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GRPE Particle Measurement Programme (PMP)

Government[1] Sponsored Work Programmes: Progress report

1. Introduction

The measurement system evaluation phases of Phases I and II of the government sponsored measurement programmes are now drawing to a conclusion, with potential systems worthy of further evaluation in a round robin test identified. The work on thermodesorbers outlined in the report to the last GRPE session in January 2003 is now in its final stages.

All of the individual reports from the national programmes are nearing completion and work is currently underway on the compilation of a summary report that draws together overall conclusions and recommendations. This will be finalised in the next few weeks once all its constituent reports are completed.

For those interested in more details of PMP and the Government contributions, a CD will be available to accompany the report containing full details of all the national programmes and other related papers.

This progress report provides a summary of the work undertaken to date, and identifies the preliminary results and conclusions.

2. Methodology

2.1 Introduction

The national measurement programmes have drawn on the first phase of the work which lead to the development of two draft testing protocols; one for light duty vehicles and the other for heavy duty engines.

Sampling systems have an important influence on the particles, particularly the number measured, and therefore within the work programmes the candidate measurement systems comprise both the sampling system and measurement device. Another important element of the measurement system is a well understood protocol for the testing, to ensure good repeatability and reproducibility.

Any new measurement system must meet a range of criteria. Through meetings between the individual contractors to the national programmes and other interested groups, the following criteria were identified as being most important for the assessment of potential measurement systems: accuracy, repeatability, reproducibility, robustness, cost, and finally the traceability of the results.

[1] This summary report relates primarily to measurement programmes undertaken by France, Germany, Sweden, Switzerland and the United Kingdom, with additional contribution from Japan.

- The term repeatability refers to the difference in results from a series of tests in the same laboratory with the same engine/vehicle, and is often expressed as the coefficient of variance (COV).
- Reproducibility refers to the results obtained from the same engine/vehicle measured using the same methodology at different laboratories.
- Robustness refers to how carefully a measurement system needs to be handled, i.e. it's suitability for a commercial testing environment rather than a specialist laboratory.
- Traceability refers to the ability to calibrate the system to a primary standard.

In addition to these criteria, the measurement system must have a detection limit sufficiently low to enable the measurement of particles at the level of emission from a current gasoline engine or from a diesel engine equipped with a diesel particulate filter (DPF).

One of the most important factors for ensuring good repeatability for number counting is the suppression of the nucleation mode particles, typically comprising volatile compounds, formed by condensation during the dilution process. A number of sample conditioning devices have been tested within these national programmes. These include thermodenuders and thermodiluters as well two early dilution and a 'diesel soot separator'. Not all instruments are compatible with all sample conditioning systems, and therefore not all combinations of conditioning systems and measurement instruments have been tested.

It is difficult to define concisely and accurately the composition of the resulting particles that are measured after the nucleation mode/volatile particles have been removed. The term 'solid' particle has been used in this report. It should be noted that the particle measurement system used would, in effect, define the particles being measured.

In addition to evaluating new particle measurement devices, a modified version of the US 2007 particulate measurement procedure for heavy-duty vehicles has also been evaluated within the national programmes.

2.2 Conditioning systems assessed

Following sampling systems were tested in Phase II:

Light duty

- Constant volume sampling (CVS)
- CVS + treatment (thermodenuder or thermodiluter)
- Raw exhaust
- Early dilution

Some of the measuring devices have their own dilution systems, which have been used after the CVS.

Heavy duty

- Constant volume sampling (CVS)
- CVS + treatment
- CVS + secondary dilution
- CVS + secondary dilution + treatment
- Raw full flow
- Raw full flow + hot dilution (rotating disk or double state ejector)

Any new measurement system should, ideally, be as compatible as possible with the existing type approval test requirements in order to minimise the cost and time of homologation testing. Therefore, there was a presumption made at the start of the work that the current systems used for type approval should be retained as far as is reasonable practical, consistent with the overall objective.

The dilution sampling systems were generally equipped with high efficiency particulate air (HEPA) filters to reduce the concentration of background particles.

