

Annex 2

Details of practical investigations into PM instrumentation

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A2.1 Introduction and objectives of Task 2

This annex reports the results obtained for Task 2 (the details of practical investigations into PM instrumentation) of Phase 3 of the research into the in-service testing of low emission diesel vehicles project. The objective specific to Task 2 was to assess the potential of various measurement principles for the quantification of particulate emissions produced by low emitting diesel engines, reporting on their relative strengths and weaknesses. The studies undertaken have:

- quantified the sensitivities of five different measurement concepts,
- investigated and reported on the applicability of these measurement concepts in terms of the concentration range of PM they can quantify,
- considered the practical aspects of using the possible measurement concepts, including the apparent potential for the instrument concepts to be developed further.

From these studies a prioritisation of the measurement concepts, together with the underlying assumptions and caveats, has been produced in the main body of the report.

The task was not to assess specific instruments to declare a “winner”. Nor was it intended to demonstrate correlation over a wide range of vehicle types and PM emission levels.

A2.2 Instruments assessed

Given the above objectives the instruments selected were intended to be illustrative of various measurement principles. The assessment was intended to make allowances for their varying states of maturity. The ease of use of the instruments, and their closeness to meeting VOSA meter specifications were not pre-eminent in the selection process.

Four types of instrumentation were assessed that encompass 4 distinctly different measurement principles:

1. an advanced opacimeter
2. filter paper reflectometry
3. a light scattering meter and
4. a quartz crystal microbalance.

The reasons for their selection will be briefly reviewed when each instrument is considered in turn.

In addition to the 4 types of instruments listed above, a Celesco 107 opacimeter and a Bosch RTM 430 smoke tube with software to configure it as a UK Reference Smokemeter were also included. This was both to provide reference measurements of the PM transient samples assessed, and also to provide a standard against which the performance of the instruments could be assessed.

A2.3 Assessment criteria, and test methodology

A2.3.1 ASSESSMENT CRITERIA

The assessment criteria were chosen to characterise the potential of the instrumentation to quantitatively measure particulate emissions from low emission diesel engines in the context of their intrinsic signal/noise characteristics and the size of interference signals generated by components other than the PM within the diesel exhaust. The evaluation criteria were:

1. fundamental precision of instrument characterised by the noise level when sampling “fresh air”
2. stability over a period of around 2 minutes
3. response to oxides of nitrogen
4. response to a “pulse” of clean hot air
5. response to liquid droplet aerosol
6. response to range of PM charges that ranged from moderately high (1.5 m^{-1}) to very low ($< 0.05 \text{ m}^{-1}$)
7. effect of a moderately high PM charge on shifting the baseline for preceding and following low emission tests.

A2.3.2 CHOICE OF VEHICLES

Consequently the vehicles that were chosen were intended to test the instruments’ ability to measure around the lower limits of the anticipated required sensitivity, i.e. they were deliberately biased towards the low emissions end of the vehicles available. Also, there was a deliberate bias towards modern technology. Further, all the vehicles assessed were light-duty vehicles (less than 2.5 litres swept capacity) as these provide a more severe test of instrumentation.

The vehicles tested are summarised in Table A2.1, in order of decreasing smoke values as indicated for an average of 8 – 10 FAS tests using a Bosch reference meter¹.

A2.3.3 TEST METHODOLOGY

Tasks 3 and 4 of this project consider the test procedure recommended for the in-service testing of low emission heavy-duty, and light-duty, diesel engines. It became apparent early in this phase of the project that the free acceleration test was the most likely cycle to be recommended for use with light duty vehicles. Therefore, any assessment of instrumentation needed to take this probable test methodology into account. The testing at steady speed, and/or testing of a loaded vehicle are likely to be less demanding on

¹ The Bosch reference meter used in this task was hired from Edit Associates, the company who were contracted by VOSA to develop the specification and software for the new UK reference meter.

