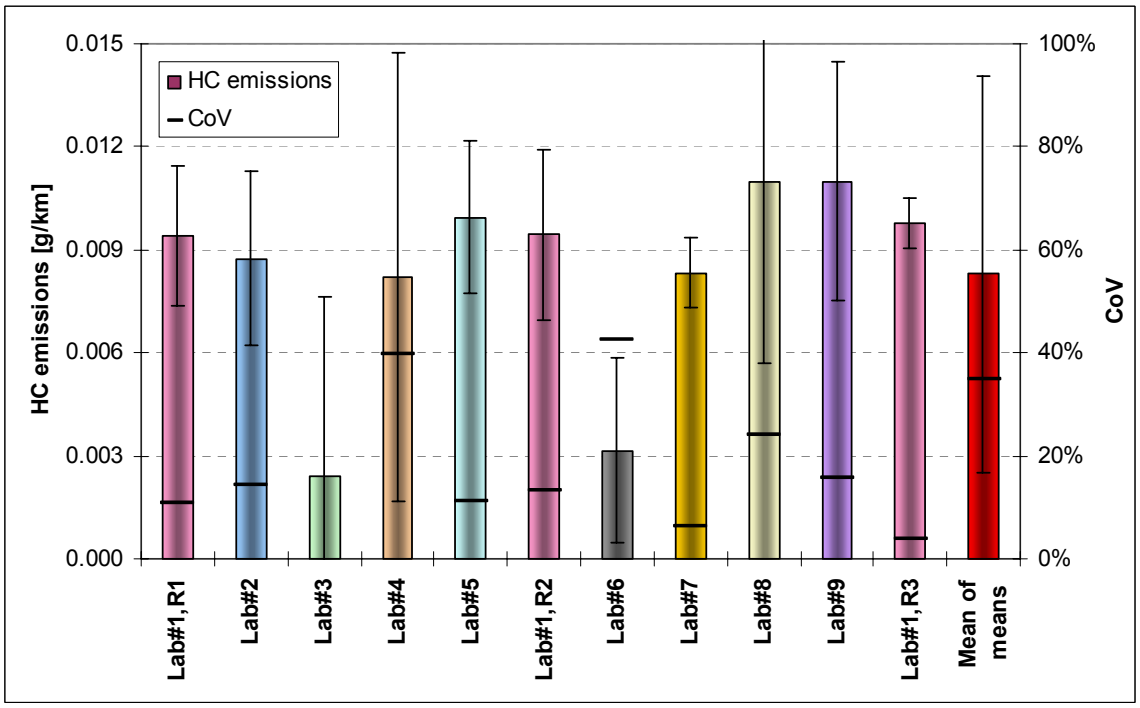


Figure 101: Hydrocarbon Emissions Repeatability and Reproducibility, Au-DV1



As observed for CO, hydrocarbon emissions (Figure 101) from the Golden Vehicle were also low and varied from lab to lab in the range 2 to ~10mg/km.

Oxides of nitrogen emissions (NOx, Figure 102), were consistently below the 0.25g/km required for Euro 4 compliance. There was a directional increase in emissions from the Golden Vehicle measured between Lab#4 and Lab#5, though this was not significant at 2-*S*. However, the results from Lab#5 were significantly higher than those for Labs#1,

#2 and #3. It is considered likely that test work conducted at Lab#5 which involved passive regeneration of the aftertreatment system, may have led to a small change in the vehicle operation and/or catalyst function and thus increased NOx emissions. This passive regeneration is representative of real-world driving and may similarly influence emission levels during in-service testing.
HC + NOx emissions, shown in Figure 104, were compliant with Euro 4 levels and showed emissions effects similar to those of the dominant NOx fraction. Mean emissions levels were ~0.23/km with a reproducibility level of ~10% across the 11 test sets.

In general, gaseous emissions reproducibility across the participating laboratories was at expected levels, with HC and CO poorest due to low emissions levels with an oxidation catalyst (3 – 45% *CoV*), NOx (and HC+NOx) showed ~10% *CoV* with CO_2 ~3%. However, it is clear that there are small differences in the emissions levels for particular gaseous species at certain laboratories and that these differences may be due to the consequences of subtle engine or catalyst changes related to impending or just-completed regenerations. Specific effects on gaseous emissions were observed at Lab#3: a regeneration event occurred during the 120kph high temperature conditioning prior to test NYM_005 (5^{th} test on the Golden Vehicle). Although the regeneration had completed, this still destabilised the vehicle to a certain extent, resulting in elevated CO, CO_2 and NO_X levels in the subsequent test (Figure 103). No significant effect was observed on HC or PM emissions.
It seems likely that the advent of discontinuously regenerating emissions control systems may lead to higher baseline variability in gaseous emissions.

Figure 102: NO + NO_2 Emissions Repeatability and Reproducibility, Au-DV1

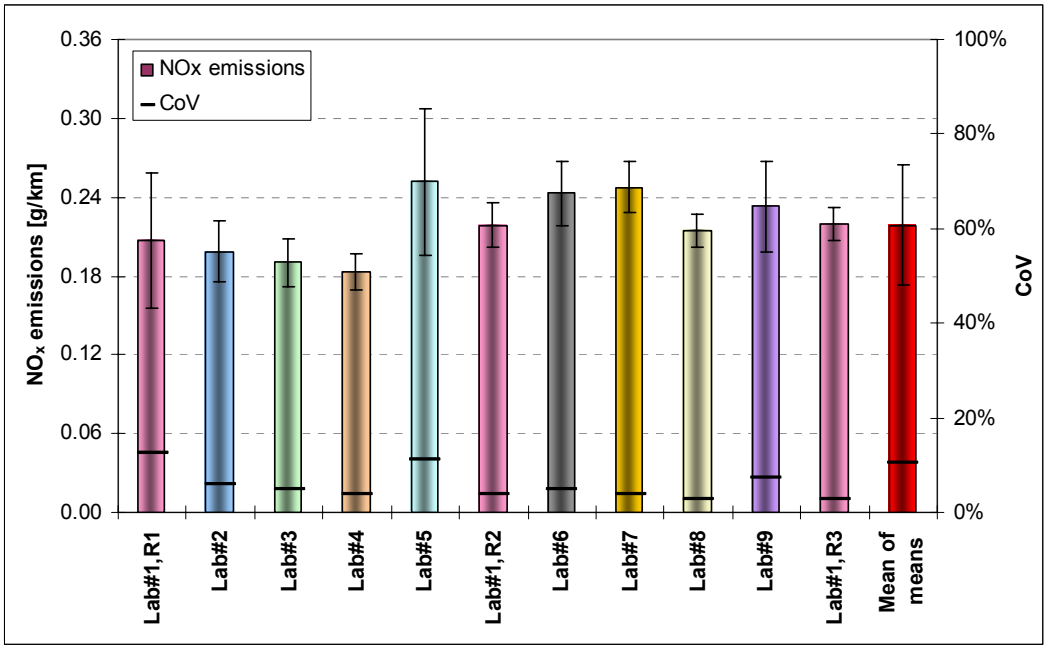


Figure 103: Post-regeneration increase in Emissions

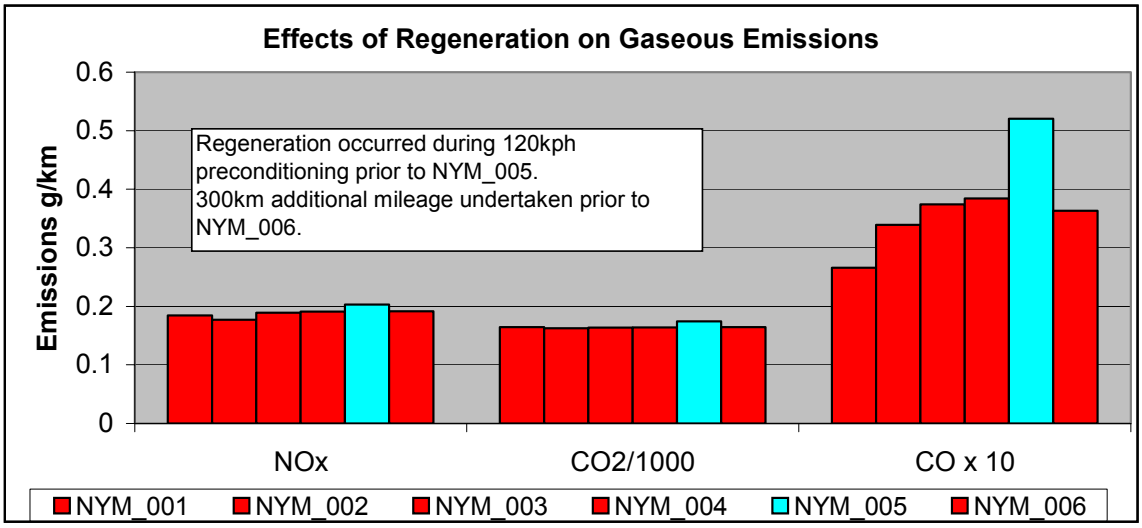
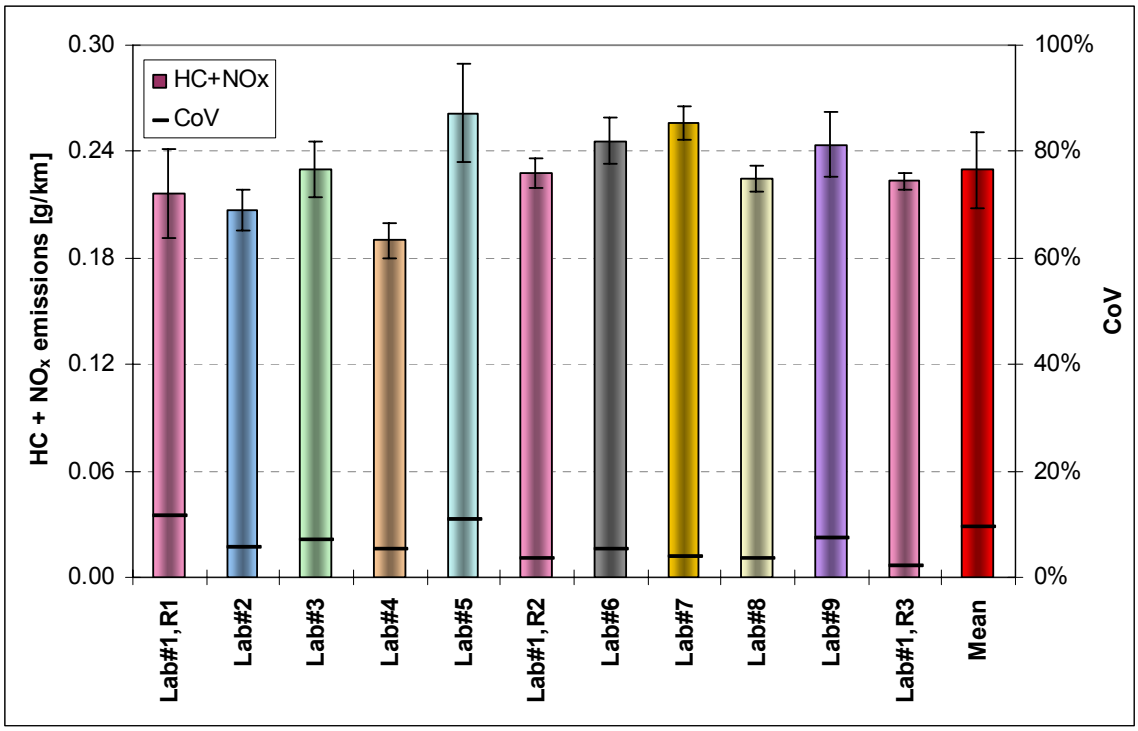


Figure 104: HC + NO_x Emissions Repeatability and Reproducibility, Au-DV1



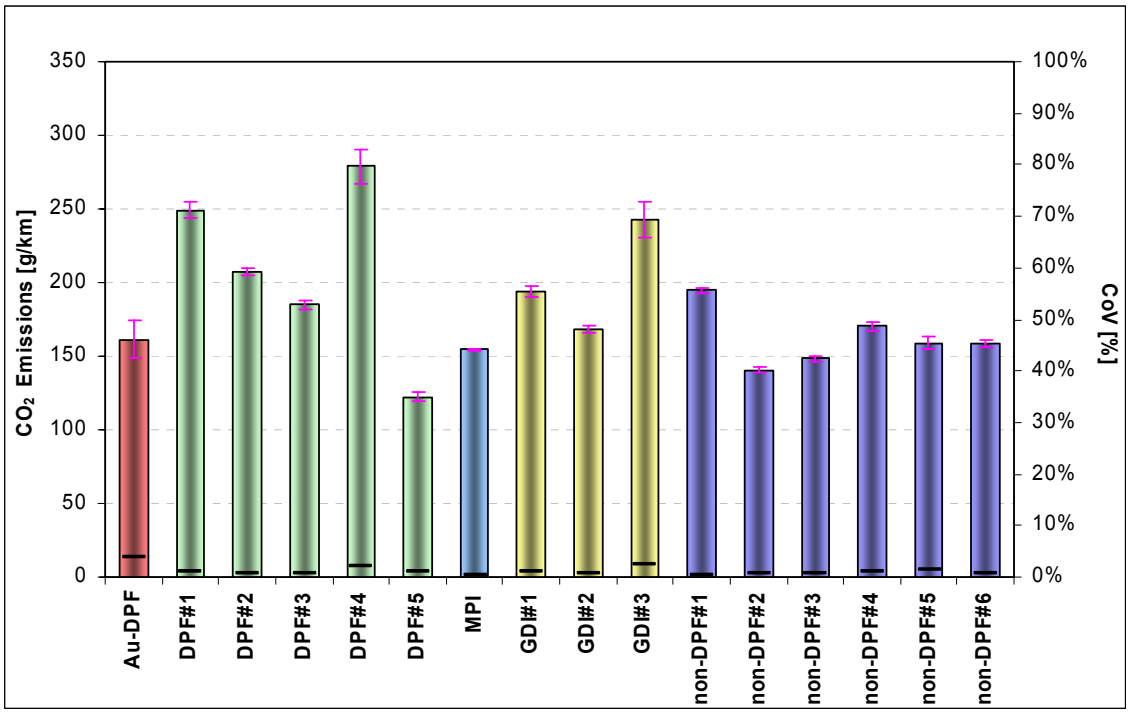
7.1.2 All Vehicles Emissions

In this section, mean gaseous emissions data from all test vehicles are shown with 2*s* repeatability (2*s* reproducibility from the Golden Vehicle). Euro 3, Euro 4, Euro 5 (proposed) limits are indicated on the charts, though it should be noted that emissions results above the appropriate limits may just reflect statistical outliers, production tolerances and expected deterioration.

Carbon dioxide emissions, shown in Figure 105, indicate the expected trend of lowest emissions from the conventional Diesel vehicles and higher results from the DPF-

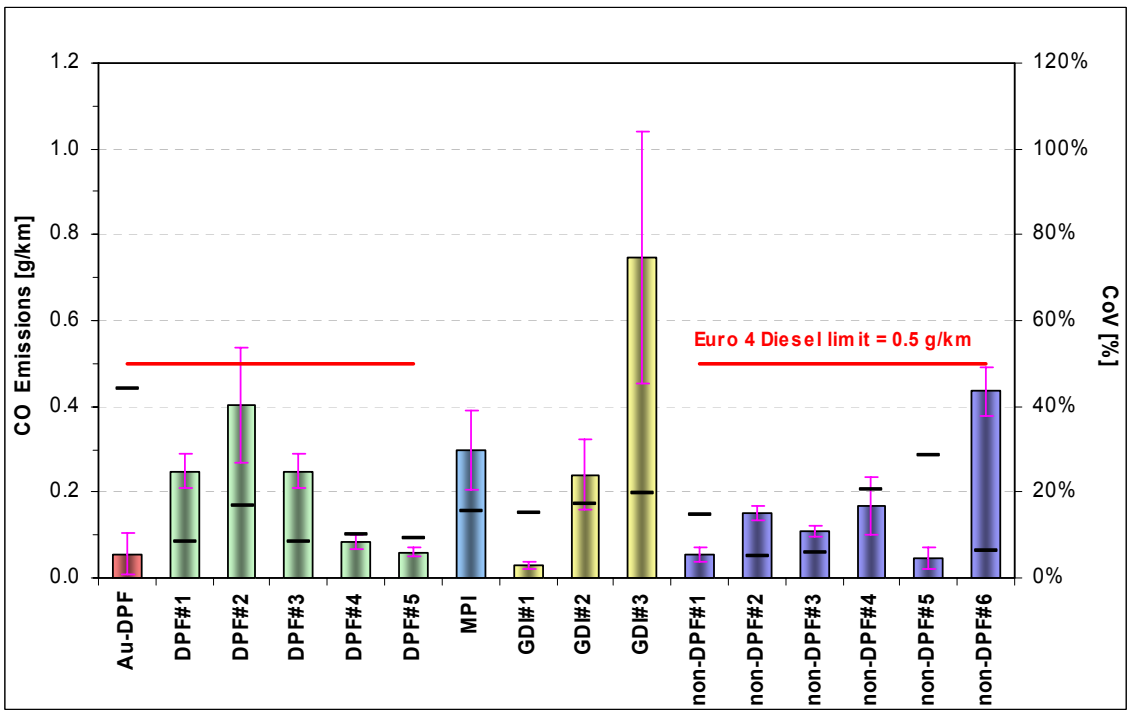
equipped Diesel and spark-ignition types. It is worth noting that the smallest DPF-Diesel (DPF#5) achieves ~120g/km during non-regenerating operation.

Figure 105: Carbon Dioxide Emissions, All Vehicles



Carbon monoxide emissions shown in Figure 106 were consistently below Euro 4/5 levels for all vehicles including G-DI#3, which is calibrated for the Japanese emissions cycles (11 mode cold and 10-15 mode hot tests).

Figure 106: Carbon Monoxide Emissions, All Vehicles



Hydrocarbon emissions (Figure 107) were typically <50mg/km but were elevated for two of the G-DI vehicles.

NOx (Figure 108) and HC + NOx (Figure 109) emissions were generally close to the Euro 4 limit for most of the Diesel vehicles. The three vehicles which showed substantial emissions above 0.25g/km were DPF#2 and non-DPF#6 plus DPF#4 which were a Japanese calibration vehicle and a European light-duty passenger car and LDV respectively.