Several sample treatment systems were tested:

- Thermodenuder – the sample is heated to desorb/evaporate the volatile compounds and an activated carbon/ceramic trap is used to absorb them. There are several different designs with the heating and absorber either in parallel or in series.
- Thermodiluter – a hot dilution system in which the formation of nucleation mode particles and the condensation of water within the diluter or sample line are prevented. Dilution is performed by a commercial rotating disk diluter, double stage ejector or porous diluter located adjacent to the exhaust system and prior to transport to the measurement devices.

As part of the work, the loss of different sizes of particles across a thermodenuder or thermodiluter operated at different temperatures and flow rates has been evaluated under several national programmes. The following systems have been evaluated:

- Commercially available thermodenuders from:
  - TSI
  - Dekati

  Plus a laboratory thermodenuder (ITEM) in one programme

- Hot dilution systems
  - Rotating disk produced by Matter Engineering
  - Ejector dilution systems by Dekati and Palas

In addition, one laboratory has explored the possible use of early dilution, close to the tailpipe, to prevent the formation of nucleation mode particles.

Finally two laboratories investigated a prototype diesel soot separator. In this device the soot particles are charged using ultraviolet light and then removed by an electrical field. The field strength is sufficient to remove all charged particles, independent of their size, but the nucleation mode particles are not charged and therefore remain unaffected. Therefore by sampling with and without the soot particle separator, the number concentration of 'solid' particles can be determined.

These assessments have been undertaken with a range of measurement devices using exhaust particles. In addition, laboratory tests using monodisperse aerosols of triacontane ($C_{30}H_{62}$), tetracontane ($C_{40}H_{82}$), eicosane, caesium iodide and sodium chloride have assessed the performance of the sample treatment systems. Results are presented as the penetration efficiency (percent) by mobility diameter.

2.3 Instruments assessed

16 different types of instruments (some operate on similar principles) were included in the government sponsored programmes plus the gravimetric filter method as shown below:

- Mass measurement systems:
  - Gravimetric (the European legislated/the modified US 2007 procedures).
  - MEXA (filter method with chemical analysis)
  - Tapered element oscillating microbalance (TEOM)
  - Laser induced incandescence (LII, measures mass of elemental carbon and primary particle size)
  - Quartz crystal microbalance (QCM)
  - Photoacoustic Soot Sensor (PASS, measures mass of elemental carbon)
  - MASS-Monitor
  - Coulometric
  - Photoelectric aerosol sensor (PAS, measures mass of elemental carbon)
  - Opacimeter

- Number measurement systems:
  - Laser-light scattering
  - Differential mobility spectrometer (DMS measures number/size distribution)
  - Electrical mobility (CPC)
  - Electrical mobility/optical counter (SMPS measures number/size distribution)
  - Electrical Low Pressure Impactor (ELPI)

- Other measurement systems:
  - Diffusion Charger/electric diffusion battery (DC/EDB) (surface number mobility)
  - Light extinction opacitimeter (average size of primary particle)

The aim of the various national programmes assessing measuring devices was to provide a comparative assessment when simultaneously exposed to a similar sample of particles from either an engine exhaust or an aerosol generator. At some laboratories the same sample conditioning system was used; the disadvantage with this approach is that not all the instruments were presented with an optimum sample (for example the flow rate may not have been ideal). In one study the instrument manufacturers could choose to sample either the raw exhaust or from the full-flow CVS tunnel and could condition the sample. The disadvantage of this approach is that the instruments were not presented with the same sample.

2.4 Draft test protocols

Draft test protocols for light-duty vehicles and heavy-duty engines were derived to enhance the compatibility of results between the individual national programmes. These are based on existing European legislated procedures (UNECE Regulations 83, 49and 24 and the corresponding EU Directives); a modified version of the US2007 testing methodology; and the draft procedures in ISO/DIS 16183. The full US2007 procedures have not been adopted due to the cost involved, particularly in respect to the standards it lays down for the clean room specification and the microbalance.