Table A2.1 Summary of vehicles used in Task 2 and their FAS values

Vehicle ²	Year of manufacture	Mileage	Engine	Smoke value
Vehicle 17	1987	55,000	2.5 litre Di with turbo	1.37 +/- 0.09
Vehicle 1	1998	10,750	1.8 litre Di with turbo oxycat and EGR	0.53 +/- 0.12
Vehicle 4	2003	8,000	1.9 litre Di common rail with turbo, oxycat and EGR	0.34 +/- 0.05
Vehicle 5	2002	29,000	2.4 litre common rail with turbo, oxycat and EGR	0.27 +/- 0.02
Vehicle 1 – modified	1998	10,750	1.8 litre Di as above but fitted with poor particulate trap	0.21 +/- 0.02
Vehicle 1 - modified	1998	10,750	1.8 litre Di as above but fitted with good particulate trap	0.026 +/- 0.011

instrumentation than a free acceleration because either the sampling time could be increased to provide the required sensitivity, or a number of measurements could be averaged, again to provide the required sensitivity. Therefore the free acceleration test also represent the most challenging test.

Therefore the data reported here is for standard free/snap acceleration tests, i.e. rapid depression of the accelerator for an unloaded engine at idle so that it rapidly accelerates against its own inertia until it reaches its governor limited speed.

In the quest for low emission levels two variants on the above standard free acceleration test were also assessed. These were:

- to rapidly depress the accelerator to, for example, 20% of its full travel, and
- to dilute the emissions from a standard free acceleration test with the make up air in a full flow dilution tunnel, and to sample from the tunnel.

The first of these led to the vehicles reaching their governor limited upper speed, but much more slowly than achieved with the standard FAS test. (It was estimated it took around 4 times as long relative to when the accelerator pedal is completely depressed.) However, the peak smoke levels recorded by a standard smoke meter (i.e. one that meets the current MOT smoke meter specification) were only reduced to around 40% of the value for a standard FAS test.

The second of these variants produced data that was totally consistent with that from the cleanest vehicle. However, there was some doubt regarding how representative the data were from instruments that did not pump sample gas into themselves but relied on the pressure in the sample tube because of the lower than ambient pressure in the tunnel. On balance, while the data is useful, and consistent with that collected from standard raw exhaust flows, it is not further analysed here.

² Vehicles used in this Phase 3 study are given a unique identifier, irrespective of the task(s) they were studied in. Hence Vehicle 2 in this table is the same vehicle as Vehicle 2 in Table A1.1 of Annex 1 etc.

A2.4 Results - on an instrument by instrument basis:

A2.4.1 ADVANCED OPACIMETER:

A2.4.1.1 Reasons for selection

It was assumed that the performance of current opacimeters/smoke meters is determined, to a large extent, by the specifications they are required to meet within a competitive market place rather than by the limits of the technology. This assumption is supported by the significantly superior performance of standard laboratory absorption spectrophotometers. Hence there are good reasons for believing improvements could be made to current opacimeters.

The advanced opacimeter can be viewed as a substantial development beyond current opacimeters (smoke meters). It was developed by ATT Hartridge and built on their considerable and extensive experience with designing and manufacturing smoke meters over several decades. It was selected to probe the sensitivity limits that might be reached by opacimeters.

A2.4.1.2 Measurement principle and instrument configuration

The measurement principle is, at its simplest, measuring the amount of light that is absorbed by the PM containing vehicle exhaust as it flows through a 430 mm long tube. This is the same principle that has been used for around four decades. The sophistication is to take a number of measurements and to employ compensations (both physical and within the signal processing). A schematic of the actual physical form of the instrument tested is shown schematically in Figure A2.1.

Exhaust gas is drawn into the instrument where, after a conditioning module, it is fed into three measurement units which measure:

- smoke opacity
- the concentration of NO₂ and
- the concentration of NO.

Only measurements from the first of the three units were assessed in this work.