Figure 107: Hydrocarbon Emissions, All Vehicles

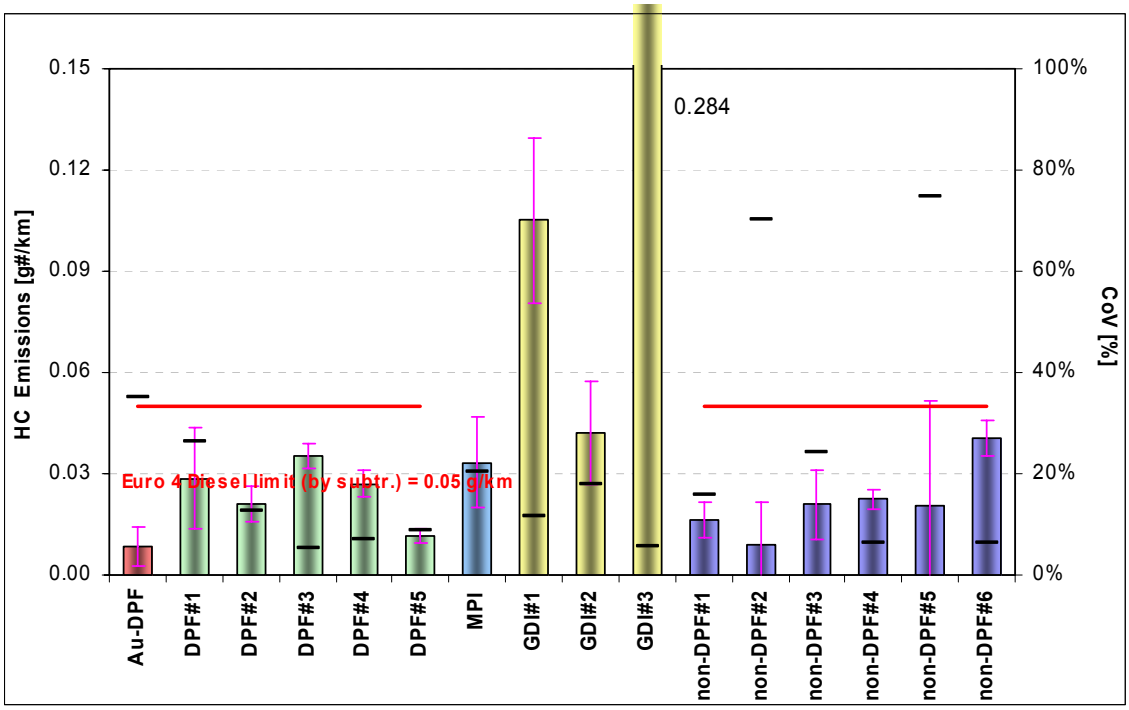


Figure 108: Oxides of Nitrogen Emissions, All Vehicles

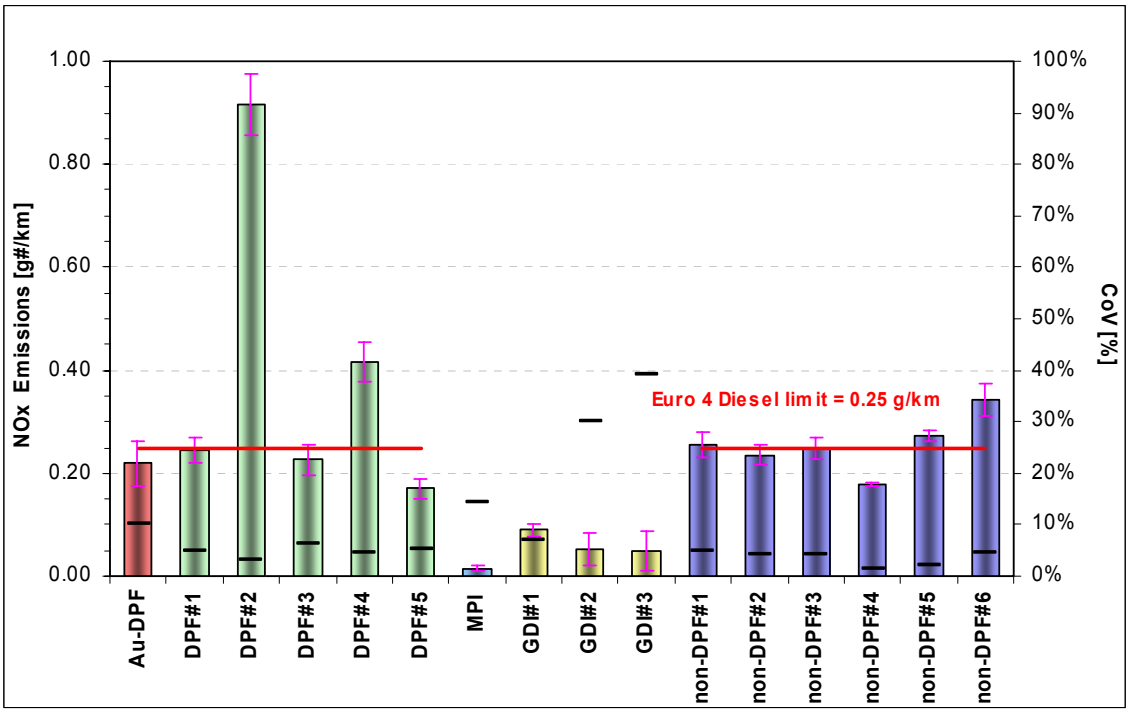
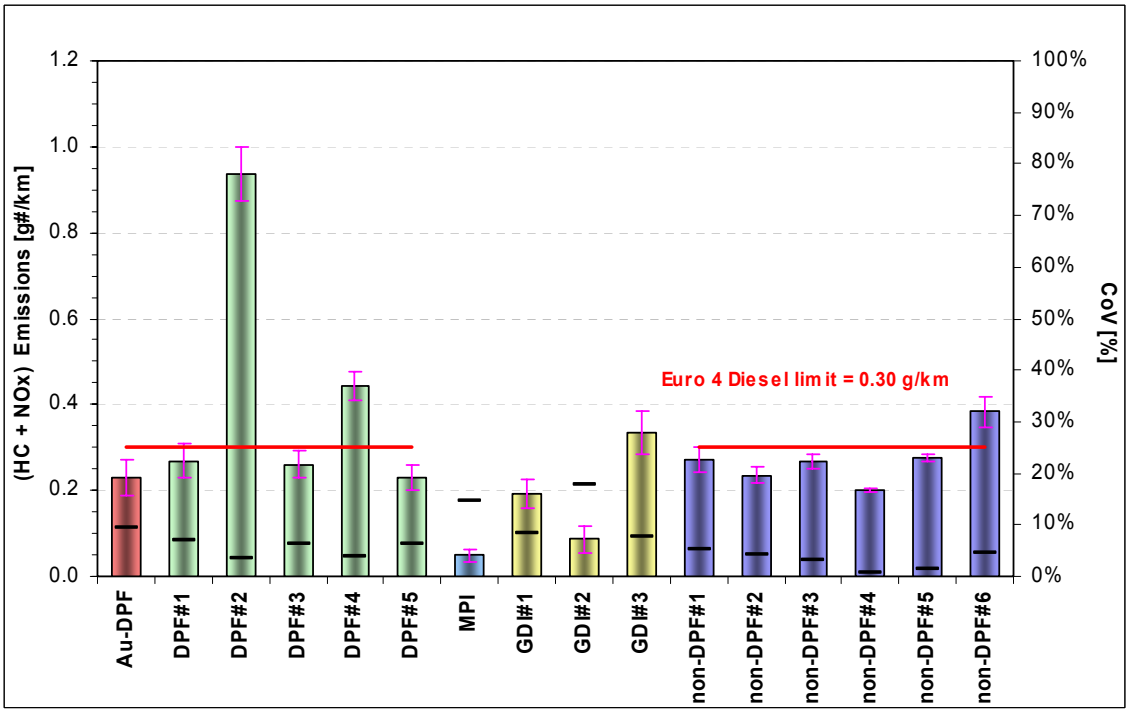


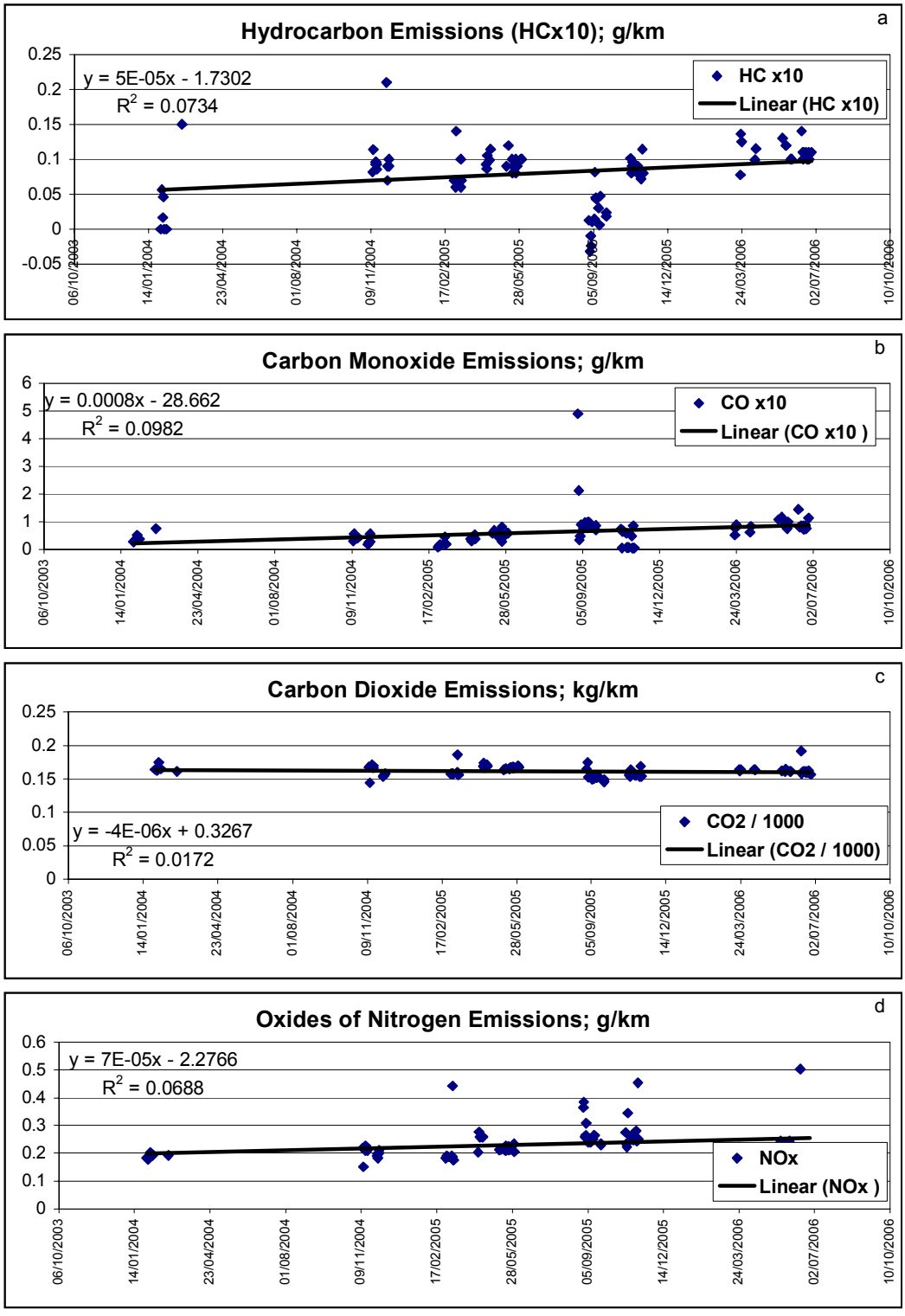
Figure 109: HC + NOx Emissions, All Vehicles



7.2 Long-Term Vehicle Behaviour

Time trends of regulated gaseous emissions are shown in Figure 110. These show all data (from valid and invalid tests) and indicate that lab-to-lab differences are much greater than any possible evolution in emissions characteristics over time.

Figure 110: Gaseous Emissions Show No Substantial Long-term Trends



8 MASS AND NUMBER MEASUREMENTS COMPARED

8.1 Correlation with All Vehicle Types

When mean mass and mean number results from all vehicle types are considered and compared (Figure 111), it is apparent that reductions measured by the PM method also reflect directional reductions in particle number emissions.

The linear relationship appears to hold true for conventional Diesels, lean-G-DI and possibly for the vehicle equipped with the increased porosity DPF (DPF#3).

The common theme between all these vehicles is the presence of carbon, even if at very low mass concentrations, during substantial periods of the drive cycle (Figure 112) and solid particle emissions which correspond to cruises and steady states like those of a conventional Diesel.

Figure 111: All vehicles - Relationship between PMP Mass and Number Emissions

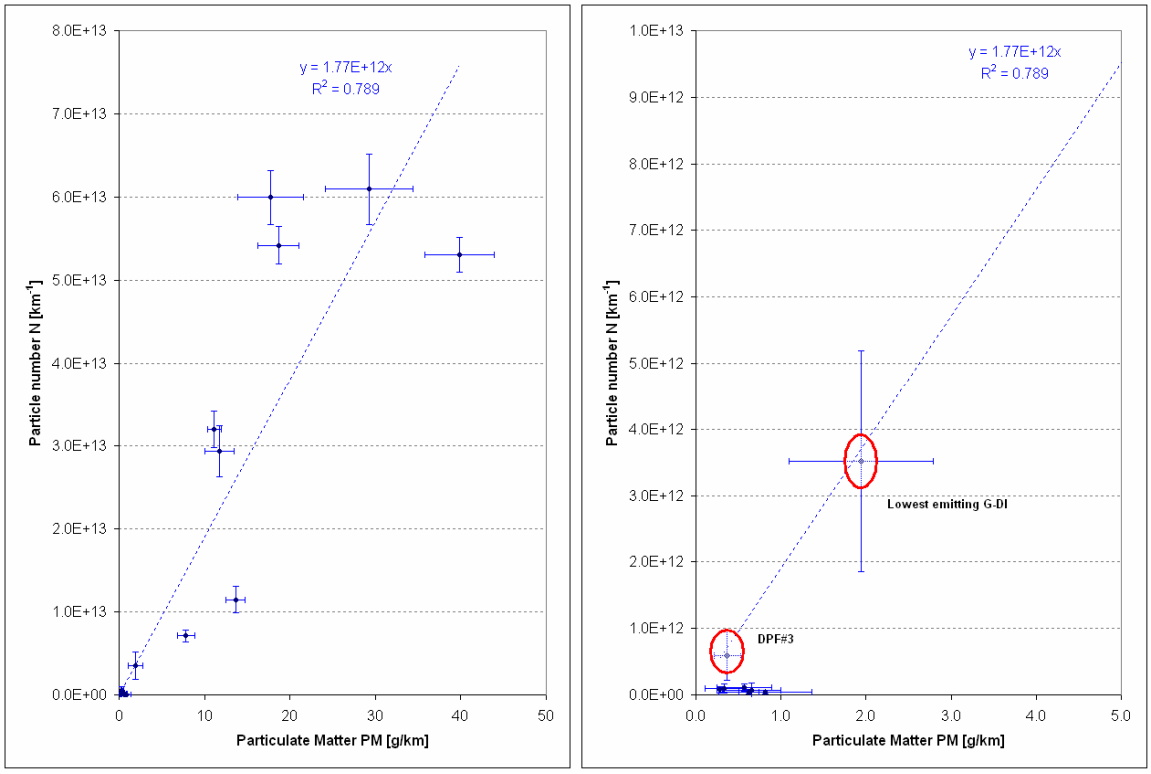
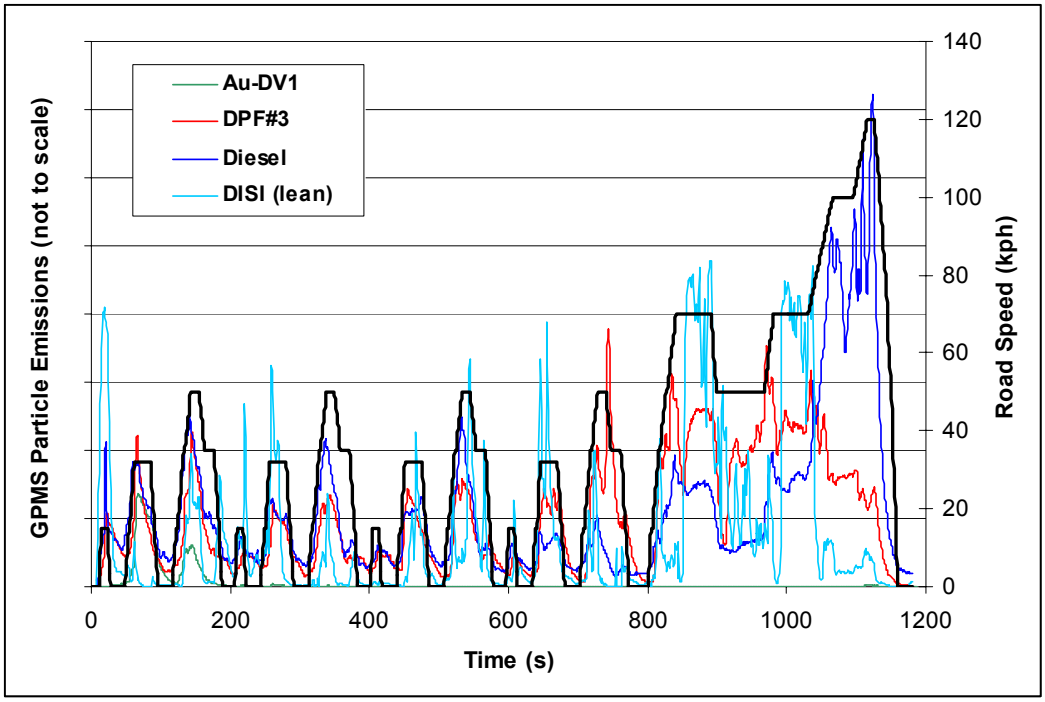


Figure 112: Solid Particle Emissions - Various Vehicle Types



8.2 Correlation with Highly Efficient Wall-flow Equipped DPF Vehicles

The relationship between mass and number breaks down with efficient wall-flow filters (Figure 113), where carbon is either totally eliminated, or emitted only in relation to specific events such as cold starts or regenerations. An example is shown for the Golden Vehicle where Laser Induced Incandescence (LII) data taken at Lab#7 shows that mass emissions of carbon particles during the first 200s of the NEDC cycle quickly reduce to baseline levels (Figure 115). The carbon mass emissions equate to ~6µg/km over the NEDC cycle, approximately 2% of the lab-to-lab NEDC PM mean.

Figure 113: Mass and Number Relationship- Low Porosity DPF and MPI

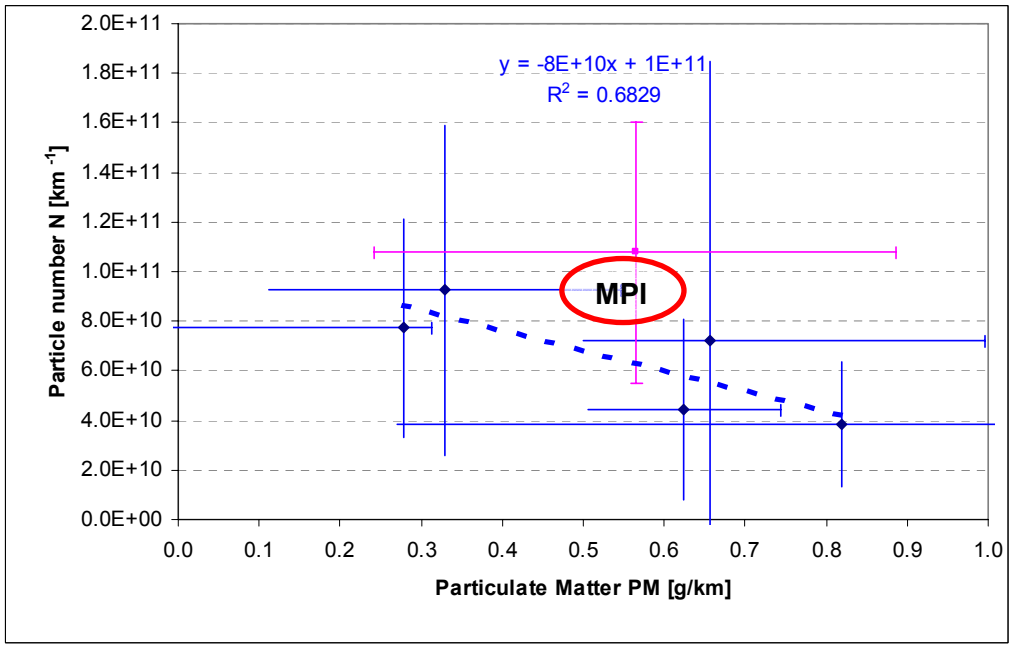
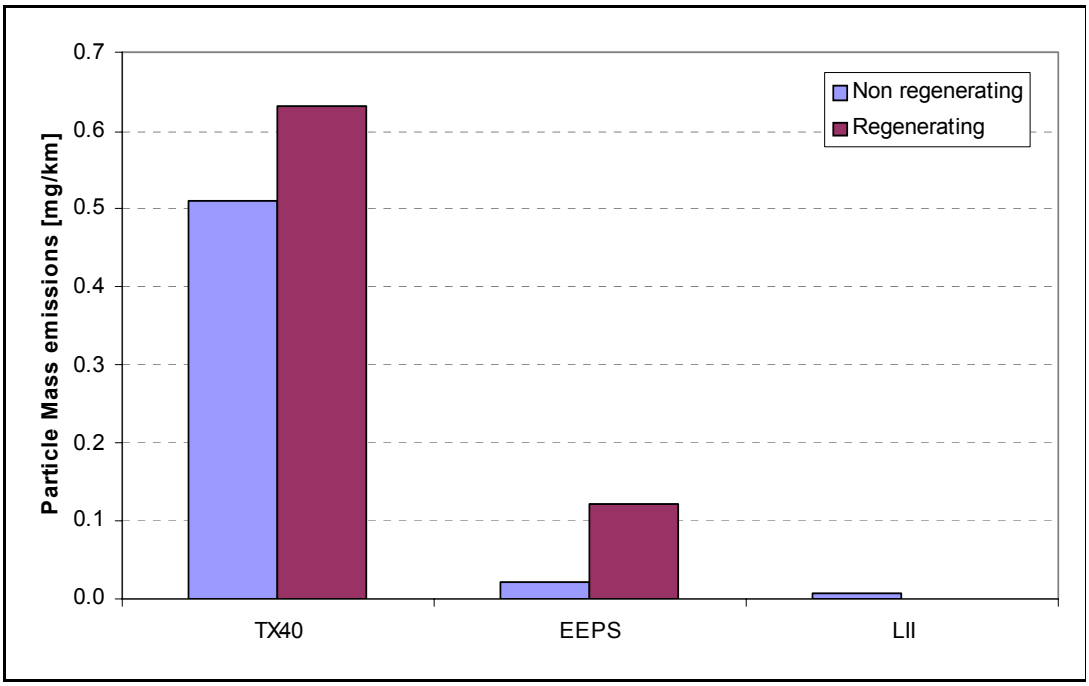
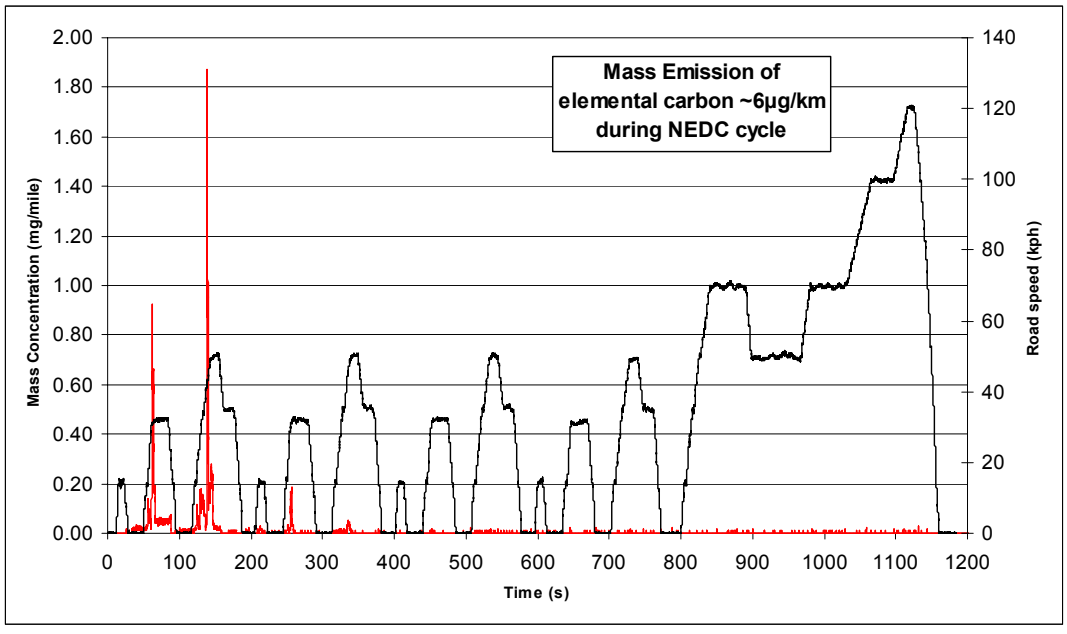


Figure 114: Regeneration Events Increase Cumulative and Real-Time PM Emissions



During the early part of DPF regeneration (commenced during the EUDC phase of a cold start NEDC and not completed before the cycle ended), particulate mass emissions can be seen to increase by both the filter method and by derivation from the EEPS data (Figure 114). However, no increase in carbon emissions is observed from LII. This suggests that the DPF was insufficiently regenerated to be porous to carbon, but that volatiles that contribute to filter mass are released by the exotherm associated with the regeneration.