There are four main differences between the standard European particulate mass measurement method and the modified US 2007 PM method (termed modified 2007PM) that has been assessed in this work:

- Use of a cyclone pre-classifier in the modified 2007PM
- Smaller filter size
- Filtering of primary and secondary dilution air
- Difference in filter face temperature
- Removal of the secondary (back-up) filter in the modified 2007PM.

- Difference in filter face velocities

In summary, the light duty protocol:

- Is based on existing LD procedures
- Uses the NEDC/FTP driving cycles
- Defines the number of tests (7) to measure variability
- Requires DPFs on diesel fuelled vehicles
- Defines the vehicle conditioning as the cold start NEDC; two phases for diesel, one for gasoline

The heavy-duty protocol:

- Is based on existing heavy duty test procedures
- Is specifically for transient testing (including the world harmonised heavy-duty drive cycle)
- Is also applicable to steady-state tests
- Defines the number of tests (7) to measure variability (consistent with US2007)
- Is applicable to non-road applications with modifications

In both light and heavy duty the background particle concentrations were not subtracted from the test cycle results.

As these protocols were developed as the programmes matured, not all the studies used them. For example, the large multi instrument evaluation undertaken in close collaboration with the manufacturers, whilst using many of the elements of the heavy duty protocol, used fewer repeat tests for the ESC cycle, and used the EPEFE engine conditioning protocols. It did, however, adopt the recommended modifications to the US 2007 mass measurement procedure.

Even those laboratories that did use the protocols adopted some different approaches. For example, one laboratory undertaking heavy duty engine testing used heated dilution air for the secondary dilution system, controlled to 47^{o}C (±5^{o}); and another laboratory used a heated filter holder. Both these approaches are permissible under the US 2007 particle measurement methodology. This may account for some of the differences in the results observed between the two laboratories in their comparisons of the current European filter method and the modified 2007PM method.

2.5 Vehicle/engines and fuels

Seven light-duty vehicles and one heavy-duty engine were tested in Phase I, with eight light duty vehicles and three heavy-duty engines in Phase II. To enable assessment of the measurement system at different emission levels and chemical composition during the engine tests an adjustable bypass for the DPF was used. Tests were undertaken to simulate the emissions from an engine meeting the levels achievable by a DPF but using other PM emission control techniques. This was to ensure that any candidate measurement system is capable of measuring both low levels of carbonaceous and non-carbonaceous particles.

The engines/vehicles were tested with fuels that generally conformed to EU Directive 98/70/EC (2005) and had a maximum sulphur content of 10 ppm. The lubrication oil used was that as recommended by the engine manufacturers.

Table 1: Light-duty vehicles tested

	Fuel	Engine type	After-treatment
Phase I	Diesel	Common rail, Euro III	Oxy cat + DPF
	Diesel	Unit injections, Euro III	Oxy cat
	Diesel	Euro II	Oxy cat
	Diesel	Euro II	EGR + Oxy cat
	Diesel	HDI turbo Euro II	Prototype catalyst based DPF
	Gasoline	GDI Euro III	TWC
	Gasoline	1.8 Euro III	TWC
Phase II	Diesel	DI, Euro III	CRT with reagent
	Diesel	DI, Euro III	DPF with regeneration
	Diesel	common rail Euro III	Oxy cat+ additive based trap
	Diesel	common rail Euro III	Oxy cat
	Gasoline	DI, Euro IV	TWC + EGR
	Gasoline	DI, Euro IV	EGR+ TWC + NOx storage
	Gasoline	DI, Euro IV	EGR+ Oxy cat +NOx storage
	Gasoline	DI, Euro 4	EGR+ Oxy cat +NOx storage

Table 2: Heavy-duty engines tested

Fuel	Engine	Type of DPF Added
Diesel	Euro III	CRT
Diesel	Euro III	Catalyst based
Diesel	Euro III	CRT

2.6 Instrument calibration

The ability to calibrate measurement systems to a traceable standard is very important. For mass-based methods the solution is already well established, whereas a primary standard for particle number and other metrics does not yet exist. Currently instruments that measure non-mass based parameters are calibrated against other instruments.