The signal processing and controlling electronics produce an answer in units of 10⁻³ m⁻¹. A digital output was extracted either as raw data at 20 Hz, or as exponentially smoothed data at 1Hz into a PC. The results reported in this work arise from the analysis of these data files.

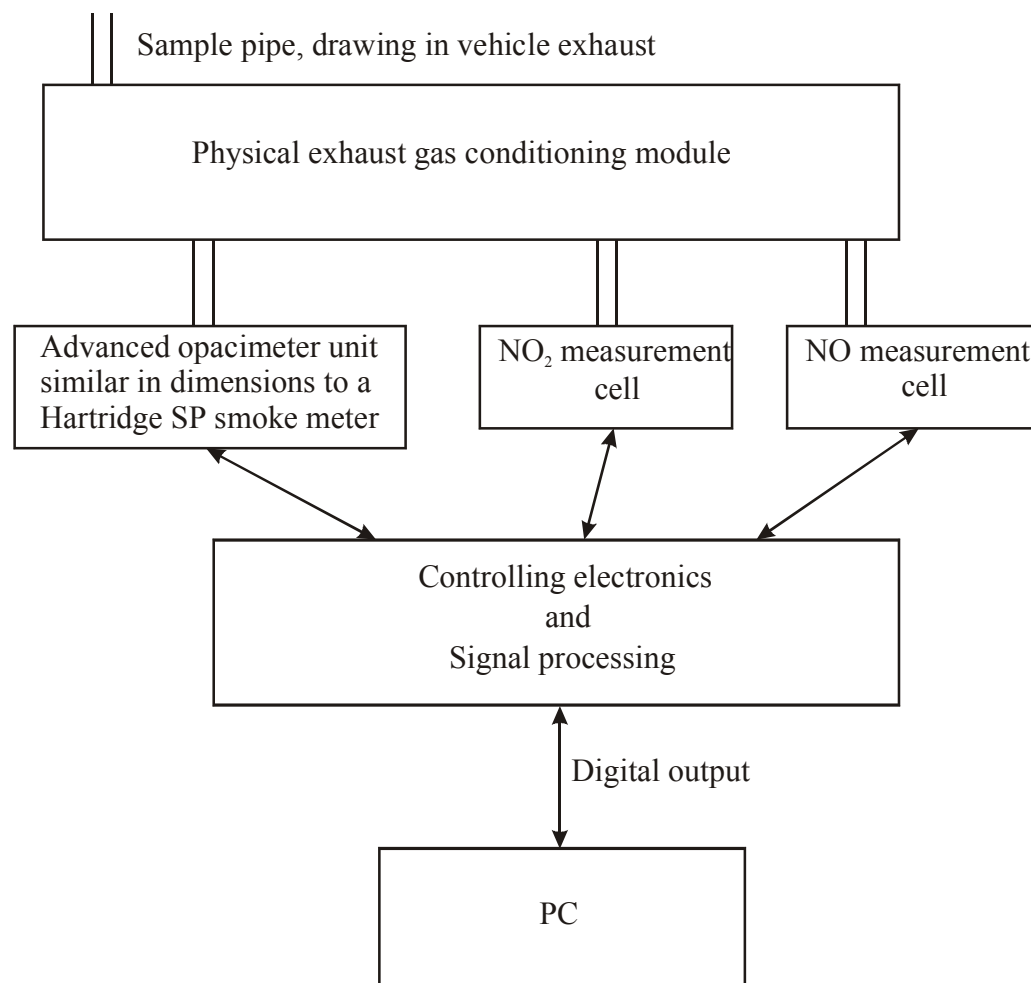


Figure A2.1 Schematic diagram of advanced opacimeter

A2.4.1.3 Results

A2.4.1.3.1 Results from free acceleration tests on vehicles and calibration

Uniquely among the four types of instrumentation assessed, the advanced opacimeter gives an output in units of smoke density (m^{-1}). However, it was acknowledged that the instrument requires calibrating such that the smoke density reported by the advanced opacimeter really is equivalent to the same smoke density as determined by the Bosch reference meter.