Figure 115: Real-time Emissions of Carbon from the Golden vehicle by LII



Data from the ILCE_LD indicate that the presence of carbon is required for mass and number to correlate, and that no agreement should be expected from particulate matter

that has alternative chemical composition. This is consistent with earlier work within the PMP [8] where it was noted that the presence of carbon is required to stabilise particulate mass measurements, and that in its absence, variance in sampling parameters becomes a significant cause of poor accuracy, repeatability and reproducibility.
At the levels of particle number measured from the Low Porosity Wall-flow DPF equipped vehicles, and with carbon almost completely eliminated, measurements of mass made using a filter based method do not represent the particle emissions from the vehicle.

8.3 Comparative Repeatability

It was not an objective of the PMP ILCE_LD to directly compare the performance of mass and number measurement systems, but to determine the performance of these systems for DPF-equipped Diesels in comparison with non-DPF Diesels.
However, when such a comparison is drawn (Figure 116), by comparing *CoV*s some surprising observations can be made:

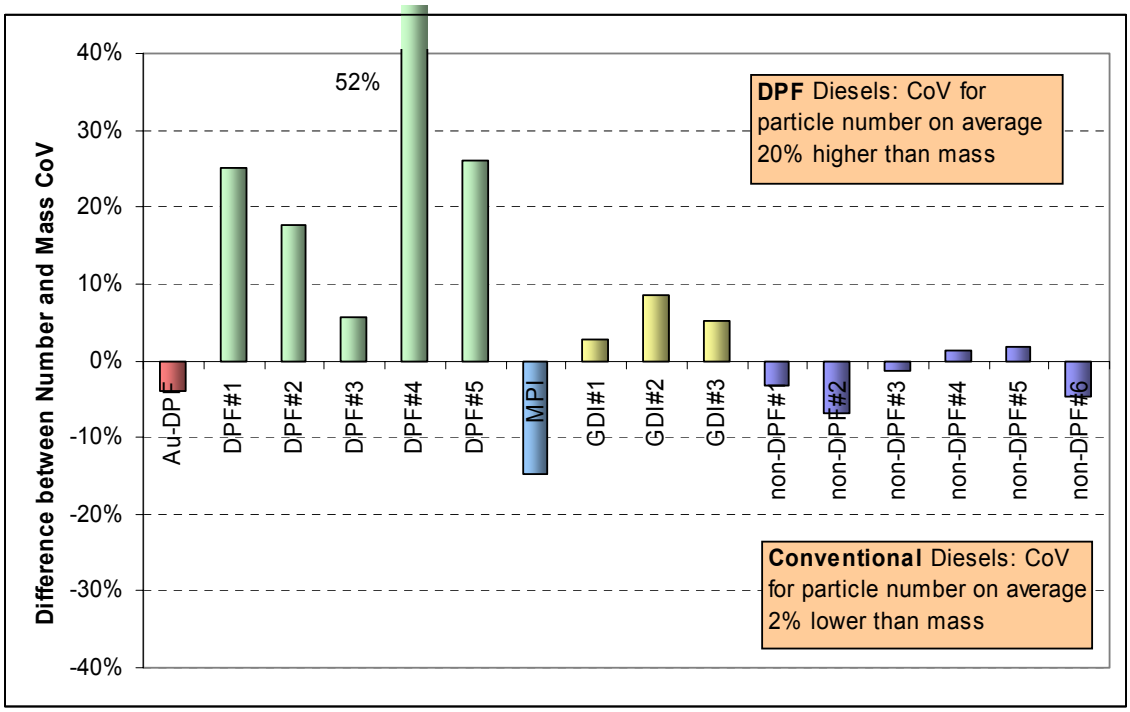
- The mass measurement method has a lower variance (*CoV*) than the number measurement for the majority of DPF-equipped Diesel vehicles
- The number measurement method has a lower variance (*CoV*) than mass for conventional Diesel vehicles

At first glance, this could be interpreted to mean that the particulate mass method should be favoured over the number method for DPF-equipped vehicles. However, repeatability is actually a poor measure for the basis of such a conclusion when post-DPF measurements are considered.

As analyses have shown during the ILCE_LD (5.1.1, 5.1.2), the particle number method can measure variances in DPF fill-state and filtration efficiency as changes in particle number emissions. These variances mean that for number measurements the DPF-equipped test vehicles can rarely, if ever, be considered to be a stable source of particles. The mass measurement method does not have the same ability to respond to these DPF effects and shows improved repeatability, but reduced sensitivity. There is sufficient evidence to propose that this is due to a volatile adsorption artefact that is possibly already quantified as hydrocarbons by the FID, which masks the 'real' mass emission of the vehicle, and can comprise >95% of the mass determined by the filter.

It is not currently clear exactly what (in chemical terms) is measured by the mass method in the absence of carbon, though it is understood that the glass-fibre element present in TX40 filters [8] more efficiently collects volatiles than the Teflon element. In addition, measurements outside the PMP [19] has shown that post-DPF PM collected on to Teflo filters can be extremely repeatable. These filters are known to be less efficient at collecting volatiles, (though in experiments during this programme they showed no significant difference [Figure 18]). The high degree of repeatability observed in one study [19] suggests that either the DPF used for this work has high porosity and is passing some stabilising carbon, or the filter is still collecting volatiles and these are masking the true variability observed with the number method.

Figure 116: Comparative Repeatability (as *CoV*) – PMP Mass and Number Methods



What is clear from these results is that data from a stable particle source (conventional diesels) show that the particle number method is both substantially more sensitive and more repeatable than the mass method employed in PMP.

9 DISCUSSION

9.1 PM measurement methods

It seems clear that the materials measured by the PMP mass method in the presence of an efficient silicon carbide DPF are gaseous (high volatility) hydrocarbons, low volatility hydrocarbons and elemental carbon. The dominant fraction is that of gaseous hydrocarbons and it is understood that Teflon-coated glass-fibre filters (TX40)[20] collect these volatiles mainly on the glass-fibre part. Earlier work in the PMP [8] showed that pure glass-fibre filters have an even higher volatile collection tendency than TX40. However, mass sampled using Teflo filters in the ILCE_LD showed no significant difference to TX40 results – suggesting that Teflo too collects at least some volatiles.

Evaluations of filter media were also undertaken as part of the US2007 methodology for heavy-duty engines: and the first phase of the CRC E-66 programme [21] selected Teflon membrane filters [2]. These are understood to be less prone to collection of volatile materials and collect solid particles (though these would be differently defined to PMP solids) with efficiencies of >99.9%. When sampled on to Teflon membranes, PM emissions levels from engines equipped with highly efficient DPFs proved so low that variability was extreme. Typical filter masses were in the 5µg to 30µg range: similar to those seen from the Golden Vehicle in the ILCE_LD. However, the chemistry of the PM may have been different due to the fuel and lubricants used and the higher exhaust temperatures observed from heavy-duty engines under certain operating conditions.

In order to be able to better evaluate the method, researchers had to implement a partial DPF bypass and use a carbonaceous source. Although very low masses were studied and repeatability improved, the chemical composition was not representative of real post-DPF exhaust: excepting, perhaps, low efficiency and partial DPFs. In a second phase [22] of the programme, true post-DPF experimentation was carried out. These experiments showed that despite moving to a Teflon-based filter method, volatile condensation (leading to increased sample mass) and evaporation (leading to reduced sample mass) were still issues.

In addition, other factors such as dilution ratio and residence time in the CVS and secondary tunnels, filter face velocity and dilution temperature were all found to be issues and the US2007 method requires further work to define control parameters for these. Many of these factors were considered for mass measurements during PMP Phase 2 [8] and consciously eliminated or rendered irrelevant by the approach in the solid particle number method. The E-66 phase 2 report concludes with the recommendation that real-time particle instruments be considered and developed as substitutes for the filter mass method.

It seems likely that after substantial further work a filter-based method could be developed that would give a reasonable estimate of the particle emissions from Diesel engines with DPFs. However, it is probable that it will never be possible to completely eliminate both positive and negative volatile artefacts. With efficient DPFs, a PM method can be used to discriminate an equipped engine from a non-equipped engine but not determine an accurate emissions level for the former.

9.2 Statistical Considerations – Tuning the Dataset to Mass

Significance
It was shown in chapter 3 that plots with error bars of 2 standard deviation show approximately the 95% confidence intervals for sample sizes of 5 measurements. When the error bars do not overlap, then the difference is statistically significant ($p<0.05$).

Outliers
The criterion used in this report for the identification of the outliers has not been used before. If the true outliers are not taken into account, from a total of 73 valid measurements 8 (11%) were considered PM outliers. The "normal" outliers" based on the statistical criteria would be only of 2 (3%) which is an acceptable percentage. In a normal distribution 5% of the sample can lie outside the 2 standard deviations. The PM criteria used in this report definitely "tunes" the results in favour of the PM method.

It is interesting to note however that even with the PM "favourable" criteria the reproducibility of the golden vehicle was 35.5% for PM and 31.5% for number indicating the superiority of the number based method (especially by taking into account the increased sensitivity).

Effects of Including Outliers
It is interesting to consider how different the results would be if all the tests were taken into account (excepting the true (procedural) outliers): the reproducibility of the PM method for the golden vehicle would be 41% and for the number method ~29%. These results show that the 30% reproducibility observed for number is a reasonable reflection of true system reproducibility even with different DPF fill states.

9.3 Mass and Number Tunnel Backgrounds Subtraction: Permissable? Necessary?

During this test programme a number of samples were acquired to evaluate both mass and number background levels and variability.

Measurements of mass backgrounds in several laboratories showed that these ranged from 25% to >100% of typical Golden Vehicle sample filter masses and were highly variable. In a study conducted at a single lab (Lab#1,R3), the mean background filter mass (~21µg) was more repeatable but was just greater than the mean sample filter mass from a series of cold start NEDC cycles.

PMP solid particle number backgrounds, conversely, were generally very low: typically equivalent to 10^8/km to 10^9/km. Even in an extreme case, where very poor CVS dilution air filtration was employed (Figure 117, blue line), the impact on solid particle emissions was only substantial in the EUDC (since EUDC emissions are consistently very low) and the effect on the overall NEDC cycle was minimal (Figure 118) (Lab#5). Low background levels (red line) had no appreciable impact on the NEDC result. In another series of tests at Lab#1,R3 where the mean background filter mass exceeded the mean sample filter mass, the number background was 460 times lower than the sample level.

Figure 117: NEDC Cycle Emissions - High and Low Number Background Levels

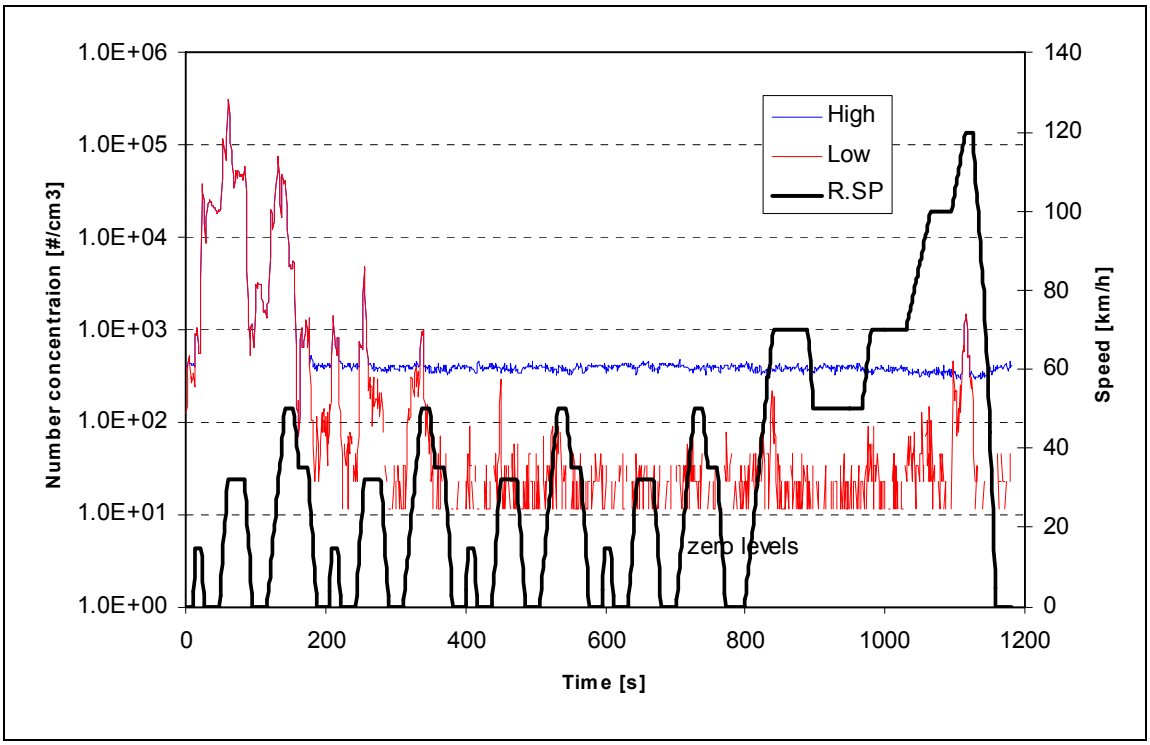
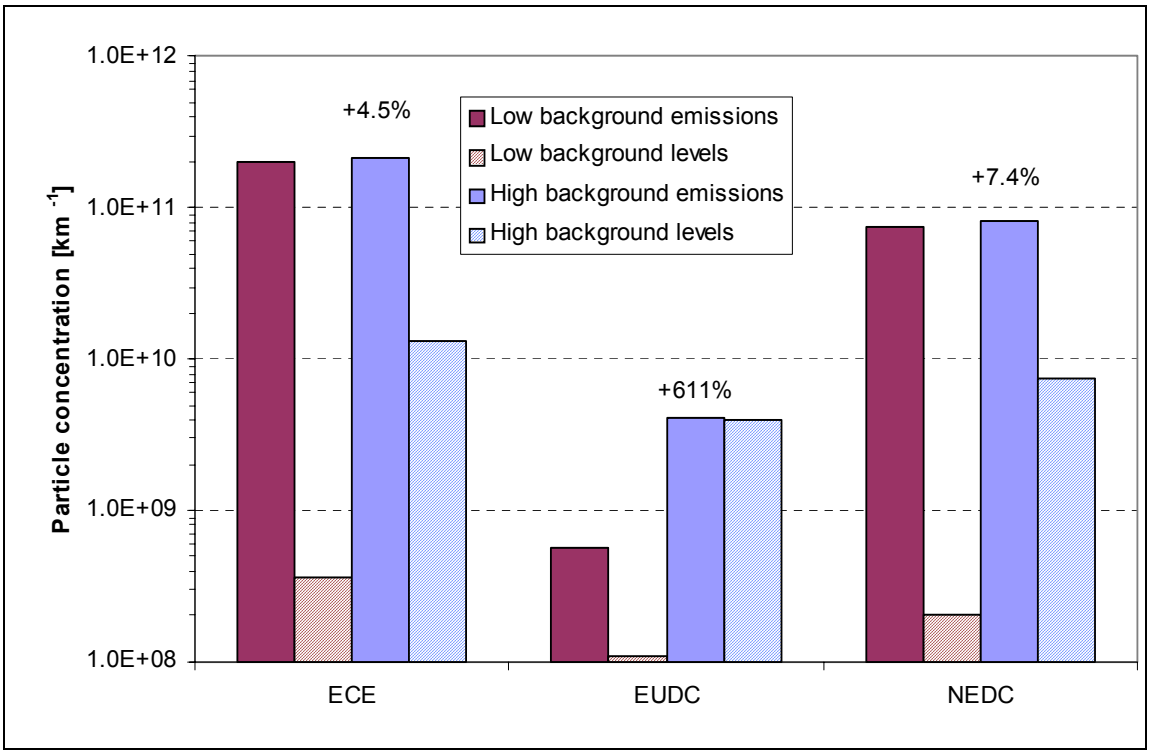


Figure 118: Effects of High and Low Particle Backgrounds On Drive Cycle Emissions



There is a large discrepancy between the possible contribution of a filter background to a sample measurement, and the possible contribution of a number background: in the Lab#1,R3 tests >100% and ~0.2% respectively. The high mass contribution to the filter measurement must come from the dilution air or from volatiles emitted from the dilution tunnel walls since the number method shows minimal levels of solid particles to be

present. It is not currently understood how these volatiles associate with the filter medium, and they may experience both condensation and evaporation during sampling. In this case, the background cannot be representative of the contribution of the dilution air or system background during an emissions test. Volatiles already present in the filter medium at the point of initial weighing may also be displaced by other volatiles during sampling: conceivably leading to an underestimation of background levels.

Whatever the sources and influences on the background mass, background filter levels are extremely high relative to sample masses. Subtraction of these levels from the sample risks reporting zero or negative mass results, when particle number measurements clearly indicate the presence of particle emissions.

At the current level of understanding, it is not clear whether background subtraction in the mass method is appropriate.

Alternatively, with the HEPA particle number filtration systems applied to the CVS the number background levels are so low that it is unnecessary to background subtract.

9.4 What Are The Real Influences On Post-DPF Solid Particle Number Emissions?

From the Golden Vehicle and considering non-regenerating cold start NEDC cycles only, the ECE phase results always dominated the combined cycle emissions level. These effects may be related to the fundamental engine-out soot emissions levels and DPF filtration characteristics such as porosity and the magnitudes of these effects will probably be vehicle dependent. In the ECE cycle the following factors were key:

- The more vigorous a preconditioning phase, the higher the solid particle number emissions since particles are forced into the walls of the DPF and released in response to pressure transients and rising temperature during the next cold start test.
- Hot start tests immediately following cold tests (including the EUDC) release virtually no solid particles. Longer soak periods (hours) allow particles to settle and be trapped within the DPF interstices (probably in response to cooling) and lead to higher solid emissions than short soak periods (minutes).
- A full DPF leads to lower particle number emissions since a filter cake is present in the DPF and filtration is most efficient
- Full regenerations (as observed under steady state operation) empty the DPF and lead to increased emissions levels in subsequent tests through reduced filtration efficiency
- Partial regenerations (as observed during the sequence of NEDCs) partially empty the DPF and lead to smaller increases in solid particle numbers.

Relative to these influences, differences between alternative cold-start drive cycles are minimal (e.g. results from Lab#6 and Lab#1,R2 *CoV* 15%).

9.5 What are Effects of Regenerations on Solid Particle Numbers?

Observations of regenerations during the ILCE_LD and additional experiments conducted at Lab#1,R3 have enabled the effects of regenerations on solid particle number emissions to be considered.

From steady state operation, both passive and active regenerations were observed. At 120kph an active regeneration resulted in a solid particle/km emissions increase of ~60 times, while a 140kph passive regeneration resulted in a solid particle/km emissions increase of ~2.5 times. Both these increases are relative to a non-regenerating 120kph steady state.

Transient cycle testing showed regenerating EUDC cycle solid particle emissions to be increased by less than a factor of 100 relative to a non-regenerating test. This was calculated from partial regenerations observed from a series of tests and restricted to the EUDC phases.

The typical loading and regeneration cycle on this vehicle, fuel and mix of driving proved to be ~1100km or 98 NEDC cycles. Considering both steady state and transient operation, the impact of regenerations on an NEDC cycle result which is weighted for regenerating and non-regenerating particle results and which considers the frequency of regeneration is roughly to double the particle number emissions.

Particle size distributions showed that while solid particle numbers showed relatively small increases, volatile particle numbers, including those smaller than 22nm, increased by over 5000 times in certain cases.

9.6 Future Scope

At present, the PMP particle measurement system defines the particles to be measured by its performance parameters using dilution and heating processes. In the future, if volatile particles were to be of concern, the system operation can be modified to change the definition of the particle measured and permit their quantification.

10 CONCLUSIONS

10.1 Golden Vehicle Operation

- There were no long-term trends in the gaseous, particulate mass or particle number emissions across the duration of the test programme. Differences between labs were apparent and there was evidence that regenerations affect gaseous, particle and perhaps particulate results in subsequent tests.
- The vehicle demonstrated Euro 4 emissions compliance for gases and particulate mass throughout the test programme.