An aerosol generation system (CAST) has been tested as a calibration device in several Phase II programmes. This generates sub-micron combustion particles that are similar to the particles emitted by diesel engines. The Swiss Federal Office of Metrology and Accreditation (METAS) has calibrated the concentration and size distribution of these particles.

Some national programmes have also used a monodisperse aerosol to undertake daily calibration of the thermodenuders.

2.7 Regulated gases

In most studies the regulated emissions were measured simultaneously with the particles.

2.8 Candidate Systems Tested

The candidate systems tested are shown in Table 4. In this table HD and LD indicates which measurement system (a combination of the measurement device, and sampling system and if appropriate sample treatment) have been testing on heavy duty engines and light duty vehicles respectively. Some systems have been tested within more than one national programme.

2.9 Round Robin Testing

An initial round robin test, to measure the reproducibility of a measurement system at four different laboratories, has been undertaken using three light duty vehicles: a common rail diesel with oxidation catalyst; a common rail diesel with DPF and oxidation catalysts and a conventional MPI gasoline. This round robin used ELPI + CVS + thermodiluter as the measurement system. These vehicles are in addition to those listed above in section 2.5.

3. Preliminary Results

3.1 Introduction

The large number of measurement systems assessed within the government sponsored programmes makes it difficult to summarise all the results succinctly. Therefore this progress report focuses on the results from those candidate systems that offer potential, based on the available results. The final results will be presented in the report of the national programmes in the coming weeks.

The main national programmes came to similar conclusions regarding the best performing measurement systems.

The programme is aimed at measuring particles at emissions levels below those required by regulation today, and most evaluation of the measuring systems has been undertaken using diesel vehicles/engines with a DPF. These devices effectively remove the predominately carbonaceous particles with mainly volatile exhaust aerosols being measured post-DPF. Comparison between the measurement techniques is poor where the mass of elemental carbon is compared with total mass due to the differences in composition.

In general the sensitivity of number based measurement systems is much greater than mass based systems with respect to the concentrations post-DPF.

3.2 Assessment of the gravimetric mass measurement method

The results of the programme comparing the modified 2007PM method with the current European filter method shows that it offers significant improvements to the COV.

In general, a rather poor correlation between the modified 2007PM method and the other mass-based methods was observed for post-DPF exhaust. It is thought that very small, in most cases not reproducible, nucleation mode particles were detected by the gravimetric system.

However, when the DPF bypass was used to increase the carbonaceous fraction in the exhaust stream the correlation was good, showing the influence of the particle chemistry on the results. Good correlation was also found between the gravimetric method and other instruments using CAST aerosols. This is because these are carbonaceous particles.

Table 3: Potential candidate measurement systems tested in Phase II with heavy duty engines (HD) or light duty vehicles (LD)

Metric	Measuring device	Raw exhaust	Raw exhaust + other dilution	Raw exhaust + thermodiluter/ thermodenuder	CVS	CVS + thermodenuder	CVS + secondary Dilution	CVS + 2nd dilution + thermodenuder/ thermodiluter
Mass	Filter methods				LD		HD	
	MEXA						HD	
	TEOM						HD	
	LII	LD			HD/LD		HD	
	QCM						HD	
	PASS			HD- heavy duty	HD/LD			
	MASS-Monitor			HD				
	Coulometric		HD partial flow dilution					
	PAS	LD	HD/LD Rotary dilution	HD				
	Opacimeter	HD	HD Internal dilution					
	Laser-light scattering		HD with heated rotating disk or Internal dilution	HD				
Number	DMS				HD/LD			
	CPC		HD (heated 2 stage ejector)			LD		HD/LD
	ELPI		HD (heated 2 stage ejector)			LD		
	SMPS		HD (heated 2 stage ejector)	HD	HD		HD/LD	HD
Other	DC/EDB	LD	HD/LD Rotary dilution (heated for HD)	HD	LD		HD	
	Light extinction	HD					HD	

The repeatability tests, expressed as COVs (coefficients of variance; standard deviation/mean) showed that the post-DPF samples had lower COVs than the bypass samples. This is unsurprising given the lower mass.