Simply noting the reported smoke density from the Bosch meter and correlating this with the maximum smoke density recorded by the advanced opacimeter is not appropriate, not least because the Bosch data have been digitally filtered. Similarly, it is not appropriate to simply correlate raw Bosch data directly with the advanced opacimeter's output because of differences in the physical time constants of the two instruments.

The approach used was:

- to average groups of 5 of the 100 Hz data points from the Bosch meter (i.e. to reduce its sampling frequency to 20 Hz),
- to convert both the raw and filtered 20 Hz opacities into smoke densities,
- to sum the area above the baseline for a peak generated by a FAS test.

For each peak this gave two areas which were found to always be within 5% of each other. These were compared with the analogous areas for the smoke densities reported at 20 Hz by the advanced opacimeter. Analysis of a number of peaks led to an optimum calibration factor being found. This factor was in good agreement with that anticipated by the instrument's manufacturer.

A2.4.1.4 Noise/background levels

Quantifying the background noise level of this instrument is easy because the recorded/displayed smoke density is reported as both positive and negative relative to a zero point. There is a quantisation of the data, the smallest change in smoke density reported is $\pm 1 \times 10^{-3} \text{ m}^{-1}$.

The air background was sampled at 20 Hz for around 80 seconds (1600 points). Statistical analysis of this signal gave a noise level of 0.0024 m^{-1} (calibrated to the Bosch meter). This corresponds to a noise level of $0.00055 \text{ m}^{-1} \text{ Hz}^{-0.5}$. Hence for data at 10 Hz this is equivalent to 0.0017 m^{-1} , which corresponds to a detection limit of 0.0043 m^{-1} .

A2.4.1.4.1 Effect of NO₂

A sample of gas containing NO₂ was pumped into the advanced opacimeter. Because of its construction and the internal pump, it was thought likely that some additional dilution would occur within the measurement volume. However, as noted earlier, this instrument also contained an NO₂ sensor. This indicated around 370 ppm of NO₂ were present.

The presence of NO₂ gas led to a small increase in opacity. The extent of interference from NO₂ was measured to be $+ 0.001 \pm 0.0002 \text{ m}^{-1} / 100 \text{ ppm NO}_2$.

The instrument is, by design, much less susceptible to interference by NO₂ than either the Bosch smoke tube or the Celesco 107 smoke meter.

A2.4.1.4.2 Effect of temperature

Heated ambient air was blown into the Advanced Opacimeter's sampling tube. As the temperature rose no discernible change in the recorded smoke density was observed. This was repeated several times, with for the most extreme case a 200° temperature rise being recorded in under 9 seconds (as measured by the 1 mm diameter stainless steel clad thermocouple normally used to measure the temperature within the Celesco). Even this gave no discernible change in the recorded smoke density. Indeed, the standard deviation of the data around and during this event was slightly less than that measured for background air. Any effect is consequently taken as being less than 0.002 m^{-1} for the 200° temperature rise, i.e. less than $0.001 \text{ m}^{-1} / 100^\circ$.

A2.4.1.4.3 Effect of droplets

This was assessed by blowing a fine water spray, made using a compressed air powered paint spray, in front of the Advanced Opacimeter's sampling tube. The instrument draws in gas to be analysed at around 30 litres/minute. When sampling the spray no discernible change in the recorded smoke density was observed relative to when clean air was sampled. The standard deviation of the data when sampling the spray was slightly less than that measured for background air.

Any effect of the presence of the spray is therefore taken as being less than 0.002 m^{-1} for the presence of the spray.

A2.4.2 FILTER PAPER REFLECTOMETRY

A2.4.2.1 Reasons for selection

This simple methodology links directly with the current type approval PM measurement technique, but it is adapted for in-service use. The basic measurement equipment anticipated is cheap and portable, making it potentially suitable for on-the-road testing.