10.2 PM Emissions

10.2.1 Golden Vehicle

- Mean emissions levels varied considerably across the programme: from ~0.2mg/km to ~0.6mg/km with a mean emissions rate of 0.34mg/km. This corresponded to a sampled filter mass of ~20µg.
- Lab-to-lab reproducibility showed a *CoV* of ~35%
- Repeatability within a lab was variable, with *CoV*s ranging from ~12% to ~66%. There may have been an influence of impending or past regeneration on this variability, but this could not be proven.

10.2.2 DPF vehicles generally

- All other DPF-equipped Diesel vehicles were capable of <1mg/km and showed mean repeatability levels (*CoV*) of 26% or less. The 1mg/km emission rate does not include contributions from regenerations or include an allowance for deterioration.

10.2.3 MPI gasoline

- The MPI vehicle tested showed PM emissions similar to those from the DPF Diesels and a similar repeatability: ~40%.

10.2.4 G-DI

- Two lean-burn G-DI vehicles with European calibrations were tested. These showed mass emissions of ~2mg/km and ~8mg/km. A third vehicle, with a Japanese calibration showed emissions of ~13.5mg/km. Repeatability levels were between those of the DPF-equipped and conventional Diesels.

10.2.5 Conventional Diesels

- Emissions levels of the conventional Diesels ranged from ~11mg/km to ~40mg/km. *COV*s ranged from ~2% to ~11% with the best result from the lowest emitting

vehicle: repeatability was not dependent on the sampled filter mass or mass emission rate.

- Using the PMP mass method and 2 standard deviations to discriminate between emissions levels, it is possible to discriminate between the 8mg/km (but not the 13.5mg/km) emitting G-DI vehicle and the 11mg/km conventional Diesel.

10.3 PM Measurement System

Particulate mass emissions followed the following general trend:

- Conventional Diesel > G-DI > porous DPF ~MPI ~ DPF

10.3.1 Golden Vehicle PM Measurements

- Removal of the back-up filter appears to reduce the overall PM by up to 25% (or ~5µg) from the Golden Vehicle.

- By using a single filter (no back-up) for the NEDC cycle rather than sampling a filter (without back-up) from each of the urban and extra-urban phases and combining the result, a reduction in measured mass of 20% to 40% (~4µg to ~8µg) was observed.

- Combining the effects of eliminating backup filters and moving from 2 filters to a single filter per NEDC cycle suggests that measured PM levels will be reduced by 30% to 50% relative to the current filter method. This is equivalent to reducing the Golden Vehicle Mass Emission from between 0.5mg/km and 0.64mg/km to ~0.32mg/km. This reduction should be taken into account when a new regulatory limit is determined.

- Tests performed at 2 laboratories comparing PM measurements using Teflo and TX40 media from the same vehicles showed no obvious difference in results.

- Background levels of particulate mass were observed to be similar to the typical sample filter loadings in one laboratory and ~50% of typical sample filter loadings at another laboratory.

- A low efficiency particle filter on the inlet of the CVS tunnel at one laboratory led to the measurement of elevated particulate mass emissions relative to those taken with a HEPA filter in place.

10.4 Particle Number Emissions:

Particle number emissions followed the following general trend:

- Conventional Diesel > G-DI > porous DPF > MPI = DPF

Repeatability levels improved as emissions levels increased across all vehicle types

10.4.1 Golden Vehicle:

- Particle number emissions from the urban phase of the NEDC dominated the overall NEDC result and the emissions from first 200-250s of the cycle made the most significant contribution
- Mean particle number results from all individual laboratories were $<2.5x10^{11}$/km and greater than $1x10^{10}$/km with the all-labs mean at ~$8x10^{10}$/km.
- Lab-to-lab reproducibility showed a *CoV* of ~31%, lower than the mass reproducibility (35%).
- High variability in the individual laboratories' particle number results (*COV*s ranged from 12% to 71%) could be directly attributed to DPF fill state and preconditioning effects, with the highest variability observed if measurements were taken either side of a regeneration.
- The GPMS was sufficiently accurate to detect changes in particle number emissions from the Golden vehicle related to DPF fill state and the change in its filtration efficiency.
- A mandatory preconditioning protocol and specific DPF fill level is recommended for best possible repeatability.

10.4.2 DPF vehicles generally

- With one exception, all DPF vehicles showed mean emissions below $2x10^{11}$/km with repeatability levels similar to, or better than the Golden Vehicle.
- Higher emissions levels ($6x10^{11}$/km) were observed for one vehicle that was equipped with both NOx and PM emissions control systems. The DPF on this vehicle is known to be of relatively high porosity: it passes low levels of solid (believed to be carbonaceous) particles throughout the NEDC cycle. This is shown by a real-time particle emissions trace which tracks the drive cycle rather than dropping down to background levels after the cold start as seen with other DPF-equipped Diesel vehicles.

10.4.3 MPI gasoline

- Emissions and repeatability levels were similar to those from the lowest emitting DPF equipped Diesels

10.4.4 G-DI

- G-DI levels were typically between $3x10^{12}$/km and 10^{13}/km (30x to 100x the mean result from the Golden vehicle)

10.4.5 Conventional Diesels

- Showed repeatability levels as low as 2% with a maximum of 7%, and emissions levels of $>2x10^{13}$/km. The lowest emitting conventional Diesel showed emissions levels 350 times higher than the Golden vehicle mean.

10.5 Measurement Systems

10.5.1 Golden System

- Validation exercises performed on the Golden System throughout the test programme demonstrated consistent performance of the GPMS elements. These proved rapid and easy to perform, but results suggest that a single daily check would be adequate rather than checks between each emissions test.
- Calibration exercises performed during the ILCE_LD showed that the GPMS met most the majority of the performance requirements of the DR83. One exception was the solid particle penetration at sizes <60nm where penetrations were <80%. It is believed that this may be due to losses related to the specific experimental method of determination. This is currently being investigated further since Horiba has successfully demonstrated compliance with the particle penetration requirements in these sizes for the SPCS [23].

10.6 Requirements for particle number measurement system components

- A HEPA filter is required at the CVS tunnel inlet to reduce background particle levels below levels observed during the EUDC part of the NEDC
- Experiments showed that neither hot dilution nor an evaporation tube is required for ECE cycle measurements on the Golden Vehicle – almost all particles emitted in this cycle are solids.
- Hot dilution is required during the EUDC to eliminate volatile particles
- Hot dilution, the evaporation tube and the modified counting efficiency of the PNC are required during DPF regenerations to eliminate volatile particles, semi-volatiles and large numbers of particles below 25nm.

10.7 Alternative Systems

- The majority of alternative systems correlated closely with the GPMS: data from NEDC cycles was similar both on a cycle averaged and real-time bases.
- The Horiba solid particle counting system (SPCS) agreed very closely with the GPMS within ± 15% and met all the requirements of the ILG_LD.
- It is clear that it is possible for manufacturers to create systems equivalent to the GPMS.

10.8 Comparison of Mass and Number Systems

- The filter mass method proved to be more repeatable than the number method for DPF Diesels, but this is because the mass method is insensitive and does not appear to reflect particle phase emissions from the Golden Vehicle in this study. Repeatability is not an appropriate metric for comparison of systems with efficient wall-flow filters.
- When a stable particle source is considered (conventional Diesels were used) repeatability levels from the number method were clearly superior to those from the mass method.
- The PMP mass method collects both solid particles (carbonaceous and organic) and volatile materials. Calculations of mass emissions determined from EEPS number data and LII elemental carbon analyses suggest that for efficient wall-flow DPF

equipped Diesel vehicles, at least 95% of the mass determined on glass-fibre/Teflon (TX40) filters is comprised of volatiles and may be considered an artefact of sampling conditions. Masses sampled on to Teflon membrane filters were similar to the TX40 masses, suggesting that these filters also accumulate volatiles.

10.9 Emissions During Regenerations

- Emissions of volatile particles during regeneration events may increase by more than 2 orders of magnitude, though many of these particles are smaller than ~20nm.

- Emissions of solid particles from the Golden Vehicle as measured by the GPMS or Alternative Systems elevated during regenerations but increased the distanced weighted average emissions by less than a factor of 2. This is similar to the increment observed for mass regeneration.

10.10 General Conclusions

- The revised PMP mass method provides repeatable measurements at well below 2.5 mg/km, but the method collects a large gaseous volatile fraction that may be 20 times the mass of the solid particles collected.

- Both mass and number measurement approaches appear to have detection limits low enough to discriminate between a highly efficient wall-flow DPF equipped Diesel and non-DPF equipped Diesel vehicles. In this testing, the mass method proved unable to discriminate a porous (cordierite) wall-flow DPF from a more efficient (silicon carbide) one.

- The PMP Particle Number method proved to be less variable than mass for Euro-4 non-DPF diesel cars with repeatability levels from 6 vehicles at 5% or better.

- Comparing the lowest emissions of the non-DPF Diesels and the highest emissions of the efficient wall-flow DPF equipped Diesels, the number method showed a difference of >300 times and the mass method a difference of ~18 times. This can be expressed as a difference in discriminating power approximately 20 times greater for the number method than for the mass method.

- Mass and number measurement equipment presented no significant functional challenges during the 2 year programme. Minor maintenance issues did occur due to some labs unfamiliarity with the equipment combined with frequent transportation, but these were dealt with as normal service issues.

- The number method presents improvements over the mass method in terms of limit of detection, accuracy, discrimination power and variability when measuring a stable particle source. For these reasons, the number method is a superior alternative to the existing or a revised mass method for future regulatory procedures.

11 RECOMMENDATIONS

11.1 Vehicle And Tunnel Pre-Conditioning

It is recommended that pre-conditioning tests on low PM emitting vehicles (those with emissions of <2mg/km), where measurements are performed alongside higher emitting vehicles, are performed last thing at night on the day before a cold start emissions test, and in the same facility. It is also recommended that the cold start test is performed as the day's first test.

During this study, the emissions of particles from the Golden Vehicle proved to be highly dependent on vehicle preconditioning, and the 120kph steady state that was used to standardise the vehicle exhaust, transfer system and CVS dilution system appears to have resulted in increased particle number emissions from cold start NEDC tests.

On this basis it is generally considered unwise to recommend this additional preconditioning for future regulatory purposes.

However, in certain circumstances – for example where the test facility might be shared between DPF and non-DPF Diesel applications – contamination from prior tests can lead to substantial mass and number carry-over. In this instance it is recommended that the 120kph is performed immediately prior to the mandatory 3xEUDC cycles.

11.2 Revisions To Draft R83 (Mandatory and Recommendations)

11.2.1 Mandatory – Number Measurements

- No background subtraction for particle numbers to be permitted
- Particle number counter calibration to be via the electrometer method traceable to NIST standards or through first generation transfer standard by a CPC calibrated by the electrometer method. (Periodicity yet to be determined, but annually would seem to be feasible.)
- Particle number counters must incorporate coincidence correction, but no other data manipulation functions.
- Maximum particle number sampling system length to be 2800mm
- Performance specifications of the VPR to be as follows:
  - n-C40 removal efficiency to be ≥ 99%
  - solid particle penetration of 30nm, 50nm and 100nm particles should be based on calibration/characterisation data from the Golden System
- Dilution factor range in the first particle number diluter to be from 10 to 500
- Dilution temperature in the first particle number diluter to be ≥ 150°C but less than the set-point of the ET
- Dilution factor set-point of the second particle number diluter to be between 10 and 15.
- During particle number measurements a maximum CVS tunnel temperature of 192°C is permitted.

11.2.2 Calibration Recommendation

- Diluter calibration shall be undertaken by measuring the concentration of the standard gas with a calibrated gas monitor at the inlet and outlet of the diluter. Calibration shall be undertaken at least 5 dilution ratios spaced as uniformly as possible across the dilution ratio range from 1 to 500. Measured dilution ratios shall be within ± 10 per cent of nominal dilution ratio settings. If a diluter is to be used at a fixed dilution setting, then the 5-point calibration should address a range of dilutions covering a factor of at least 100, with the set-point included as the middle dilution value.

11.2.3 Mandatory – Mass Measurements

- If the increase in pressure drop across a sample filter during an NEDC cycle exceeds 25kPa then the filter must be discarded and the test repeated.
- The statement addressing maximum allowable mixing length for the CVS must be modified to permit mixing tees
- Weighing room temperature and humidity set-points unchanged. Humidity control should be tightened: to 45% +/- 2%
- Filter weighing: it is currently implicit in the DR83 that filters may be weighed multiple times in 80h if earlier weighings fail on reference filter criteria. This should be made explicit
- Reference filters – rolling average of previous weighings to be used for daily comparisons
- Reference filters – valid test to be based upon both reference filters passing the +/- 5µg criterion
- Reference filters: both to be replaced if the variance of one is outside the 5µg criterion and the other is inside. Sample filter weighing to be considered valid if the difference in variances of the two reference filters is 2µg or less.
- Reference filters to replaced every 30 days.
- CVS Tunnel temperature – no upper temperature restriction for CVS when particle number measurements are made
- CVS dilution air must pass through a HEPA filter of at least Class H13.

11.2.4 Recommendations – Mass Measurements

- One filter shall be the recommended approach for mass sampling during the combined ECE+EUDC.
- For Diesel vehicles which produce carbon based particulates, single filters without back-ups are recommended for the ECE and EUDC phases separately.
- The minimum filter weight for DPF-equipped Diesels from an NEDC Cycle should be 20µg
- Balance specification should recommend 1µg resolution or better.
- It is recommended that a weighing chamber is employed, rooms are also allowed.
- It is recommended that temperature and humidity readings are recorded along with the initial filter weighing(s).

- A reference weight similar to the expected filter loading (20µg – 50µg) and another similar to the expected total mass (50mg –100mg) be weighed daily.
- The repeatability of reference weighings should be equivalent or better than the readability of the balance.
- Mass system heating – it is recommended that the sample be heated to 47°C +/- 5°C for a period of ≥ 0.2s prior to encountering the filter face
- It is recommended that the filter face velocity employed for sampling particulate mass be controlled to a single velocity within the range 50cm/s to 80cm/s
- Dilution air quality for particle numbers requires a clearer minimum specification to be recommended
- CVS filtration should be the highest possible efficiency without compromising delta-P
- There should be a recommended DPF loading for regeneration tests
- For particulate mass measurements it is recommended that an inertial separation device is placed upstream of the filter holder. This can be an impactor or a cyclone

11.2.5 Recommendations – Particle Number Measurements

- In the VPR, the temperature set-point of the ET should be between 300°C and 400°C
- In the VPR, the residence time at temperature in the ET should be ≥ 0.2s and ≤ 0.5s
- It is recommended that the second particle number diluter is capable of achieving the dilution factor range 10 to 30.
- Where the CVS is used for both high particulate mass emitting vehicles (> 5mg/km) and low particulate mass emitting vehicles, an additional 20 minutes at 120kph preconditioning for DPF vehicles should be recommended prior to the existing 3 x EUDC mandatory conditioning.
- The exhaust transfer tube should be left connected to the test vehicle and the CVS running for 30 mins after the test has completed.
- A recommendation for a minimum 35% loading state (1/3 of the mileage from one scheduled regeneration to another) prior to type approval tests
- The HEPA filters attached to the inlet of the CVS should be of the highest possible efficiency without compromising the system pressure drop.

11.3 Considerations for Achievable Number and Mass Emissions Levels

Although the PMP programme has focused on a single 'Golden Vehicle' other vehicles have also been tested. These vehicles represent all size classes from B (Peugeot 206) through to E (BMW 520d) and also LCVs (Mercedes Vito). Both additised DPF systems and catalysed DPF systems have been evaluated with at least 5 NEDC tests performed on each vehicle.

With the exception of one vehicle that was equipped with a low porosity cordierite DPF, all these vehicles proved capable of similar levels of solid particle number emissions. It is reasonable to assume therefore, that the emissions levels from current on-road emissions control technologies will be represented by the mean emissions of this set of vehicles. These emissions levels already take into account the effects of preconditioning and DPF fill state.

For particulate mass measurements the emissions levels from the vehicle that was equipped with a low porosity cordierite DPF were equivalent to those from the other DPF applications.

It must be considered that all the test vehicles are relatively new, and the emissions levels observed are unlikely to have been influenced by age or mileage related deterioration. It is also possible, though perhaps unlikely given the similarity of emissions levels from different manufacturers and the inclusion of results from both coated and uncoated DPFs, that data from these vehicles represents the extremes of the emissions distributions. In addition, variance in the data due to production variance has not been considered.

In order to account for robustness of the dataset, repeatability and reproducibility issues and common engineering margins, it may be possible to use a multiple standard deviation scatter of the mean data to ensure all 'valid' tests lie within the dataset with a wide margin. This standard deviation could be drawn from the test data set that showed the poorest repeatability – ensuring the widest margin. In this study, this would be a mean emissions value of ~6 x 10^{10}/km and a worst-case *CoV* (from data taken prior to DPF fill stabilisation) of ~90%.

It is anticipated that this approach would be ideal for the PMP particle number method since there is such a large separation between DPF and non-DPF technologies. However, it should also be capable of resolving porous DPFs, cracked DPFs and open-filters from higher efficiency DPF systems.

This approach will also enable the PMP mass method to discriminate between DPF and non-DPF technologies and since it is based upon the ILCE_LD dataset, will include consideration of the effects of eliminating back-up filters and moving to a single filter for the entire NEDC cycle.

12 Regeneration Particle Number Emissions: The Ki approach Appears Applicable

Evaluations of solid particle number emissions from the Golden Vehicle have indicated that the effect of weighting an NEDC cycle result to include either an active or a passive regeneration is relatively small: in comparison with a baseline cold start test, emissions did not increase by more than a factor of two.

From this vehicle at least, the approach currently used in regulations for incorporating the effect of regenerations on gaseous and particulate mass emissions would be equally valid for particle numbers.

Appendix 1: Light-duty Inter-laboratory Guide (ILG_LD)

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UN-GRPE PMP Phase 3
Inter-laboratory Correlation Exercise: Framework and Laboratory Guide
A Document For The UK Department for Transport

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PMP PHASE 3 – Inter-laboratory Correlation Exercise

1. INTRODUCTION

This document has been prepared in response to a request from UK DfT as part of the Particle Measurement Programme (PMP).

The document's purpose is to specify the testing guidelines and protocol for an inter-laboratory correlation exercise. This exercise is specifically designed to evaluate the draft revised Regulation 83 document - and its approach to particulate mass and particle number measurements - generated as part of the UK PMP Phase 2 reporting process.

In Section 9, the document contains specific and detailed guidelines on how the testing should be conducted at each laboratory.

2. SCOPE

This document proposes the scope for Phase III of PMP, the inter-laboratory correlation exercise and addresses the measurement and evaluation methods for particulate (all materials collected by the conventional filter method) and particle (exhaust aerosol; solid particles as defined by the measurement system) exhaust emissions from light duty vehicles under transient conditions on a chassis dynamometer. It is derived from the existing LD procedure and from draft procedures for future HD legislation (Regulation 49, ISO 16183 and US 2007).

Regulated gaseous emissions will be measured at the same time as particulate and particle emissions, using established regulatory measurement techniques.

This document is specifically concerned with an exhaust dilution system comprising a full flow primary tunnel with constant volume sampler (CVS).

3. REFERENCES

This specification is based upon or draws from the following documents:

Draft UN Working documents:

- R83 - Working Document 6/Rev. 1
- R49 - Working Document 7a (summary)/Rev. 2

Code of Federal Regulations Title 40 Part 86 Subpart N – Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedures (Revised July 1 2001). "US2007"

ISO/DIS 16183 Heavy-Duty Engines – Measurement of gaseous emissions from raw exhaust gas and of particulate emissions using partial flow dilution systems under transient test conditions. Not yet an approved document and referred to as "16183".

Euro Directives 1999/96/EC Annex III and 1998/69/EC "Euro"

Aerosol Measurements: Principles, Techniques and Applications.

Ed: Klaus Willeke and Paul A Baron 1993. Van Nostrand Reinhold

4. TEST SPECIFICATIONS

4.1 Testing Environment

The participating laboratories shall provide facilities and resources required to perform light duty vehicle emissions tests according to the Regulation 83, plus additional capability as required for particulate and particle measurements as defined in this document. They will also be required to supply test vehicles and measurement systems, and to liaise with the managing agent and "golden engineer"

4.2 Vehicle Specifications

A "golden" vehicle will be supplied by the managing agent and tested at all participating laboratories. This will be a diesel-fuelled vehicle equipped by the manufacturer with a diesel particulate filter (DPF) and nominated as Au-DV1.

Optionally, a number of additional vehicles, up to a total of four, shall be selected and supplied by each laboratory. Additional vehicles shall meet the following criteria:

- A Euro IV compliant conventional diesel (without DPF); nominally DV2
- A Euro IV compliant conventional petrol fuelled vehicle; nominally PV1
- A Euro III/IV compliant direct injection spark ignition vehicle (DISI); nominally GDIV1

4.3 Lubricating Oil

The lubrication oil shall meet the standard specified by the engine manufacturer. Where a range of oils are specified, the minimum sulphur level standard shall be employed.

A large single batch of lubricant will be secured by the project-managing laboratory, analysed and shipped to the test laboratories in advance of the arrival of the test vehicles. The total volume acquired will be sufficient for a rigorous flush and fill procedure for all vehicles tested at each laboratory across the entire inter-laboratory correlation exercise.

4.3.1 Lubricant Flush and Fill

A defined flush and fill procedure will be developed, and this employed upon arrival of each vehicle at each test laboratory. Each vehicle will then be subjected to identical conditioning procedures to ensure equivalence between laboratories. An example flush and fill procedure is shown in Appendix 1.