Close control and consistency of dilution air temperature enabled a large improvement in repeatability. The repeatability did not appear to be related to the filter loading; the system was capable of COVs below 10% on both daily and day-to-day bases, with filter loadings as low as 65 µg post DPF and as high 900 µg with the by pass on a steady state cycle.

Using the heated filter holder approach also resulted in good COVs over the WHTC; typically around 10% but less good over the ETC test and the WHSC (about 19%). The COVs increased as emissions decreased, even when using advanced gravimetric methods. For the light duty vehicles few results are currently available for the modified 2007 method.

Using the heated dilution air method resulted in the modified 2007PM method typically measuring approximately 50% of the mass from the standard European method over all transient drive cycles. However, this result was not observed using the heated filter holder approach, with results being slight higher with the modified 2007 PM method. Further work, to understand these differences might result in a closer definition of crucial parameters.

Calibration procedures are well established for gravimetric methods, based on reference masses.

Depending on the effects of any changes agreed in the future, correlation factors with established the PM mass based emission limits may need to be developed.

In conclusion, the CVS based gravimetric procedure remains useful for type approval purposes for heavy-duty engines. Further results from the light duty measurement programmes are required before conclusions for these vehicles can be drawn.

3.3 Other mass measurement systems

Laser induced incandescence

In two programmes the instrument performed well during the tests and needed no maintenance, while in another it had to be adjusted. In general the LII proved to be robust during the test programmes.

The data were generally very repeatable, even though post-DPF measurements were close to the instrument noise levels. Post-DPF COVs from one day's testing of HD transient cycles were <12.5%; with steady state COVs < 20%. In one programme COVs with transient cycles were <5%. The repeatability for light duty vehicles was variable, typically <10% but up to 50%.

The response of LII to concentration changes was fast and stable. It was able to detected individual peaks in particle concentration during the transient ETC test due to brief load peaks. The response time is strongly affected by the sample line length and dilution systems.

The limit of detection measured in one test programme was about 22% of that measured on the ETC post-DPF.

In general a good agreement to other mass-based methods was observed for the higher emissions tests. LII can be calibrated using the coulometric reference method (VDI 2465), although due the length of time it takes, not before or after the measurements. Provided it proves to be stable over long periods of time this may not be a concern.

Sensitivity is low compared to number based instruments.

The system design and set-up is commercially available, although the system's electronics had to be adjusted during the raw exhaust tests. The LII was the most expensive candidate measuring devices considered to have further potential.

The LII instrument might be a valuable tool for detection of DPF failures and because of its transient capability, engine/aftertreatment development and in-service testing.

PASS

PASS provides time-resolved real mass data.

It showed satisfactory repeatability (COV). In the engine tests the repeatability was in the range <20% for transient tests; up to 40% for steady tests, depending on the test programme. In the light duty tests the repeatability was in the range 5 to 27%.

Its overall robustness during the testing programmes was good despite it being a prototype. The systems electronic had to be adjusted during some of the tests so that general advice on its operation would be necessary for type-approval purposes.

The response time was similar to that for LII, at a few seconds at 1 Hz. The response time is strongly affected by the sample line length and dilution systems. The PASS was able to follow a transient test cycle and detect individual peaks in particle concentrations due to brief load peaks during the ETC.

The limit of detection (3 sigma) measured in one programme was found to be approximately 38% of the emission measured from an engine equipped with DPF and assessed over the ETC test cycle. With the CAST the device showed rather high noise to signal values, but very good linearity.

A reasonable fast and traceable calibration of the system is not available in the testing environment. A coulometric calibration system for carbonaceous material, according to VDI 2465, could be performed. This, however, is relatively time consuming and it could not be performed routinely before or after measurements. However, if the device is proven to be stable over a long period of time calibration less regularly may be possible.

The PASS system might be suitable for type approval, but further investigation of its repeatability is needed, having shown has poorer repeatability compared to the LII in one programme but comparable repeatability in another.