4.4 Test Fuel

The diesel and gasoline fuels to be employed during this programme will be secured by the project-managing laboratory, analysed and shipped to the test laboratories in advance of the arrival of the test vehicles. Both fuels will be drawn from single batches, will comprise sulphur levels of <10ppm and will otherwise comply with Annexes 3 and 4 of Directive 2003/17/EC describing fuel specifications to be employed after 1st January 2009.

5. TEST PROTOCOL

5.1 Delivery and Preparation of Vehicles

All vehicles to be tested shall be inspected for damage on arrival at the laboratory. Any problems shall be reported to the golden engineer and project manager. Vehicles shall be stored in an appropriate manner prior to pre-test conditioning.

5.2 Test Cycles

All vehicles shall be tested over the NEDC cold start drive cycle as defined in European Directive 70/220/EC as amended by 98/69/EC.

5.3 Criterion for Repeat Tests

A minimum of 5 tests shall be performed on each vehicle. Additional tests shall be carried out if one or more of the initial tests appears to be an outlier. A result is defined as an outlier if the specific particulate mass for that test lies outside $\pm 2\sigma$ of the mean of the remaining tests. The outlier will only be rejected if it remains outside the distribution inferred from 5 tests. The results of all tests, including those deemed to be outliers, shall be reported.

5.4 Testing Approach

The test work shall be carried out according to a pre-defined schedule for vehicle conditioning, measurement system checks and test cycles. This schedule will depend on the number of different vehicles being tested, and will be subject to agreement with the project manager.

5.5 Test Order and System Preconditioning

Test order shall consider the possibility of contamination of test results by a previously tested vehicle, and in general, a low particulate emitting vehicle shall always be tested prior to a less clean vehicle. For example, an outline daily test protocol for testing four vehicles within one laboratory is shown in Figure 1: this ensures that Au-DV1 is always tested before DV2 and PV1 is always tested before GDIV1. Further example test protocols can be found in Appendix 1.

5.5.1 Diesel System Preconditioning

In a dedicated diesel dilution system, Au-DV1 shall always be last vehicle to be conditioned each day. This ensures that the entire transfer and dilution system is

preconditioned with the cleanest vehicle. This final conditioning shall comprise a 20 minute 120kph steady state followed by the standard diesel conditioning*.

5.5.2 Gasoline System Preconditioning

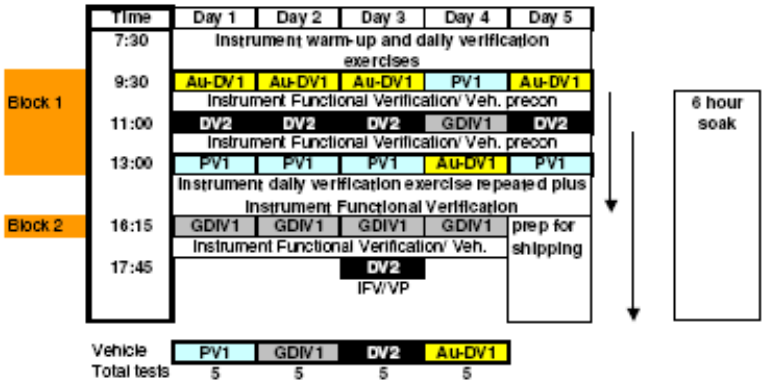
In a dedicated gasoline dilution system, the same PFI vehicle of at least Euro 3 specification shall always be last vehicle to be conditioned each day. This ensures that the entire transfer and dilution system is preconditioned with a clean vehicle. This final conditioning shall comprise a 30 minute 120kph steady state followed by the standard gasoline conditioning. If the only vehicle to be tested is GDIV1, then this may be used for the preconditioning.

5.5.3 Shared Dilution System

In a shared dilution system, where the GDIV1 vehicle must be tested in a diesel dilution tunnel, the GDIVI vehicle shall follow the Au-DV1 vehicle in the test order, but precede any conventional (non-DPF equipped) diesel. The preconditioning for the dilution tunnel shall follow the protocol described in Section 5.5.1.

It is not recommended that PFI gasoline vehicles be tested in a dedicated diesel dilution system.

Figure 1: Example Test Protocol: Four Vehicles Tested in One Laboratory



6. MEASUREMENT AND SAMPLING SYSTEMS FOR GASEOUS EMISSIONS

The mass of gaseous emissions shall be measured during all tests in accordance with the current R83 regulation. If possible, raw tailpipe and engine out emissions shall also be measured on a continuous basis throughout the test.

* This paragraph previously contained the option to trigger elective regeneration. This is not possible on the Golden Vehicle, so sentence is deleted.

7. MEASUREMENT AND SAMPLING SYSTEMS FOR PARTICULATES

7.1 Introduction

The mass of particulate material emitted by each engine technology and for the combined phases of the NEDC† test will be measured using the system defined below.

7.2 Primary Dilution System

A full flow CVS exhaust dilution tunnel system meeting the requirements of Regulation 83 shall be used. The flow rate of dilute exhaust gas through the tunnel shall be 12m^3/min at standard reference conditions (20°C and 1bar).

It is recommended that the dilution air used for the primary dilution of the exhaust in the CVS tunnel shall be first charcoal scrubbed and then passed through a secondary filter. The secondary filter should be capable of reducing particles in the most penetrating particle size of the filter material by at least 99.95%, or through a filter of at least class H13 of EN 1822; this represents the specification of High Efficiency Particulate Air (HEPA) filters.

If both gasoline and diesel vehicles are to be tested, then there shall be a dedicated dilution tunnel for each fuel type. If a single tunnel only is available, then priority should be placed on testing the golden vehicle and other diesel vehicles.

7.3 Particulate Mass Sampling

A sample probe shall be fitted in the dilution tunnel. It shall be installed near the tunnel centre-line, 10 - 20 tunnel diameters downstream of the gas inlet and have an internal diameter of at least 12 mm. The sample probe will be sharp-edged and open ended, facing directly into the direction of flow.

A cyclone or impactor based pre-classifier shall be employed.

A pump will draw a sample of dilute exhaust gas proportional to the total tunnel flow through the sample pre-classifier and filter holder.

The distance from the sampling tip to the filter mount shall be at least five probe diameters, but shall not exceed 1,020 mm.

7.4 Sample Pre-classifier

In accordance with the recommendations of the draft Regulation 83 document, a cyclone or impactor pre-classifier shall be located upstream of the filter holder assembly. The pre-classifier 50% cut point particle diameter shall be between 2.5 µm and 10 µm at the volumetric flow rate selected for sampling particulate mass emissions. The pre-classifier shall allow at least 99% of the mass concentration of 1µm particles entering the pre-classifier to pass through the exit of the pre-classifier at the volumetric flow rate selected for sampling particulate mass emissions. Evidence of compliant performance to this specification shall be presented (e.g. manufacturer's calibration certificate).

† Clarification that a single PM measurement is required from the combined ECE (UDC) and EUDC phases of the NEDC drive cycle.

7.5 Sampling Filters

7.5.1 Filter holder assembly

The filter holder assembly shall be of a design that provides for a single filter only. The shape of the holder should be such that an even flow distribution of sample across the filter stain area is achieved.

In order to meet the requirement that a temperature of 47±5°C be maintained for a period of at least 0.2s within 2.5cm of the filter face, the filter holder and transfer tubing from the CVS tunnel will either need to be heated directly, or be mounted inside a temperature-controlled enclosure.

7.5.2 Filter medium

Pallflex TX40 Fluorocarbon coated glass fibre filters shall be employed. All filters will be drawn from a single batch procured by the project-managing laboratory.

7.5.3 Filter size and Stain Area

The filter diameter shall be 47mm and the stain area shall be at least 1075 mm².

7.5.4 Filter face velocity/ volumetric sample flow rate (xcm/s, ylitres/min)

Filter face velocity shall be in the range 50cm/s to 80cm/s , which corresponds to a flow rate range of 35l/min to 51l/min. Filter face velocity should be calculated at 47 °C[‡].

7.5.5 Filter Preparation

The particulate sampling filters shall be conditioned (as regards temperature and humidity) in an open dish that has been protected against dust ingress for at least 2 and for not more than 80 hours before the test in an air-conditioned chamber. After this conditioning the uncontaminated filters will be weighed and stored until they are used. If the filters are not used within one hour of their removal from the weighing chamber they shall be re-weighed.

The one-hour limit may be replaced by an eight-hour limit if one or both of the following conditions are met:

- a stabilised filter is placed and kept in a sealed filter holder assembly with the ends plugged, or;
- a stabilised filter is placed in a sealed filter holder assembly which is then immediately placed in a sample line through which there is no flow.

7.5.6 Sample Filter Weighing

Once loaded, the used particulate filter shall be taken to the weighing chamber within one hour following the analyses of the exhaust gases. The filter shall be conditioned for at least 2 hours and not more than 80 hours and then weighed.

[‡] Filter face velocity temperature reference added.

7.6 Measurement Equipment and Environment

7.6.1 Microgram balance

The analytical balance used to determine filter weight must have a precision (standard deviation) of better than 2 µg for a clean filter; better than 0.25µg for a reference weight and a resolution or readability of 1µg or better. To eliminate the effects of static electricity: the balance should be grounded through placement upon an antistatic mat and particulate filters should be neutralised prior to weighing; this can be achieved by a Polonium neutraliser or a device of similar effect.

7.6.2 Weighing Chamber Parameters

The temperature of the chamber (or room) in which the particulate filters are conditioned and weighed must be maintained to within 295K ± 3 K (22°C ± 3°C) during all filter conditioning and weighing. The humidity must be maintained to a dew point of 282.5K ± 3 K (9.5°C ± 3°C) and a relative humidity of 45 % ± 8 %. The environmental conditions of the weighing room during the test programme shall be monitored and reported.

Limited deviations from weighing room temperature and humidity specifications will be allowed provided their total duration does not exceed 30 minutes in any one filter conditioning period. The weighing room should meet the required specifications prior to personal entrance into the weighing room. During the weighing operation no deviations from the specified conditions are permitted.

7.7 Calibration Requirements

7.7.1 Microbalance Calibration

The microbalance shall be calibrated according to the manufacturer's specification within 3 months prior to the commencement of the test programme.

7.7.2 Reference Filter Weighing

At least two unused reference filters must be weighed within 4 hours of, but preferably at the same time as the sample filter weighings. They must be the same size and material as the sample filters. If the average weight of the reference filters changes between sample filter weighings by more than ± 5µg, then the sample filter must be discarded and the emissions test repeated.

8. GOLDEN PARTICLE MEASUREMENT SYSTEM AND SAMPLING SYSTEMS

The number of particles emitted by each engine technology and for each test cycle shall be determined using the 'Golden Particle Measurement System' (GPMS) defined below. The majority of these components will be provided, though certain items indicated in the text shall be provided by the laboratory (Table 1, Page 14).

8.1 Particle Sampling System

The particle sampling system shall consist of a sampling tube in the dilution tunnel (PST), a particle pre-classifier (PCF) and the GPMS particle conditioning and measurement system comprising a volatile particle remover (VPR) upstream of the

particle number counter (PNC_GOLD) unit. The particle sampling system is required to draw a sample from the CVS, size classify it, transfer it to a diluter, condition the sample so that only solid particles are measured, and pass a suitable concentration of those particles to the particle counter.

8.1.1 Sample Probes

A particle sampling tube shall be installed near the tunnel centre line, roughly ten tunnel diameters downstream of the gas inlet, facing upstream into the tunnel gas flow with its axis at the tip parallel to that of the dilution tunnel. The tube shall be sharp edged and open-ended and have an internal diameter of approximately 12.5mm. The PST may be heated to no greater than 52°C.

The distance from the sampling tip to the point at which the probe leaves the dilution tunnel shall be less than 200 mm and the distance from the sampling tip to the entrance to the particle pre-classifier unit shall not exceed 1,000 mm. The particle sampling tube shall be placed in a position equivalent to that of the probe employed for particulate mass sampling: all sampling probes and tubes shall be equally spaced about the centre line of the dilution tunnel with at least 5cm separation between them.

8.1.2 Particle Pre-classifier[§]

The upper limit of the particle size range to be measured shall be determined by the use of the cyclone particle size pre-classifier provided. The 50% cut-point of the particle pre-classifier shall lie at 2.5µm. The laboratory will provide a suitable pump capable of 90l/min (+/- 5l/min) to ensure an upper limit of particles sampled into the measurement system of ~2.5µm.

8.2 Volatile Particle Remover (VPR)

The VPR shall be used to define the nature of the particles to be measured.

8.2.1 Description

The VPR provides heated dilution, thermal conditioning of the sample aerosol, further dilution for selection of particle number concentration and cooling of the sample prior to entry into the particle number counter.

8.2.2 Elements of the VPR

The VPR shall comprise the following elements:

8.2.2.1 First Particle Number Diluter (PND_1)[**]

The PND_1 diluter shall be specifically designed to dilute particle number concentration and output a dilute sample equal to 150°C +/- 5°C. The diluter should be supplied with HEPA filtered dilution air and be capable of a dilution ratio range of 1 to 1000 times. For the Golden Vehicle, the dilution ratio of this diluter; $PNDR_1$ will be ~17:1 as determined by a potentiometer setting of 75%. This setting should be employed for MPI gasoline vehicles and other DPF-equipped Diesels. An initial setting of 5%-10% may be appropriate for conventional Diesel vehicles, but this should be optimised.

[§] Pump requirements included, now that 2.5µm @ 90l/min cyclone is being provided.
[**] Mandatory setting for PND1 after Golden Vehicle tests in first laboratory.

8.2.2.2 Evaporation Tube[††]

The ET shall be a length of tubing 240mm +/-10 mm and I.D 6mm +/- 0.1mm equipped with a heating mantle. The entire length of the ET must be controlled to a temperature greater than that of PND_1, with a portion of the length equivalent to a gas residence time of 0.2s +/- 0.05s held at a constant temperature (+/-20°C) of 300°C.

8.2.2.3 Second Particle Number Diluter (PND_2)[‡‡]

The PND_2 device shall be specifically designed to dilute particle number concentration. The diluter shall be supplied with HEPA filtered dilution air and be capable of a dilution ratio of ~ 10 times. The dilution ratio of this diluter; $PNDR_2$ is selected such that particle number concentration downstream the PND_2 diluter is $<10^4$ particles/cm^3 and the gas temperature prior to entry to the PNC_GOLD is <35°C.

8.2.3 Performance

The VPR shall operate under conditions that achieve greater than 99% reduction of 30nm C_{40} (tetracontane) particles and greater than 80% solid particle penetration at 30, 50 and 100nm particle diameter.

8.2.4 Location of Sampling and Measurement Equipment

The distance from the sampling tip of the PST to the entrance to the PND_1 shall not exceed 1000mm.

The distance from the sampling tip to the point at which the probe leaves the dilution tunnel shall be less than 200 mm.

The distance from the sampling tip to the entrance to the particle number counting instrument shall not exceed 2,500 mm.

8.3 Particle Counter (Particle Number Measurement Unit, PNC)

The particle counter is used to determine the number concentration of solid particles in a diluted sample of vehicle exhaust aerosol continuously drawn from the CVS.

8.3.1 PNC Performance Characteristics

The particle number concentration measurement unit (PNC_GOLD) shall meet the following conditions:

- It shall operate under full flow operating conditions.
- It shall have a counting accuracy of ± 10% across the range 10^2cm^{-3} to 10^4cm^{-3} and +/- 10cm^{-3} below this concentration against a traceable standard.
- It shall have a readability of 0.1 particles/cm^3.

[††] Matter Engineering VPR employed.
[‡‡] PND_2 has fixed dilution ratio of ~9.5:1

- It shall have a linear response to particle concentration over 1 to 10,000 particles/cm^3.
- It shall have a data logging frequency of equal to or less than 0.5 Hz.
- It shall have a T90 response time of between 5s and 15s
- It shall have a data-averaging period of between 1 and 6s and shall not incorporate automatic data manipulation functions.

The lower particle size limit characteristics of the PNC_GOLD shall be such that the 10% (D10), 25% (D25), 50% (D50) and 90% (D90) inlet efficiencies of the instrument correspond to the particle sizes 16nm (+/-nm), 18nm (+/-2nm), 23nm (+/-3nm and 37nm (+/-4nm)) respectively.

8.3.1.1 Reference Particle Counter

A second particle counter (PNC_REF), with identical specification to PNC_GOLD will be transported with PNC_GOLD to act as a reference instrument. This instrument will also be operating during testing to indicate the real time function of the VPR.

8.4 Sampling lines

All sampling lines shall be either TYGON (specifically R3603), conductive silicone tubing or of stainless steel composition, contain smooth internal surfaces and be of minimal length. Sharp bends and abrupt changes in section should be avoided in all sampling lines.

8.5 Calibration of Particle Number Measurement System

Prior to commencement of the test programme, calibration of the PNCs, diluters and VPR will be undertaken. This may be undertaken by the instrument manufacturers, but shall be according to the protocols described in the following sections:

8.5.1 Calibration of Particle Number Concentration Measurement Device

The particle counter shall be calibrated according to the manufacturer's specification within one month prior to testing in the first laboratory. Calibration shall be traceable to a standard calibration method:

- comparison of the response of the counter under calibration with that of a calibrated aerosol electrometer when simultaneously sampling electrostatically classified calibration particles, or
- comparison of the response of the counter under calibration with that of a second counter which has been calibrated by the above method.

In either case, calibration shall be undertaken at five concentrations spaced as uniformly as possible across the single particle detection region of the counter's measurement range. Calibration spacing will be ~10000, ~8000, ~6000, ~4000, ~2000cm^{-3} (plus zero check). Measured concentrations shall be within ±10% of the standard concentration for each calibration concentration used. The gradient from a linear regression of the two data sets shall be calculated and recorded. Linearity of

response is calculated as the square of the Pearson product moment correlation coefficient (R^2) of the two data sets and shall be equal to or greater than 0.95.

8.5.2 Calibration of the diluters

It is considered unlikely that fully characterised diluters (with fully understood size-related losses) will be available within the timeframe of the inter-laboratory correlation exercise and it is recognised that calibration with gases will not necessarily indicate the exact dilution ratios obtained for aerosols. However, the practicality of the inter-laboratory exercise is for consistency between test laboratories, and this can be provided by a well designed diluter with low predicted losses and stable gas dilution ratio performance.

The diluter shall be calibrated with a traceable standard gas mixture within one month prior to testing in the first laboratory. Calibration shall be undertaken by measuring the concentration of the standard gas with a calibrated gas monitor at the inlet and outlet of the diluter.

Calibration shall be undertaken at least 5 dilution ratios spaced as uniformly as possible across the dilution ratio range from 0 to 1000.

Measured dilution ratios shall be within ±10% of nominal dilution ratio settings. If a diluter is to be used over a narrower dilution range, then the 5-point calibration should span that range.

8.5.3 Calibration of the Volatile Particle Remover

The penetration efficiency of solid particles through the apparatus shall be established within one month prior to testing in the first laboratory.

The test aerosol for these measurements shall be solid particles of diameters 30, 50 and 100 nm and a minimum concentration of 1,000 particles/cm^3. Particle concentrations shall be measured upstream and downstream of the apparatus operating at the temperature and flow conditions employed during an emission test. A minimum penetration efficiency of 80% shall be achieved at all three test particle diameters.

8.6 Additional Sampling And Measurement System For Particles

The laboratory shall propose its own specific particle number measurement system and operate this in tandem with the GPMS. Data from this system shall be collected simultaneously with that from the GPMS, and the two sets compared and contrasted. The sampling and measurement of particles with the laboratories' own systems shall not interfere with measurements from the GPMS. [55]Alternative systems installations will be subject to approval by the Golden Engineer and/or project manager.

[55] Reference to dedicated sample probe for alternative systems deleted: there are circumstances where this is not necessary.

9. TEST PROCEDURES

9.1 Preparation of the Vehicle

Vehicles shall be prepared in accordance with R83 and good engineering practice for emissions testing. The fuel and lube oil used shall be as specified in section 4 of this document.

9.2 Dynamometer Preparation

The chassis dynamometer controller shall be adjusted to simulate the inertia of the test vehicle. The inertia shall be set according to the generic inertia classes given in R83, with corresponding coefficients for the road load curve. The road load setting shall be verified by performing a coast-down test on the golden vehicle.

9.3 Test and Conditioning Protocols

The vehicle shall be conditioned prior to each test in accordance with Regulation 83. In addition, the first vehicle to be tested on the subsequent day shall be the last conditioned on the previous night. In addition to the conditioning required by Regulation 83, this last daily conditioning shall be preceded by a 20 minute period of operation at 120kph[**]. This period of high temperature operation is required to raise the temperature of the vehicle's exhaust and transfer system above that to be encountered during the NEDC test and thus eliminate the possibility of cross contamination from other vehicles and artefact formation.

If an elastomer coupling is used to connect a vehicle's tailipipe to the CVS transfer tube, care must be taken to minimise the exposure of the elastomer surface to the exhaust stream

[†††]Following the completion of the preconditioning procedures (120kph, 20 minutes and 3 x EUDC), the vehicle should be switched off but the CVS tunnel left running and exhaust transfer line attached. This is in order to allow volatiles to be carried away from the exhaust during post-conditioning cooling.

Real-time regulated gaseous emissions must be logged during the conditioning procedure and if possible exhaust temperature at the tailpipe, in order to determine whether a regeneration has occurred[‡‡‡]. A regeneration will appear as an elevated period of CO, CO_2 and NOx emissions above the baseline operation of the vehicle during the steady state conditioning. This will be accompanied by a significant increase in exhaust temperature. If DPF regeneration does occur, testing must not proceed: approximately 300km of additional vehicle mileage accumulation will be required first and the vehicle and measurement system reconditioned. The Golden Engineer and/or Project Manager must be consulted prior to any further testing.

A minimum soak period of six hours shall be included between successive tests on each vehicle.

[**] This is the minimum preconditioning required prior to the standard 3 x EUDC conditioning. More severe conditioning up to 130kph, 30 minutes will be permitted upon approval by the Golden Engineer and/or Project Manager.
[†††] Additional paragraph added addressing procedure to ensure exhaust and transfer system are cleared of semi-volatiles after the preconditioning procedures.
[‡‡‡] Additional paragraph added addressing procedure to detect regeneration and subsequent actions required by laboratory.

Warm-up and pre-conditioning procedures shall be carried out on the measurement and sampling systems as appropriate. System verification and calibration checks as required shall be performed daily, but not necessarily as part of the warm-up schedule.

An example test protocol for 4 vehicles is given in Figure 1, Section 5.4.

9.4 Test Procedures – Gaseous Emission

9.5 Preparation for the Test

Prior to the test the gaseous emissions analysers shall be calibrated using suitable reference gases, on the ranges that will be used during the test. The zero and span readings shall be recorded.

9.6 During the test

At the start of the test, the bag-sampling unit shall be switched to start filling the sample and ambient bags.

During each test the data from the gaseous emissions analysers shall be recorded with a logging rate of at least 0.5 Hz.

9.7 Post-test

At the end of the test the bag sampling unit shall be stopped.

Following the test the zero and span readings of the gaseous emissions analysers shall be checked and recorded. The analysers shall then be calibrated using suitable reference gases, on the ranges that will be used for analysing bag samples. The emissions concentrations in the bag samples shall then be measured and recorded.

9.8 Test Procedures – Particulate Emissions

These procedures are applicable to the single filter used for the single sample from the combined phases of the NEDC cycle[666].

9.8.1 Preparation for the Test (filter weighing, switch to bypass)

Prior to the test the test filter shall be conditioned in the weighing room. The initial filter mass shall be measured and recorded on a microbalance with 1µg resolution.

During the system stabilisation procedure the particulate sampling system shall be operated on bypass

9.8.2 During the test (switch to sample)

At the start of the test, the particulate sampling system shall be switched from the bypass to sample filter.

[666] Clarification that a single filter should be used both ECE and EUDC phases of the NEDC.

9.8.3 Post-test (condition and weigh filters)

On completion of the test the particulate sampling system shall be stopped. The filter holder shall be removed and the filter returned to the weighing room or chamber for conditioning.

After conditioning the filter shall be weighed and the mass recorded

9.9 Test Procedures – Particle Emissions

The following sections describe the procedures that shall be followed by each laboratory in receiving, installing and operating the GPMS.

9.9.1 Equipment Arrival at Laboratory

On arrival at the laboratory, all equipment shall be unpacked and inspected for damage. If any components are missing or damaged the Golden Engineer and Project Manager shall be informed.

9.9.2 List Of Equipment/Components

The equipment accompanying the Golden Vehicle that will be circulated between laboratories is summarised in Table 1.

Table 1: Components For Circulation Around Participating Laboratories

Golden Particle Measurement System Components	Transport (Y/N)	Comments
Cyclone	Y	
Sampling point, Stainless steel tube to 90l/min pump	N	
90l/min pump	N	
Diluter head (rotating disc)	Y	
2 x cables (1m sampling line, 3m dilution air line)	Y	
VPR assembly (diluter controllers, heaters and ET)	Y	
Exhaust tube from peristaltic pump	Y	
Tube from upstream of ET to PNC_REF	Y	
Tube from downstream of PND2 to t-piece	Y	
Steel t-piece for diluted samples	Y	
Tube from t-piece to PNC_GOLD	Y	
Tube to spill excess overpressure air from t-piece	Y	
Tube bypassing cooler assembly	Y	
PNC_REF	Y	
PNC_REF pump plus 2 x clear plastic tubes	Y	
PNC_GOLD	Y	
PNC_GOLD pump plus 2 x clear plastic tubes	Y	
Teflon t-piece to dump exhaust from PNC pumps	Y	
2 x power plugs (PNCs)	Y	
2 x serial cables (PNCs)	Y	
Compressed air line for VPR secondary dilution	N	
1 x power plug for VPR	Y	
2 x HEPA filter	N	
Particulate Matter Sampling Components		

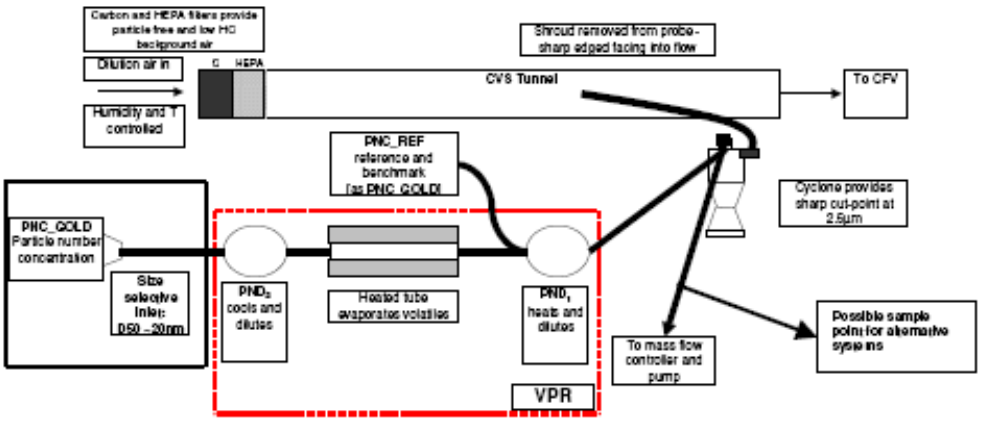
Cyclone	Y	
Other Components		
TSI software for data logging	Y	
Packaging for VPR, diluter etc	Y	
All instrument booklets, plus copies of certificates	Y	

9.9.3 Initial Checks and Assembly of GPMS

A PNC linearity check will be carried out on PNC_GOLD and PNC_REF simultaneously. The purpose of this procedure is to verify the similarity of the counters and their responses across the concentration range of interest. Using an aerosol source with an initial concentration of less than 100000/cm^3, and a calibrated diluter supplied as part of the GPMS, five dilution factors spanning at least a factor of 20 shall be selected: for example; 300, 200, 100, 50, 15. The R^2 (correlation coefficient) value of the five concentration values obtained shall then be compared with the R^2 value from the CPC_GOLD calibration certificate. Linearity of response is calculated as the square of the Pearson product moment correlation coefficient (R^2) of the two data sets and shall be equal to or greater than 0.95.

The GPMS will then be assembled ready for analysis, and all elements of the system tested for functionality. The system shall be installed in the chassis dynamometer facility with suitable connections to a sample probe in the CVS tunnel such that the requirements of Section 8.1.1 and Section 8.4 are fulfilled. A schematic of the assembled system is shown in Figure 2. The laboratory will provide a suitable particle pre-classifier (Section 8.1.2) and pump to ensure that the upper size limit of particles sampled into the measurement system is 2.5µm. Good aerosol sampling practice will be employed in the construction of the GPMS with the best available diluters, ET and PNC employed and aerosol transport distances minimised.

Figure 2: Schematic Layout for GPMS[****]



[****] Figure 2 modified to show take-off point for alternative measurement systems

Appropriate dilution ratios for PND_1 and PND_2 will be determined in the first laboratory, and these shall be employed for the first test at each subsequent laboratory.

9.9.4 Preparation for the Daily Protocol: Instrument Warm-up and Daily Verification Exercises

First thing each morning all the elements of the measurement system will be activated, and left for at least 30 minutes to stabilise. This includes pumps, heaters, diluters and particle counters. The temperature of heated sections will be inspected to ensure compliance with the requirements of Section 8.2.2.

Instrument manufacturers of the various elements of the GPMS will provide calibration certification for the diluter(s), evaporation tube and particle counter employed for PMP particle number measurements. These data will be appropriate to address those requirements for primary calibration of instrumentation defined in the draft R83 regulation. However, it should be noted that the regulations are drafted with the intention that instrument manufacturers will have time to develop entirely suitable equipment and at this time exact compliance of all instrumentation with the draft regulations may not be possible.

Therefore the main issues are that operation consistent with the baseline calibrations is ensured, and that repeatable and valid operation can be demonstrated and maintained. In order to ensure this, regular calibration checks shall be performed. These are summarised as follows:

9.9.4.1 Verification of Free Sample Flow and Flow rate– The GPMS shall be checked for physical blockages and the CPC flow rate checked. The measured flow rate shall be within 5% of the instrument's nominal value.

9.9.4.2 Verification of Counter Zero – An initial concentration of around 10000/cm^3 (e.g. background number concentration) will be applied to both PNCs via a HEPA filter and using clean, particle free tubing. Testing shall commence if the measured particle count is less than 1/cm^3.

9.9.4.3 Verification of Counter High Response – Background particle concentration will be simultaneously sampled into both PNC_GOLD and PNC_REF. Testing may commence when a comparable response is observed from both PNCs. If the source aerosol shows a concentration above 10^4cm^{-3}, a diluter may be employed to reduce the concentration introduced to the CPCs.

9.9.4.4 Verification of System Contamination and Leak Integrity – After heating the evaporation tube a HEPA filter will be applied to the inlet of the diluter and particle number concentration through the whole system measured using PNC_GOLD. Testing can commence providing the measured particle count is less than 5/cm^3.

The GPMS shall then be fully reassembled. A sample line connected downstream of the particle pre-classifier shall then be connected to the inlet of the VPR. Sampling shall commence.

Any problems encountered during the daily verification exercise should be referred to the Golden Engineer or Project Manager who will make a decision on whether to proceed with the test programme.

9.10 During the test

During each emissions test, particle number concentrations from both PNC_Gold and PNC_REF shall be measured continuously in the particle sampling system with a frequency of >=0.5 Hz. The average concentrations shall be determined by integrating the analyser signals over the test cycle, with data recorded electronically. The system response time shall be ≤20 s, and shall be co-ordinated with sampling time/test cycle offsets, if necessary[††††].

9.11 Post-test

Following each emissions test, the following instrument function verification tests will be performed:

Verification of Free Sample Flow – The GPMS shall be checked for physical blockages. (Section 9.9.4.1). The PNC flow rate will be checked.

Verification of Counter Zero – An initial concentration of around 10000/cm^3 (e.g. background number concentration) will be applied to both PNCs via a HEPA filter and using clean, particle free tubing. Testing shall commence if the measured particle count is less than 1/cm^3. (Section 9.9.4.2)

Verification of Counter High Response – Background particle concentration (below 10^4cm^{-3}) will be simultaneously sampled into both PNC_GOLD and PNC_REF. If background concentration is >10^4cm^{-3} dilution may be employed to reduce the concentration. Testing may commence when a comparable response is observed from simultaneously from both PNCs. (9.9.4.3)

Data from each test will be inspected to determine whether instantaneous concentrations at the PNC_GOLD have exceeded 10^4 particles cm/^{3} during the emissions cycle. If this has occurred, the dilution ratios of PND_1 and PND_2 may need to be modified. These modifications shall be discussed with and approved by the project manager or golden engineer prior to the next test on that vehicle.

If necessary, the PND_1 and PND_2 diluters[‡‡‡] should be cleaned at this stage. It is not anticipated that this will be required with the Golden Vehicle, but laboratories testing conventional diesels may encounter contamination issues.

9.11.1 Repeat Daily Verification Exercise

Prior to Block 2 testing, correct VPR functional temperatures will be established and the checks described in Sections 9.9.4.1 to 9.9.4.4 inclusive conducted.

9.12 On Completion Of The Test Matrix

On completion of all testing, the GPMS and Golden vehicle will be prepared for despatch to the next laboratory for testing.

However, prior to testing at the first laboratory and subsequent to testing at some additional laboratories, the VPR will be returned to a predefined calibration facility for a

†††† Data logging needs to continue for at least 30s (60s recommended) following completion of the NEDC test, so that system response time can be accounted for
‡‡‡ Requirement for diluter cleaning added

performance check. This check will determine the penetration and volatile removal performance of the VPR as described below:

Verification of VPR Function – When the VPR is fully operational, the removal of at least 99% of a volatile test aerosol where the initial concentration is >10,000/cm^3 and concentration downstream of the thermoconditioner is >100/cm^3 shall be demonstrated. A polydisperse volatile aerosol of modal diameter between 20 and 60nm will be generated using a suitable aerosol generator. Measurements will be made before and after the thermoconditioner using a PNC.

VPR Penetration - A second verification is to demonstrate that the solid particle (a particle that is not volatile under the VPR operating conditions) penetration through the VPR conforms to the manufacturer's specification. A polydisperse aerosol will be classified in order to produce solid particles with a modal diameter of 60nm and passed through the VPR. Measurements will be made pre- and post-VPR at 20:1 and 300:1 dilution settings, and the actual penetration determined and recorded.

These performance evaluations will be undertaken during the shipping process for the Golden Vehicle and shall not delay the test programme. The decision as to when the VPR will be returned to the calibration facility will depend on the number of participating laboratories and will be at the discretion of the project manager and Golden Engineer.

10. DATA CAPTURE AND PRESENTATION IN CORRECT FORMAT

All data will be presented in a format compatible with Microsoft Excel. A standard spreadsheet for these data will be provided, prior to the commencement of testing, by the Project manager.

10.1 Regulated Emissions

Summary regulated gaseous emissions, carbon dioxide and fuel consumption data shall be quoted as g/km according to current European regulations. Data will be presented from individual UDC, EUDC phases and from the combined, NEDC, cycle.

In addition, raw and dilute logged gaseous regulated emissions shall be logged at a frequency of at least 1Hz in order to provide diagnostic capability if repeatability or reproducibility of vehicle tests is poor. On gasoline vehicles, the air/fuel ratio should be recorded or calculated at a frequency of 1Hz. These data shall be employed to interpret catalytic activity and engine management control. All logged data shall be presented in a time-aligned format on a CD-R.

10.2 Particulate Mass

Summary particulate mass data shall be quoted as g/km according to current European regulations. Data will be presented from the combined, NEDC, cycle.[9999]

10.3 Particle Number

Summary particle number data shall be quoted as number/km. Data will be presented from individual UDC, EUDC phases and from the combined, NEDC, cycle.

[9999] Particulate mass reported from the combined cycle only

In addition, logged particle number data, time-aligned and synchronised with the regulated gaseous emissions shall be presented in a time-aligned format on a CD-R.

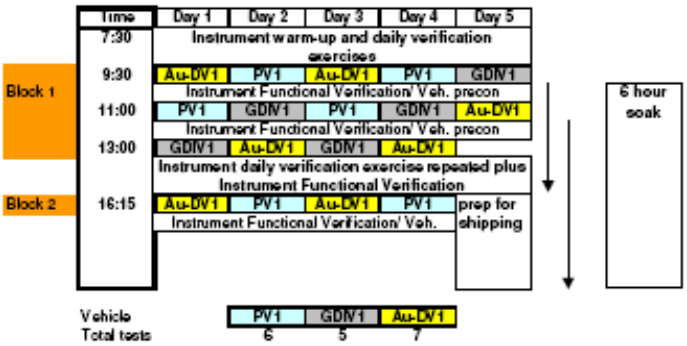
Appendix 1: Fill and Flush Procedure

1. Warm the oil by 10 minutes low load driving
2. Install vehicle on elevated ramp
3. Release sump plug and drain oil. Retain 1 litre sample
4. Drain oil filter and refit
5. Lower ramp add 4.5 litres of fresh oil to the engine.
6. Start engine and idle for a fixed period (40 minutes[****]), sufficient to reach operating temperature
7. Install vehicle on elevated ramp. Drain oil again
8. Remove oil filter and discard.
9. Fill engine with 4.5 litres test oil.
10. Switch ignition off and allow to settle for 5 minutes. Check dipstick to ensure correct oil level

[****] 40 minute idle period determined at Lab 1: JRC

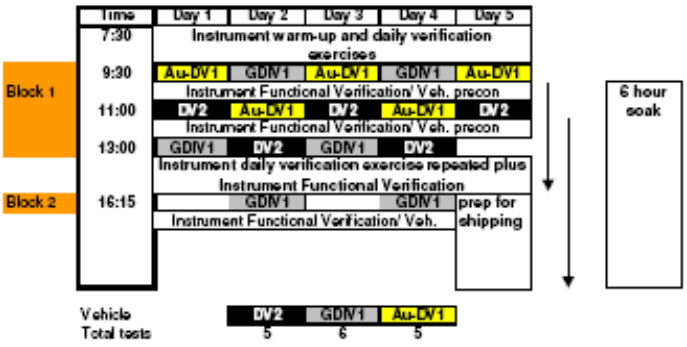
APPENDIX 2: Example Protocols

3 Vehicles – Golden Vehicle Plus Two Petrol Vehicles



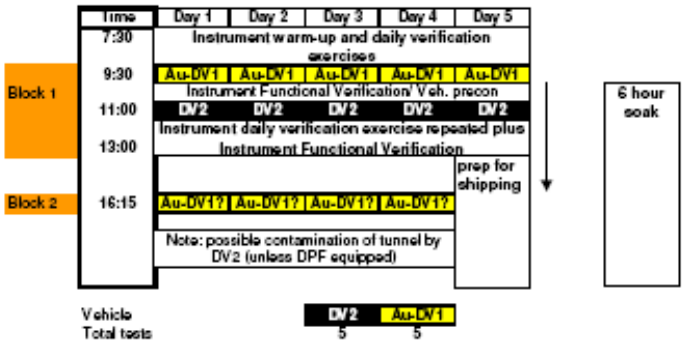
Notes:
Testing in 2 blocks (am and pm, with 6 hour soak on first vehicle between)
NEDC test takes 30 mins however with up front prep, reading emissions, coastdowns and precon for the next test this is nearer 2h
Impractical to be more than 4 tests pr day (with conditionings for subsequent days)
Assume Golden Vehicle and two petrol vehicles
Au-DV1 cannot follow DV2
PV1 cannot follow GDV1

3 Vehicles – Golden Vehicle Plus One Diesel and One Petrol Vehicle



Notes:
Testing in 2 blocks (am and pm, with 6 hour soak on first vehicle between)
NEDC test takes 30 mins however with up front prep, reading emissions, coastdowns and precon for the next test this is nearer 2h
Impractical to be more than 4 tests pr day (with conds for subsequent days)
Assume Golden Vehicle, one petrol and one diesel vehicles
Au-DV1 cannot follow DV2
PV1 cannot follow GDV1

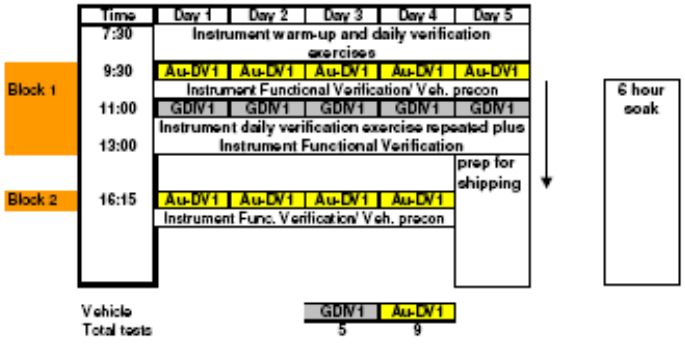
2 Vehicles – Golden Vehicle Plus One Diesel



Notes: Testing in 2 blocks (am and pm, with 6 hour soak on first vehicle between)
NEDC test takes 30 mins however with up front prep, reading emissions, coastdowns and precon for the next test this is nearer 2h

Assume Golden Vehicle, and one diesel vehicle
Au-DV1 cannot follow DV2

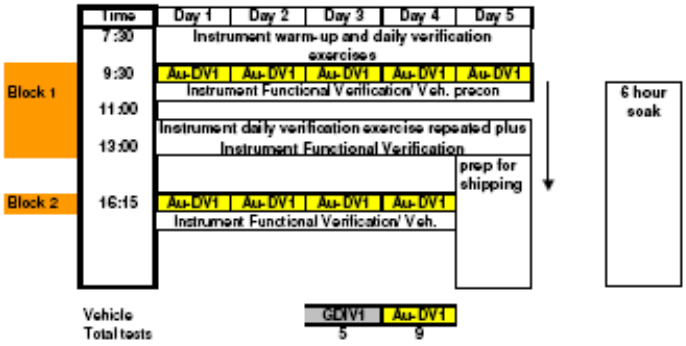
2 Vehicles – Golden Vehicle Plus One Petrol



Notes: Testing in 2 blocks (am and pm, with 6 hour soak on first vehicle between)
NEDC test takes 30 mins however with up front prep, reading emissions, coastdowns and precon for the next test this is nearer 2h

Assume Golden Vehicle plus one petrol vehicle

1 Vehicles – Golden Vehicle



Notes: Testing in 2 blocks (am and pm, with 6 hour soak on first vehicle between)
NEDC test takes 30 mins however with up front prep, reading emissions, coastdowns and precon for the next test this is nearer 2h

Assume Golden Vehicle only

Appendix 2: Fuel Specification

Direction Additifs et Carburants Spéciaux
Chemin du canal - BP 22 - 69360 Solaize France
Tél: +33 4 78 02 60 64 - Fax: +33 4 78 02 60 91

APPELLATION : GAZOLE TYPE CEC RF 06-03		Référence analyse : 6160
GAZOLE INDUSTRIE	N° de lot : B7274081	Date : 03/09/2004
CERTIFICAT DE CONFORMITE [x]		BULLETIN D'ANALYSES [ ]