MEXA

MEXA is a filter-based method with vaporisation of the particle followed by chemical analysis. During the tests it operated without any problems. There is limited data available for this instrument as it was only tested in one programme on one heavy-duty engine.

This measurement device shows good repeatability on a transient cycle with COVs in the range 3 to 6% on the ETC post DPF. On the EST the repeatability was 25%. There was good agreement with the gravimetric filter method. In common with other mass based methods it is less sensitive compared with number based methods.

The limit of detection measured in one programme was about 18% of the measured ETC post-DPF concentration.

No linearity tests were undertaken due to the need for a high flow rate for filter based methods.

It measures a sample over the whole test cycle and therefore cannot give time resolved results. It does, however, enable the chemical composition of the particles to be determined (elemental carbon, organic carbon and sulphate). Calibration can be undertaken using CO_2 and SO_2 calibration gases.

3.4 Number measurement systems

CPC

The CPC provides time-resolved total number concentrations.

The overall robustness of the instruments tested was generally good during the entire programme. The CPC can show good repeatability (COV) when operated with appropriate sample pre-treatment; otherwise the COV was relatively poor.
The device proved to be very linear in experiments using the CAST system.

The CPC was the most repeatable of all systems within one day of testing, with COVs of less than 10%. In one programme using a commercial thermodenuder typical ‘all days’ repeatability was of the order 25%. Seven tests over two days gave COVs of 11% or less.

In one programme a CPC and thermodenuder approach was employed, with the same engine, in both Phase I and Phase II. Between the two programmes single day repeatability levels for ETC improved from 18.5% (Phase I) to 3.4% (Phase II). This can be attributed to closer control of the testing parameters in Phase II.

The day-to-day variation is thought to be a function of changes in the baseline/background particle number concentration. This may be due to changes that are introduced to the CVS with dilution air, through vents in the dilution system or via the exhaust system bypass.

ETC cycle total reductions in particle numbers across the DPF were of the order 97%.

The time response of the CPC can be fast, within a few seconds. However there can be long response times during reductions in concentrations. The CPC was able to follow a transient cycle and detect individual peaks in concentrations in response to short load pulses during the transient ETC.

A reasonable fast and traceable calibration of the system is not currently available in the testing environment. However, if the flow through the measuring cell is stable and measured, the number concentration of particles (> 15 nm) can be measured by CPC's very exactly without further frequent calibration. CPC sample probe flow should be measured with the same accuracy as used, for example, for CVS sample probe flows. Nonetheless a standard CPC calibration procedure has to be established.

CPCs with internal flow splitting or dilution should not be used.

Since the lower particle size limit is generally different from CPC to CPC the lower detection limit (low with respect to particle size) of a CPC must be taken into account if small solid particles are to be measured. CPCs are only exact in the counting mode. Because of the limited dynamic range of many CPCs with regard to the number concentration secondary and/or tertiary dilution systems may be used. Dilution systems are critical components and blocking by pollution may occur. For this reason secondary/tertiary dilution procedures should be established; general operating parameters should be described too.

EDB

The EDB provides time resolved real number concentrations including some size information. The instrument performed well in repeatability tests with a COV of less than 15% at post-DPF levels.

Measurements post-DPF revealed large differences in number concentrations compared to other measurement devices and a lack of sensitivity. It is expected that further development will overcome these shortcomings. Calibration of the device is difficult.

The EDB tested were prototypes, but proved to be very robust during the tests. On one programme the system's electronics had to be adjusted during the tests, so advice will be needed on operation of the device for type approval purposes.

The response is independent of both particle chemistry and particle morphology, and without some form of sample conditioning, this measurement cannot address the issue of whether particles are solids or condensed phase volatiles.`

3.5 Removal of volatile material by sample conditioning

Laboratory tests have shown that there are several sample treatment systems that can efficiently remove volatile material from the exhaust gases of vehicles/engines.

Thermodenuders

The thermodenuders tested performed in a repeatable manner from day to day and with multiple tests at any single operating condition or drive cycle, but exhibited different characteristics based upon changes in the chemistry of the sample aerosols. This suggests that if exhaust chemistry varies between drive cycles, catalyst systems or engines the post thermodenuder response may change. To avoid this the performance of thermodenuder device must be fully standardised for losses, particle removal and penetration irrespective of exhaust composition.