GAZOLE	SPECIFICATIONS	UNITE	RESULTATS	METHODES
DONNEES PHYSIQUES				
Masse Volumique 15 °C	**833 à 837**	kg/m3	**835**	ASTM D 4052
Viscosité à 40°C	**2.3 à 3.3**	mm2/s	**2,7**	ASTM D 445
DISTILLATION				
PI		°C	**185**	ASTM D 86
5 % Vol		°C	**201**	ASTM D 86
10 % Vol		°C	**208**	ASTM D 86
20 % Vol		°C	**219**	ASTM D 86
30 % Vol		°C	**233**	ASTM D 86
40 % Vol		°C	**251**	ASTM D 86
50 % Vol	**245 mini**	°C	**274**	ASTM D 86
60 % Vol		°C	**293**	ASTM D 86
70 % Vol		°C	**309**	ASTM D 86
80 % Vol		°C	**320**	ASTM D 86
90 % Vol		°C	**333**	ASTM D 86
95 % Vol	**345 à 350**	°C	**346**	ASTM D 86
PF	**370 maxi**	°C	**356**	ASTM D 86
E 250 °C		%Vol	**39.6**	ASTM D 86
E 350 °C		%Vol	**96**	ASTM D 86
E 370 °C		%Vol	**96.5**	ASTM D 86
INDICE DE CETANE				
Cétane calculé		index	**53.5**	ASTM D 4737
Cétane mesuré	**52 à 54**	index	**53**	ISO 5165-98
Point Eclair	**55 mini**	°C	**75**	EN 22719
COMPOSITION				
Aromatiques Totaux		%Mass	**21.8**	IP 391
Poly-Aromatiques	**3.0 à 6.0**	%Mass	**4,4**	IP 391
TENUE AU FROID				
Point de trouble		°C	**-9**	ASTM D2500
TLF	**-5 maxi**	°C	**-18**	EN 116, NF M 07042
COMBUSTION				
Pouvoir Calorifique Inférieur (G)		MJ/kg	**43.355**	ASTM D 4868
%C, %H, %O		%Mass	**87.4/11.4/<0.5**	GC / Calculated
DONNEES COMPLEMENTAIRES				
Stabilité à l'Oxydation	**25 maxi**	g/m3	**10**	ISO 12205
Corrosion Cuivre 3H, 50°C	**C1**	merit	**1a**	ASTM D 130
Soufre	**10 maxi**	mg/kg	**8**	ISO 4260 / ISO 8754
Carbone conradson sur résidu 10% Vol	**0.2 maxi**	%m/m	**0**	ISO 10370
Teneur en cendres	**0.01 maxi**	%m/m	**0,01**	ISO 6245
Indice d'acide	**0.02 maxi**	mg KOH/g	**0**	ASTM D 974
Teneur en sédiments		mg/kg	**2**	ASTM D 2276
Teneur en esters méthyliques d'acides gras	**néant**	%Mass	**0**	
Teneur en eau	**200 maxi**	mg/kg	**55**	EN ISO 12937
Pouvoir Lubrifiant à 60°C	**400 maxi**	µm	**360**	ISO/DIS 12156

Observation :

VALIDATION LABO
le 24/09/2004
par Metin KELLE

Document confidentiel. Diffusion extérieure soumise à l'accord de RM/SPE/ACS
L'interprétation des résultats des mesures relève de la norme NF EN ISO 4259

Fiche de données de sécurité : 60030000 DE / EN / ES / FR / IT

Date specs : 26/06/2003 Rév: 0

24/09/2004

Appendix 3A: Summarised Test Results (Including Outliers) of Golden Vehicle

Lab ID	Acronyms	Dates	GPMS NEDC [#/km]	PM NEDC [mg/km]	PM valid tests	HC [g/km]	CO [g/km]	CO2 [g/km]	NOx [g/km]	HC+NOx [g/km]	COMMENTS
Lab#1,r1	Au-DPF	11-Nov04	4,12E+10	0,312	valid	0,008	0,030	168,106	0,219	0,227	
Lab#1,r1	Au-DPF	12-Nov04	8,15E+10	0,524	valid	0,009	0,032	166,753	0,208	0,217	afternoon tests (second test in a same day)
Lab#1,r1	Au-DPF	15-Nov04 #1	4,09E+10	0,503	valid	0,010	0,042	171,434	0,228	0,238	
Lab#1,r1	Au-DPF	15-Nov04 #2	9,25E+10	0,314	valid	0,009	0,041	168,413	0,209	0,218	afternoon tests (second test in a same day)
Lab#1,r1	Au-DPF	16-Noε-04	5,22E+10	0,398	valid	0,010	0,040	169,543	0,217	0,227	
Lab#1,r1	Au-DPF	16-Noε-04	7,08E+10	0,378	valid	0,009	0,045	167,563	0,216	0,225	afternoon tests (second test in a same day)
Lab#1,r1	Au-DPF	17-Nov04 #1	4,05E+10	0,443	valid	0,010	0,041	169,808	0,210	0,220	
Lab#2	Au-DPF	30-Nov04	6,96E+10	0,557	PM non valid	0,021	0,019	153,000	0,191	0,212	mass outlier
Lab#2	Au-DPF	01-Dic04 #1	8,80E+10	0,390	valid	0,009	0,022	155,000	0,183	0,192	
Lab#2	Au-DPF	01-Dic04#2	2,54E+10	0,389	valid	0,007	0,025	155,000	0,199	0,206	afternoon tests (second test in a same day)
Lab#2	Au-DPF	03-Dic04 #1	8,79E+10	0,123	valid	0,010	0,026	157,000	0,201	0,211	
Lab#2	Au-DPF	03-Dic04 #2	1,67E+10	0,185	valid	0,009	0,056	158,000	0,211	0,220	afternoon tests (second test in a same day)
Lab#3	Au-DPF	31-Jan05	4,35E+10	1,067	PM non valid	0,000	0,027	164,446	0,185	0,211	mass outlier (2 filter test)
Lab#3	Au-DPF	01-Feb05	1,55E+10	0,145	valid	0,0057	0,034	162,736	0,177	0,211	
Lab#3	Au-DPF	02-Feb05	3,55E+10	0,678	valid	0,0017	0,037	163,721	0,189	0,227	
Lab#3	Au-DPF	03-Feb05	1,79E+11	0,564	valid	0,0046	0,038	163,810	0,191	0,229	prior to Test4 a regeneration event was reported
Lab#3	Au-DPF	04-Feb05	1,41E+11	0,356	valid	0,0000	0,052	174,348	0,203	0,255	after Test5 250 Km additional mileage was performed
Lab#3	Au-DPF	07-Feb05	1,06E+11	0,373	valid	0,0000	0,036	164,572	0,192	0,228	
Lab#4	Au-DPF	28-Feb05	3,12E+09	1,50	non valid	0,015	0,075	161,633	0,193	0,208	no preconditioning
Lab#4	Au-DPF	01-March05	7,30E+10	1,40	PM non valid	0,007	0,008	156,960	0,183	0,190	mass outlier
Lab#4	Au-DPF	02-March05	7,21E+10	1,10	valid	0,007	0,014	157,770	0,191	0,158	
Lab#4	Au-DPF	03-March05	4,62E+09	0,20	non valid	0,006	0,011	156,429	0,187	0,194	no preconditioning
Lab#4	Au-DPF	04-March05	9,55E+10	0,40	valid	0,014	0,016	157,646	0,187	0,201	
Lab#4	Au-DPF	09-March05	1,05E+11	0,60	valid	0,007	0,021	160,342	0,190	0,196	
Lab#4	Au-DPF	10-March05 #1	6,97E+10	0,50	valid	0,006	0,020	160,259	0,188	0,193	
Lab#4	Au-DPF	10-March05 #2	6,83E+10	0,50	non valid	0,010	0,045	186,148	0,443	0,449	Tested aborted (PDF regeneration at 900 seconds).Then about 230 km at constant speed about 85 km/h
Lab#4	Au-DPF	11/3/2005 #1	2,18E+11	0,60	valid	0,007	0,020	156,255	0,176	0,179	
Lab#4	Au-DPF	11/3/2005 #2		0,50	valid	0,007	0,018	155,987	0,176	0,180	afternoon test (second test in a same day). No particle emission was reported for this test.
Lab#5	Au-DPF	06-April05	1,89E+11		non valid						High background PN concentration.
Lab#5	Au-DPF	07-April05	1,76E+11		non valid						High background PN concentration. Prior to Test3, the Golden vehicle was forced to regenerate at 100, 110, 120, 130 and 140 kph. Conditioning of the vehicle after regeneration was performed at 80 kph.
Lab#5	Au-DPF	13-April05	6,37E+10	0,206	valid	0,009	0,038	169,053	0,204	0,213	
Lab#5	Au-DPF	14-April05	3,10E+10	0,292	valid	0,009	0,031	173,684	0,277	0,286	
Lab#5	Au-DPF	15-April05	2,75E+10	0,275	valid	0,011	0,045	167,056	0,258	0,269	
Lab#5	Au-DPF	18-April05	8,61E+10	0,218	valid	0,010	0,053	170,903	0,260	0,270	
Lab#5	Au-DPF	19-April05	1,30E+11	0,269	valid	0,011	0,038	169,193	0,258	0,270	

Lab ID	Acronyms	Dates	GPMS NEDC [#/km]	PM NEDC [mg/km]	PM valid tests	HC [g/km]	CO [g/km]	CO2 [g/km]	NOx [g/km]	HC+NOx [g/km]	COMMENTS
Lab#1,r2	Au-DPF	11-Μαϊ-05	1,01E+11	0,935	non valid	0,009	0,058	163,576	0,212	0,221	Test1 without preconditioning (2-filter test: primary counted only) Test6 and Test8: afternoon tests (second test in a same day).
Lab#1,r2	Au-DPF	13-Μαϊ-05	1,20E+11	0,584	valid	0,012	0,068	165,316	0,214	0,226	Before Test2, the vehicle was forced to regenerate. 140 km/h for 30 minutes.
Lab#1,r2	Au-DPF	18-Νοε-05	1,54E+11	0,474	valid	0,010	0,061	165,385	0,212	0,222	2-filter test: primary counted only
Lab#1,r2	Au-DPF	19-Μαϊ-05	1,29E+11	0,418	valid	0,008	0,043	165,800	0,209	0,217	2-filter test: primary counted only
Lab#1,r2	Au-DPF	20-May05 #1	9,85E+10	0,377	valid	0,009	0,056	166,864	0,219	0,228	2-filter test: primary counted only
Lab#1,r2	Au-DPF	20-May05 #2	1,14E+11	0,522	valid	0,009	0,056	166,978	0,227	0,236	2-filter test: primary counted only
Lab#1,r2	Au-DPF	23-May05#1	1,64E+11	0,478	valid	0,010	0,082	166,344	0,212	0,222	Prior to Test7 a regeneration event was observed. 2-filter test: primary counted only
Lab#1,r2	Au-DPF	23-May05#2	1,40E+11	0,499	valid	0,008	0,029	168,471	0,225	0,233	2-filter test: primary counted only
Lab#1,r2	Au-DPF	25-Μαϊ-05	1,12E+11	0,483	valid	0,009	0,046	167,222	0,214	0,223	2-filter test: primary counted only
Lab#1,r2	Au-DPF	30-Μαϊ-05	9,42E+10	0,724	PM non valid	0,010	0,060	169,539	0,234	0,243	mass outlier. 2-filter test: primary counted only
Lab#1,r2	Au-DPF	31-Μαϊ-05	1,28E+11	0,449	valid	0,010	0,059	167,838	0,206	0,216	2-filter test: primary counted only
Lab#6	Au-DPF	30-Αυγ-05	1,42E+11	1,712	non valid	0,001	0,491	164,934	0,364	0,364	non valid test (The driver could not perform suitable operation)
Lab#6	Au-DPF	31-Αυγ-05	2,11E+11	1,166	non valid	-0,003	0,213	174,126	0,385	0,385	non valid test (The driver could not perform suitable operation)
Lab#6	Au-DPF	1-Σεπ-05	5,72E+10	0,972	non valid	-0,001	0,034	152,718	0,259	0,259	There is no failure on this test. But after Test5, long regeneration arose and a tendency of PM trapped by filter was changed.
Lab#6	Au-DPF	2-Σεπ-05	2,68E+11	0,615	non valid	-0,002	0,048	152,424	0,265	0,264	non valid test: There are two electrical noises on GPMS results and this couses hightotal particle number.
Lab#6	Au-DPF	3-Σεπ-05	8,60E+10	0,955	non valid	0,001	0,090	154,721	0,309	0,309	There is no failure on this test. But after Test5, long regeneration arose and a tendency of PM trapped by filter was changed.
Lab#6	Au-DPF	6-Σεπ-05	9,88E+10	0,189	valid	0,001	0,077	149,697	0,238	0,238	
Lab#6	Au-DPF	7-Σεπ-05	8,88E+10	-0,273	non valid	0,008	0,082	151,786	0,245	0,246	non valid test (negative value was obtained on PM filter weighing method)
Lab#6	Au-DPF	8-Σεπ-05	9,54E+10	0,485	valid	0,004	0,096	150,571	0,238	0,239	
Lab#6	Au-DPF	9-Σεπ-05	9,99E+10	0,234	valid	0,004	0,095	151,703	0,242	0,242	
Lab#6	Au-DPF	12-Σεπ-05	8,57E+10	0,222	valid	0,003	0,100	152,112	0,252	0,252	
Lab#6	Au-DPF	13-Σεπ-05	8,39E+10	0,851	PM non valid	0,001	0,081	152,779	0,264	0,264	mass outlier
Lab#6	Au-DPF	14-Σεπ-05	7,62E+10	0,547	valid	0,005	0,097	154,157	0,266	0,266	
Lab#6	Au-DPF	-September05	1,01E+11	0,577	valid	0,002	0,086	145,799	0,229	0,229	
Lab#6	Au-DPF	-September05	1,10E+11	0,031	valid	0,002	0,069	149,200	0,236	0,236	Test14: afternoon tests (second test in a same day)

Lab ID	Acronyms	Dates	GPMS NEDC [#/km]	PM NEDC [mg/km]	PM valid tests	HC [g/km]	CO [g/km]	CO2 [g/km]	NOx [g/km]	HC+NOx [g/km]	COMMENTS
Lab#7	Au-DPF	25-Oct-05	1.85E+11	1.110	non valid	0.010	0.739	160.293	0.276	0.286	Test1: non valid test (exhaust pipe welding effect)
Lab#7	Au-DPF	26-Oct-05	9.14E+10	0.190	valid	0.008	0.051	156.000	0.233	0.241	
Lab#7	Au-DPF	27-Oct-05	3.87E+11	0.310	non valid	0.009	0.650	153.315	0.221	0.230	non valid test (DPF regeneration)
Lab#7	Au-DPF	28-Oct-05	1.11E+11	0.290	non valid	0.010	0.662	163.612	0.346	0.355	non valid test (DPF regeneration)
Lab#7	Au-DPF	1-Nov-05	1.43E+11	0.280	non valid	0.008	0.581	156.736	0.258	0.267	non valid test (DPF regeneration)
Lab#7	Au-DPF	2-Nov-05	9.54E+10	0.260	valid	0.009	0.071	156.000	0.262	0.271	
Lab#7	Au-DPF	3-Nov-05	9.42E+10	0.210	valid	0.008	0.062	155.000	0.249	0.257	
Lab#7	Au-DPF	4-Nov-05	5.51E+10	0.270	valid	0.009	0.059	156.000	0.247	0.256	
Lab#7	Au-DPF	8-Nov-05	1.02E+11	0.480	non valid	0.007	0.483	156.471	0.280	0.288	Test 9: non valid test (hot NEDC)
Lab#7	Au-DPF	9-Nov-05	6.86E+10	0.240	valid	0.008	0.055	154.000	0.244	0.252	
Lab#7	Au-DPF	10-Nov-05	4.23E+10	0.110	non valid	0.011	0.850	168.855	0.453	0.465	Test 11: non valid tests (high NOx)
Lab#7	Au-DPF	11-Nov-05	5.64E+10	0.210	valid	0.008	0.043	154.000	0.251	0.259	
Lab#8	Au-DPF	22-Mar-06	3.48E+10	0.270	valid	0.008	0.052	163.833	0.214	0.222	
Lab#8	Au-DPF	23-Mar-06	2.91E+10	0.193	valid	0.014	0.076	162.099	0.213	0.227	
Lab#8	Au-DPF	24-Mar-06	4.41E+10	0.271	valid	0.013	0.089	163.829	0.222	0.234	
Lab#8	Au-DPF	11-Apr-06	7.18E+10	0.067	valid	0.010	0.062	164.220	0.207	0.217	
Lab#8	Au-DPF	12-Apr-06	4.10E+10	0.000	PM non valid	0.012	0.083	163.169	0.209	0.220	mass outlier
Lab#9	Au-DPF	18-May-06	8.32E+10	0.242	valid	0.013	0.108	161.800	0.243	0.244	
Lab#9	Au-DPF	22-May-06	9.23E+10	0.366	PM non valid	0.012	0.116	161.000	0.220	0.221	mass outlier
Lab#9	Au-DPF	23-May-06	8.42E+10	0.327	valid	0.012	0.104	164.600	0.221	0.222	
Lab#9	Au-DPF	29-May-06	1.46E+11	0.264	valid	0.010	0.074	161.200	0.213	0.214	
Lab#9	Au-DPF	30-May-06	1.42E+11	0.287	valid	0.010	0.100	161.400	0.243	0.244	
Lab#1,r3	Au-DPF	13-Jun-06	5.40E+10	0.963	non valid	0.014	0.145	191.892	0.504	0.518	non valid test. Regeneration at 900 seconds of Test1.
Lab#1,r3	Au-DPF	14-Jun-06	1.83E+11	0.937	non valid	0.011	0.082	158.058	0.140	0.151	non valid test. Post regeneration test
Lab#1,r3	Au-DPF	15-Jun-06	1.14E+11	0.809	non valid	0.010	0.080	160.840	0.213	0.223	non valid test. Post regeneration test
Lab#1,r3	Au-DPF	16-Jun-06	7.68E+10	0.855	non valid	0.011	0.085	161.070	0.212	0.223	non valid test. Post regeneration test
Lab#1,r3	Au-DPF	19-Jun-06	5.19E+10	0.683	non valid	0.011	0.085	159.422	0.204	0.215	Insatallation of new filtering system. Not working properly
Lab#1,r3	Au-DPF	20-Jun-06	5.26E+10	0.853	non valid	0.010	0.071	161.681	0.211	0.221	Insatallation of new filtering system. Not working properly
Lab#1,r3	Au-DPF	21-Jun-06	5.92E+10	0.808	non valid	0.010	0.085	160.052	0.216	0.226	Insatallation of new filtering system. Not working properly
Lab#1,r3	Au-DPF	22-Jun-06	4.48E+10	0.893	non valid	0.011	0.081	159.591	0.213	0.224	Insatallation of new filtering system. Not working properly
Lab#1,r3	Au-DPF	23-Jun-06	7.97E+10	0.635	non valid	0.010	0.074	162.226	0.218	0.228	Insatallation of new filtering system. Not working properly
Lab#1,r3	Au-DPF	26-Jun-06	9.60E+10	0.744	non valid	0.011	0.113	156.728	0.216	0.227	Insatallation of new filtering system. Not working properly
Lab#1,r3	Au-DPF	26-Jul-06	9.78E+10	0.160	valid	0.009	0.072	161.325	0.219	0.228	
Lab#1,r3	Au-DPF	26-Jul-06	1.85E+10	0.252	non valid	0.009	0.069	158.037	0.214	0.223	afternoon tests (different preconditioning)
Lab#1,r3	Au-DPF	27-Jul-06	1.48E+11	0.450	valid	0.009	0.066	158.143	0.215	0.223	
Lab#1,r3	Au-DPF	27-Jul-06	2.33E+10	0.344	non valid	0.009	0.100	157.468	0.271	0.280	afternoon tests (different preconditioning)
Lab#1,r3	Au-DPF	28-Jul-06	1.08E+11	0.461	valid	0.010	0.077	156.411	0.224	0.233	
Lab#1,r3	Au-DPF	31/7/2006#1	8.37E+10	0.510	valid	0.009	0.077	156.124	0.215	0.224	
Lab#1,r3	Au-DPF	31/7/2006#2	1.13E+10	0.254	non valid	0.010	0.078	154.429	0.218	0.228	afternoon tests (different preconditioning)
Lab#1,r3	Au-DPF	8-Aug-06	1.50E+11	1.246	PM non valid	0.010	0.082	156.227	0.225	0.234	mass outlier
Lab#1,r3	Au-DPF	9-Aug-06	1.08E+11	0.106	valid	0.009	0.075	156.729	0.226	0.235	
Lab#1,r3	Au-DPF	11-Aug-06	1.57E+11	0.446	valid	0.010	0.080	156.158	0.211	0.220	
Lab#1,r3	Au-DPF	18-Aug-06	9.62E+10	0.679	valid	0.010	0.081	154.942	0.214	0.224	SPCS data after recalibration of the system.

Appendix 3B: Summarised Test Results (Including Outliers) of rest vehicles

Lab ID	Acronyms	Dates	GPMS NEDC [#/km]	PM NEDC [mg/km]	PM valid tests	HC [g/km]	CO [g/km]	CO2 [g/km]	NOx [g/km]	HC + NOx [g/km]	COMMENTS
Lab#3	DPF#1	01-Feb05	6.91E+10	0.559	valid	0.033	0.232	247.513	0.231	0.264	
Lab#3	DPF#1	02-Feb05	3.55E+10	0.678	valid	0.031	0.235	250.757	0.236	0.267	
Lab#3	DPF#1	03-Feb05	2.99E+10	0.677	valid	0.036	0.254	252.162	0.262	0.298	
Lab#3	DPF#1	04-Feb05	4.28E+10	0.564	valid	0.017	0.243	245.212	0.243	0.245	
Lab#3	DPF#1	07-Feb06	3.01E+10	0.645	valid	0.025	0.283	251.247	0.249	0.274	
Lab#6	DPF#2	1-Sep-05	5.21E+10	0.984	valid	0.020	0.402	206.100	0.915	0.935	
Lab#6	DPF#2	2-Sep-05	2.83E+10	0.949	valid	0.016	0.270	207.100	0.862	0.878	
Lab#6	DPF#2	6-Sep-05	3.26E+10	0.682	valid	0.023	0.443	205.100	0.920	0.943	
Lab#6	DPF#2	9-Sep-05	5.32E+10	0.936	valid	0.023	0.447	208.600	0.935	0.958	
Lab#6	DPF#2	12-Sep-05	4.05E+10	0.320	**PM non valid**	0.021	0.426	207.800	0.920	0.941	**mass outlier**
Lab#6	DPF#2	13-Sep-05	2.29E+10	1.040	valid	0.022	0.427	206.800	0.947	0.969	
Lab#8	DPF#3	22-Mar-06	6.50E+11	7.433	**PM non valid**	0.032	0.218	185.213	0.248	0.280	**mass outlier**
Lab#8	DPF#3	24-Mar-06	5.93E+11	0.394	valid	0.038	0.261	186.041	0.247	0.285	
Lab#8	DPF#3	29-Mar-06	4.10E+11	0.256	valid	0.034	0.219	183.289	0.218	0.252	
Lab#8	DPF#3	11-Apr-06	5.26E+11	0.379	valid	0.035	0.264	183.739	0.219	0.255	
Lab#8	DPF#3	12-Apr-06	8.49E+11	0.438	valid	0.034	0.253	186.031	0.219	0.253	
Lab#8	DPF#4	7-Apr-06	1.37E+11	0.759	valid	0.03	0.10	280.81	0.42	0.45	
Lab#8	DPF#4	11-Apr-06	9.84E+10	0.826	valid	0.03	0.08	270.71	0.39	0.42	
Lab#8	DPF#4	12-Apr-06	4.12E+10	0.448	valid	0.03	0.08	283.85	0.42	0.45	
Lab#8	DPF#4	13-Apr-06	1.18E+10	0.594	valid	0.02	0.08	281.40	0.43	0.46	
Lab#8	DPF#4	19-Apr-06	3.31E+09	0.007	**PM non valid**	0.02	0.08	285.39	0.44	0.46	**mass outlier**
Lab#9	DPF#5	18-May-06	2.07E+10	0.263	valid	0.011	0.058	121.00	0.163	0.221	
Lab#9	DPF#5	22-May-06	1.38E+10	0.300	valid	0.011	0.053	121.80	0.162	0.215	
Lab#9	DPF#5	23-May-06	1.80E+10	0.223	**PM non valid**	0.012	0.061	121.20	0.168	0.229	**mass outlier**
Lab#9	DPF#5	29-May-06	9.07E+09	0.284	valid	0.013	0.066	122.80	0.176	0.242	
Lab#9	DPF#5	30-May-06	1.59E+10	0.266	valid	0.011	0.062	124.50	0.180	0.242	
Lab#1,r2	MPI Vehicle	11-May-05	7.54E+11	1.646	**non valid**	0.102	0.281	155.571	0.018	0.120	**Test1 without preconditioning**
Lab#1,r2	MPI Vehicle	12-May-05	9.65E+10	0.251	valid	0.027	0.262	154.922	0.018	0.045	
Lab#1,r2	MPI Vehicle	13-May-05	1.42E+11	0.418	valid	0.04	0.276	154.214	0.016	0.056	**2-filter test: primary counted only**
Lab#1,r2	MPI Vehicle	17-May-05	-	0.705	valid	0.041	0.375	154.782	0.015	0.056	**2-filter test: primary counted only**
Lab#1,r2	MPI Vehicle	18-Nov-05	1.13E+11	0.703	valid	0.029	0.298	155.099	0.015	0.044	**2-filter test: primary counted only**
Lab#1,r2	MPI Vehicle	19-May-05	7.95E+10	0.431	valid	0.029	0.272	154.174	0.012	0.041	**2-filter test: primary counted only**
Lab#4	GDI#1	01-March05	6.47E+12	7.60	valid	0.097	0.027	191.748	0.079	0.176	
Lab#4	GDI#1	02-March05	7.10E+12	7.80	valid	0.095	0.026	191.780	0.092	0.187	
Lab#4	GDI#1	03-March05	7.39E+12	8.60	**PM non valid**	0.108	0.031	193.624	0.085	0.193	**mass outlier**
Lab#4	GDI#1	09-March05	7.23E+12	7.90	valid	0.122	0.038	195.466	0.094	0.215	
Lab#4	GDI#1	10-Mar-05	7.51E+12	8.20	valid	0.097	0.031	195.263	0.088	0.184	
Lab#4	GDI#1	11-Mar-05	6.83E+12	7.70	valid	0.114	0.030	193.760	0.093	0.207	
Lab#1,r2	GDI#2	11-May-05	2.83E+12	2.370	valid	0.055	0.241	168.878	0.054	0.109	
Lab#1,r2	GDI#2	12-May-05	4.09E+12	2.589	**PM non valid**	0.080	0.356	165.941	0.083	0.163	**mass outlier. 2-filter test: primary counted only**
Lab#1,r2	GDI#2	17-May-05	3.06E+12	1.652	valid	0.038	0.212	169.328	0.043	0.081	**2-filter test: primary counted only**
Lab#1,r2	GDI#2	18-Nov-05	4.46E+12	1.713	valid	0.039	0.201	165.840	0.039	0.078	**2-filter test: primary counted only**
Lab#1,r2	GDI#2	23-May-05	2.47E+12	1.623	valid	0.042	0.241	168.404	0.050	0.092	**2-filter test: primary counted only**
Lab#1,r2	GDI#2	24-May-05	4.21E+12	1.696	valid	0.036	0.308	167.744	0.080	0.069	**2-filter test: primary counted only**

Lab ID	Acronyms	Dates	GPMS NEDC [#/km]	PM NEDC [mg/km]	PM valid tests	HC [g/km]	CO [g/km]	CO2 [g/km]	NOx [g/km]	HC + NOx [g/km]	COMMENTS
Lab#6	GDI#3	30-Aug-05	1.28E+13	13.856	valid	0.272	0.537	234.100	0.065	0.337	
Lab#6	GDI#3	3-Sep-05	1.12E+13	14.540	**PM non valid**	0.271	0.727	245.300	0.034	0.305	**mass outlier**
Lab#6	GDI#3	5-Sep-05	1.08E+13	13.239	valid	0.277	0.805	248.900	0.039	0.316	
Lab#6	GDI#3	6-Sep-05	1.10E+13	13.156	valid	0.308	0.775	245.400	0.063	0.371	
Lab#6	GDI#3	9-Sep-05	1.14E+13	13.373	valid	0.291	0.873	242.800	0.026	0.317	
Lab#8	non-DPF#1	7-Apr-06	5.86E+13	47.542	**PM non valid**	0.01	0.04	197.31	0.24	0.25	**mass outlier**
Lab#8	non-DPF#1	12-Apr-06	4.49E+13	32.727	**PM non valid**	0.01	0.05	193.77	0.25	0.27	**mass outlier**
Lab#8	non-DPF#1	19-Apr-06	5.31E+13	37.842	valid	0.02	0.06	195.09	0.24	0.26	
Lab#8	non-DPF#1	20-Apr-06	5.41E+13	39.748	valid	0.01	0.05	194.78	0.26	0.27	
Lab#8	non-DPF#1	22-Apr-06	5.20E+13	41.934	valid	0.02	0.06	193.77	0.27	0.28	
Lab#3	non-DPF#2	31-Jan06			**non valid**						**test aborted**
Lab#3	non-DPF#2	01-Feb06	5.63E+13	33.277	valid	0.013	0.154	141.802	0.246	0.247	
Lab#3	non-DPF#2	02-Feb06	5.81E+13	32.103	valid	0.013	0.148	139.567	0.222	0.223	
Lab#3	non-DPF#2	03-Feb06	6.01E+13	31.130	valid	0.013	0.141	141.118	0.231	0.232	
Lab#3	non-DPF#2	04-Feb06	5.53E+13	26.690	valid	0.000	0.153	140.343	0.233	0.233	
Lab#3	non-DPF#2	07-Feb07	5.50E+13	26.516	valid	0.005	0.162	140.095	0.244	0.245	
Lab#4	non-DPF#3	01-March05	5.42E+13	17.80	valid	0.025	0.110	148.322	0.244	0.269	
Lab#4	non-DPF#3	02-March05	5.33E+13	17.50	valid	0.028	0.112	147.111	0.237	0.266	
Lab#4	non-DPF#3	03-March05	5.28E+13	17.50	valid	0.022	0.112	149.145	0.260	0.275	
Lab#4	non-DPF#3	09-March05	6.09E+13	19.90	valid	0.015	0.099	149.113	0.256	0.265	
Lab#4	non-DPF#3	10-Mar-05	5.54E+13	20.10	valid	0.017	0.101	149.315	0.254	0.271	
Lab#4	non-DPF#3	11-Mar-05	5.52E+13	19.20	valid	0.018	0.113	147.239	0.236	0.251	
Lab#5	non-DPF#4	13-April05	5.75E+13	16.841	valid	0.023	0.148	171.727	0.180	0.203	
Lab#5	non-DPF#4	14-April05	6.12E+13	20.581	**PM non valid**	0.021	0.118	177.597	0.200	0.221	**mass outlier**
Lab#5	non-DPF#4	19-April05	6.04E+13	16.934	valid	0.021	0.147	170.780	0.179	0.200	
Lab#5	non-DPF#4	20-April05	6.07E+13	16.452	valid	0.024	0.206	168.492	0.176	0.200	
Lab#7	non-DPF#5	1-Nov-05		12.04	valid	0.013	0.040	159.000	0.273	0.274	
Lab#7	non-DPF#5	2-Nov-05		11.10	valid	0.013	0.040	161.000	0.276	0.277	
Lab#7	non-DPF#5	4-Nov-05	2.70E+13	12.64	valid	0.013	0.039	160.000	0.279	0.280	
Lab#7	non-DPF#5	10-Nov-05	3.10E+13	12.25	valid	0.044	0.066	156.000	0.266	0.270	
Lab#7	non-DPF#5	11-Nov-05	2.80E+13	10.56	**PM non valid**	0.015	0.055	155.000	0.277	0.279	**mass outlier**
Lab#8	non-DPF#6	19-Apr-06	3.19E+13	11.688	valid	0.042	0.445	159.672	0.350	0.391	
Lab#8	non-DPF#6	20-Apr-06	3.33E+13	41.362	**PM non valid**	0.042	0.449	158.394	0.369	0.411	**mass outlier**
Lab#8	non-DPF#6	21-Apr-06	3.22E+13	10.993	valid	0.044	0.471	158.123	0.358	0.402	
Lab#8	non-DPF#6	25-Apr-06	3.02E+13	9.682	valid	0.038	0.406	156.818	0.343	0.381	
Lab#8	non-DPF#6	26-Apr-06	3.06E+13	11.188	valid	0.039	0.421	157.58	0.32	0.360	
Lab#8	EURO3	13-Apr-06	7.17E+13	46.57	valid	0.02	0.10	161.62	0.49	0.51	
Lab#8	EURO3	20-Apr-06	7.51E+13	47.28	valid	0.01	0.10	161.47	0.55	0.57	
Lab#8	EURO3	21-Apr-06	6.96E+13	45.67	valid	0.02	0.15	157.36	0.52	0.54	
Lab#8	EURO3	25-Apr-06	6.84E+13	43.94	valid	0.02	0.15	156.13	0.47	0.49	
Lab#8	EURO3	26-Apr-06	6.64E+13	41.83	**PM non valid**	0.02	0.15	156.78	0.48	0.50	**mass outlier**

Appendix 4: Comparative Specifications of Alternative Particle Number Systems

Particle Systems: DR83 and ILCE_guide compliance

Compliance: DR83 Recommended and ILCE_LD | Partial Compliance (with comments) | NEITHER (with comments on non-compliance) | UNKNOWN (data missing/secret)

Note 1: ILCE_LD guide states that exact compliance of all instrumentation with the draft regulations may not be possible
Note 2: ILCE_LD guide states that fully calibrated (for particles) diluters unlikely to be available in timescale of programme. Gas calibrations accepted.
Note 3: DR83 to be modified based upon experiences in ILCE_LD

Alternative System and Test Laboratory	Probe				Pre-classifier & Flow rate	PND1			Evaporation Tube						PND2			PNC								Total System probe tip to PNC
System Property	Probe Type (Stainless steel)	Max In-tunnel length (mm)	Max pre-cyclone length (mm)	Diameter (mm)	d50 Diameter (µm)	Spec	set-point Temp °C	Ratio range	Solid Particle Penetration	Volatile Particle Removal	Length (mm)	Diameter (mm,id)	Temp °C	Residence (s)	Spec	Temp °C	Ratio range	Flow	Counting accuracy 10^2 to 10^4 (cm^{-3})	Readability (cm^{-3})	Linear response range (cm-3)	Data logging frequency (>Hz)	T90 response time (s)	Data averaging period (s)	Counting Efficiency (%,nm)	Length (<mm)
ILCE_Guide Criteria for GPMS and ALT systems RD04_80801.5	Unshrouded	200	1000	12.5	2.5	gas + particle calibration criteria	150	~15	>80% penetration of 30, 50, 100nm particles	>99% removal of 30nm C40 particles	240	6	300	0.2	gas + particle calibration criteria	Ambient	~9.5	Full flow	10%, +/- 10 absolute below 100	0.1	1 to 10000	0.5	5 to 15	1 to 6	d10 = 16±1 d25 = 18±2 d50 = 23±3 d90 = 37±4	2500
DR83 Criteria for Particle Measurement systems	Requirements as current mass regulations: Unshrouded or shrouded	200	1000	12.5	Recommended: 2.5 to 10	As part of total system: 1 to 1000 times dilution in one or more stages. Gas calibration of diluters	>=150	1 to 1000 (total with PND2)	Performance defined by early Matter Engineering data, superseded by GPMS performance data				300 to 400	0.5±0.05	As part of total system: 1 to 1000 times dilution in one or more stages. Gas calibration of diluters	Ambient	1 to 1000 (total with PND1)	Full flow	10%, +/- 10 absolute below 100	0.1	1 to 10000	0.5	5 to 15	1 to 6	d10 = 16±1 d25 = 18±2 d50 = 23±3 d90 = 37±4	Not currently a specific requirement: 2500
DR83 Recommended System	Unshrouded or shrouded	200	1000	~12	>99% of 1µm particles sampled: 2.5 to 10	Conc first diluter is $<10^5$ and $>10^3$	>=150	1 to 1000	>90% penetration of 30, 50, 100nm particles	>99% removal of 30nm C40 particles	350±10	6±0.1	300 to 400	0.5±0.05	Gas temp <35°C ; $<10^4 cm^{-3}$	Ambient	1 to 30	Full flow	10%, +/- 10 absolute below 100	0.1	1 to 10000	0.5	5 to 15	1 to 6	d10 = 16±1 d25 = 18±2 d50 = 23±3 d90 = 37±4	2500
"GPMS" ALL LABS [example Ricardo]		250, but low priority: 1000mm met				Gas calibration data exists		Close to full range. Fixed in ILCE_LD	Compliant except at 30nm		Performance matched, but temp controlled to 300°C, residence time lower, shorter length				Gas calibration		Fixed dilution ratio adequate	TSI 3010D employed								
Dekati [FPS-ET-EJCT] JRC						Gas calibration exists at fixed ratios		Close to full range. Fixed in ILCE_LD	Results broadly similar, but no calibration data provided						Gas calibration		Fixed dilution ratio adequate	GRIMM 5.404 supplied along with letter proposing compliance, but no experimental data						Data provided		
Dekati [FPS-ET-EJCT] Ricardo						Gas calibration exists at fixed ratios		Close to full range. Fixed in ILCE_LD	Results broadly similar, but no calibration data provided						Gas calibration		Fixed dilution ratio adequate	GRIMM 5.403/5.404 supplied along with letter proposing compliance, but no experimental data						Data provided		
Dekati [FPS-ET-EJCT] Shell GS						Gas calibration exists at fixed ratios		Close to full range. Fixed in ILCE_LD	Results broadly similar, but no calibration data provided						Gas calibration		Fixed dilution ratio adequate	GRIMM 5.403/5.404 supplied along with letter proposing compliance, but no experimental data						Data provided		~3000mm
GPMS_CLONE AVL-MTC (similar to Swiss PMP)						Gas calibration		Ejector. Fixed in ILCE_LD	Home-made evaporation tube results broadly similar, but no calibration data provided						Thermophoretic dilution - through cooling		Fixed dilution with fixed temperature drop	TSI 3010 modified to 3010D operation; modified GRIMM 5.403						Data provided		
GPMS-clone NTSEL		300, but low impact: 1000mm met				Gas calibration data exists		Close to full range. Fixed in ILCE_LD	Compliant except at 30nm		Performance matched, but temp controlled to 300°C				Gas calibration		Fixed dilution ratio adequate	TSI 3010D employed								
GPMS-clone RWTUEV						Gas calibration data exists		Close to full range. Fixed in ILCE_LD	Results broadly similar, but no calibration data provided						Gas calibration		Fixed dilution ratio adequate	TSI 3010 modified to 3010D operation								
HORIBA SPCS JRC						Gas cal exists, particle cal may but no data			Solid Particle Counting System: SPCS, Cambridge Particle Conference 22nd May 2006. Les Hill		Data not released by Horiba				Gas cal exists, particle cal may but no data			TSI 3010D employed								
HORIBA SPCS NTSEL		330, but low impact: 1000mm met				Gas cal exists, particle cal may but no data			Solid Particle Counting System: SPCS, Cambridge Particle Conference 22nd May 2006. Les Hill		Data not released by Horiba				Gas cal exists, particle cal may but no data			TSI 3010D employed								

Appendix 5: List of Acronyms and Abbreviations

ADD:	Additional
AECC:	Association For Emissions Control by Catalyst
ALT:	Alternative
Au:	Golden
C:	Cordierite
CO:	Carbon Monoxide
CO2:	Carbon Dioxide
CoV:	Coefficient of Variance
CVS:	Constant Volume Sampling
DI:	Direct Injection
DISI	Direct Injection Spark Ignition
DPF:	Diesel Particulate Filter
DR:	Dilution Ratio
DV:	Diesel Vehicle
ECE:	Urban part of the NEDC
EEPS:	Engine Exhaust Particle Sizer
ET:	Evaporation Tube
EUDC:	Extra Urban Driving Cycle
FBC:	Fuel born Catalyst
FPS:	Fine Particle Sampler
G-DI:	Gasoline Direct Injection
GOLD:	Golden Instrument
GPMS:	Golden Particle Measurement System
HC:	Hydrocarbons
HEPA:	High Efficiency Particle Filter
ILCE:	Inter-Laboratory Correlation Exercise
ILG:	Inter-laboratory Guide
JRC:	Joint Research Centre
LD:	Light Duty
LII:	Laser induced Incandencence
LOD:	Limit of Detection
MPI:	Multi-Port Injection
N:	Number of samples
NEDC:	New European Driving Cycle
NIST:	National Institute of Standards and Technology
NO:	Nitrogen Oxide
NOx:	Nitrogen Dioxide
OEM:	Original Equipment Manufacturers
PAO:	Polyalphaolefin
PE:	Penetration Efficiency
PFI:	Port Fuel Injection
PM:	Particulate Matter
PMP:	Particle Measurement Programme
PN:	Particle Number
PNC:	Particle Number Counter
PND:	Particle Number Diluter
R.SP:	Speed
REF:	Reference instrument
Ri	Repetition
S:	Standard Deviation
Si:	Silicon
SYS:	System
Teflon:	47 mm teflo membrane PTFE with PMP (polymethylpentene) support ring
TX40:	47 mm Teflon-coated glass-fiber Pallflex® TX40H120-WW filters
VPR:	Volatile Particle Remover

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Abstract

The Light Duty Inter-Laboratory Correlation Exercise has conducted testing at 9 test laboratories in the EU, Korea and Japan in order to demonstrate the practicality, robustness, repeatability and reproducibility of the particle emissions measurement techniques proposed by the Particle Measurement Programme (PMP). The exercise involved testing 16 light duty vehicles including 6 diesels equipped with wall-flow Diesel Particulate Filters (DPFs), 6 conventional diesel vehicles, 3 direct injection petrol engined vehicles and one conventional, multi-point injection petrol-engined vehicle. A DPF equipped Peugeot 407 was tested at all participating laboratories to allow the inter-laboratory reproducibility of measurements to be assessed. The DPF equipped vehicles tested included 2 light goods vehicle derivatives (a Mercedes Vito and a Mazda Bongo). Vehicles were tested over multiple repeats of the EU regulatory Type 1 emissions test. Measurements of solid particle number emissions, particulate mass and regulated gaseous emissions were taken over each test. In addition to particle number measurements made with a Golden System circulated between laboratories, particle number measurements were made with several alternative systems to compare the performance of different measurement systems.

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