For known particle size distributions thermodenuder data can easily be recalculated to yield the number concentration of non-vaporisable particles. The lower the penetration of these particles the more inaccurate the results. For that reason penetration behaviour and transfer function parameters need to be established. The residence time distribution of the thermodenuder used is an important characteristic. Unfavourable layouts of the thermodenuder may drastically reduce time resolution.

Charcoal adsorbent lifetime appears to be in excess of 40 hours thermodenuder operation (with particular engine and operating conditions). Entrainment of carbon from the thermodenuder bed has been identified in some cases. Two matched thermodenuders provided similar loss, removal and penetration curve performance.

Commercial thermodenuders have been shown to effectively remove C30 compounds; but to have more difficulty in removing C40 compounds.

<u>Thermodiluters</u>

Two thermodiluters have been tested within Phase II. The best performing shows virtually no loss of particles in any size range, and therefore these systems can offer the potential advantage over thermodenuders of not requiring transfer functions to be developed to correct the results. They are also not dependent on activated charcoal that requires periodic replacement, and can follow transient test cycles with little delay.

Thermodiluters have been shown to effectively remove large volatile compounds (C30 and C40). These are heavier than those likely to be uncounted in engine exhaust. The reduction in number concentration particles was more than 4 orders of magnitude.

3.6 Round robin test

The results from an initial round robin test of a measurement system using ELPI + CVS + hot dilution, measured at four different laboratories, are shown in Figure 1 (annexed). The results for this one vehicle look promising; further data is due shortly.

4. <u>Preliminary Conclusions</u>

The government sponsored programmes have identified the following systems as having potential as candidate measurement system:

- Modified 2007PM
- Raw exhaust + hot dilutor + EDB
- CVS + LII
- Raw exhaust + LII
- CVS + thermodenuder/thermodiluter + CPC
- CVS + PASS
- CVS + secondary dilution + MEXA

Most of these systems measure either total mass or the mass of elemental carbon, and therefore provide little additional information to the conventional filter mass approach (other than time resolution). Improvements to the filter method, adopting some of the requirements in the US 2007 procedure for heavy duty engines, has improved repeatability for the low emissions levels tested in this programme, chosen to be approximately representative of future emissions. Whilst there remain some questions to be resolved on some details of the procedure, improvements in mass measurement would best be achieved by refinement to the filter based approach.

Consideration may be given to the inclusion of other mass based approaches identified as potential candidate systems if instrument manufacturers are prepared to offer appropriate support.

One of the measurement systems, CVS + thermodenuder/thermodiluter + CPC, offers the advantage of counting the number of particles and so increasing the overall sensitivity of the measurement procedure. Whilst the medical evidence remains unclear over which metric is responsible for the health impacts observed, it appears prudent to further evaluate the potential of a number based system.

Number based measurement systems are sensitivity to the volatile/nucleation mode particles, which can be present in very large numbers. A sample treatment system that removes these particles, or prevents them from forming, to ensure that only the solid particles are countered, is an important element of the overall system. Such a system must have the same impact on the sample presented to the CPC regardless of the engine, emission control system or fuel used.

Within Phase II several national programmes have investigated the performance of commercially available and laboratory produced sample treatment systems. The results to date suggest that the best approach to use is a thermodilution rather than a thermodenuder. The results of the evaluation of two further devices are due shortly.

5. Preliminary Recommendations

It is recommended that two of the measurement systems identified by these work programmes as potential candidate type approval measurement systems be further evaluated in a round robin test.

Based on an overall judgement of their performance with key criteria identified in section 1 using the results currently available these are:

- Modified 2007 PM (a gravimetric filter based mass measurement system).
- CVS + thermodiluter + CPC (a number based measurement system).

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Chairman, PMP subgroup to GRPE
15 May 2003

Figure 1: Round robin results for a diesel with DPF car using ELPI + CV +hot dilution