One difference between this approach and that of smoke meters is that the technique accumulates the answer, rather than providing detailed values for each free acceleration. On the other hand, the current smoke meters measure the smoke produced and then release it, whereas this approach retains the sample of the filter for later quantification as required.

A2.4.2.2 Measurement principle and instrument configuration

The fundamental measurement principle is that of catching PM on a filter paper and then using reflectometry to quantify the amount of PM. There are two possibilities for the filtering of the vehicle exhaust:

- active sampling, where a pump is used to sample a controlled volume of exhaust gas, and
- passive sampling, where the pressure in the vehicle's exhaust system pushes the exhaust gas through a filter, possibly venting excess through a pressure relief valve.

Following the collection of a sample on a filter paper, reflectometry is used to quantify the amount of PM accumulated. This is ultimately less accurate than a mass based technique, but it obviates the need for conditioning filters prior to weighing and the need for an expensive 7 figure balance. The issue of interference by water is essentially removed because the addition of water to an exposed filter causes a very large change in mass, but very little change in the amount of light reflected from the filter.

Figure A2.2 shows a schematic of the system used. The gas flow through the system was calibrated by replacing the exhaust sample probe with a standard gas volume meter. The controlling valve was adjusted such that the gas flow was 1 l s^{-1} , i.e. 60 l min^{-1} .

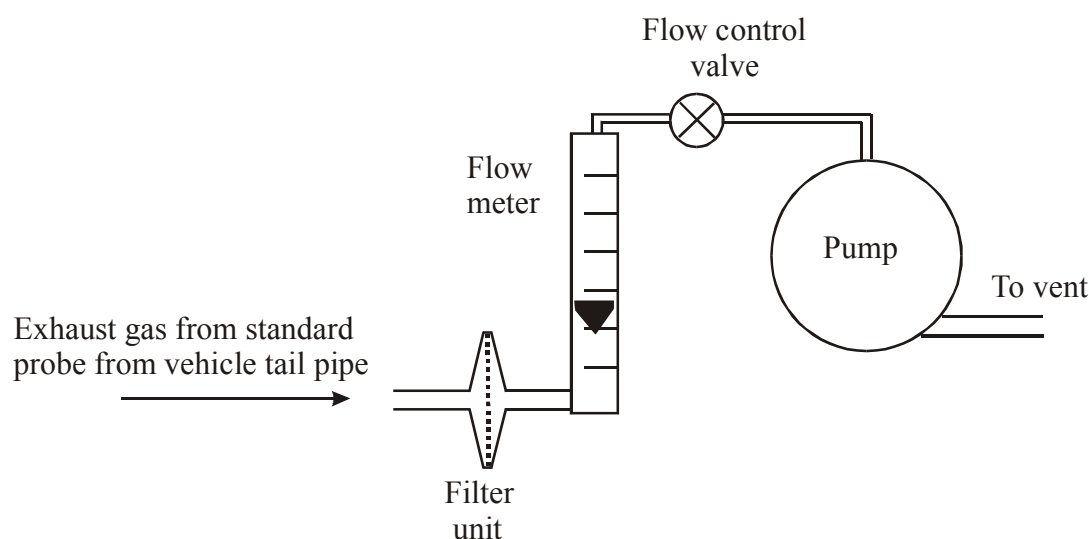


Figure A2.2 Schematic of the filter paper system evaluated

In this work a crude method of reading was used to confirm the proof of the concept and to quantify the detection limit. This comprised printing ten 50 mm diameter circles on a piece of A4 paper which were filled to 10%, 20%, 30%.....100% of blackness. With the white background this gives 11 grey levels, and filters were categorised as belonging to one of ten ranks, 0 – 10%, 10 – 20% etc.

In practice if this technique were to be pursued further a meter to quantify the deposits could comprise a digital camera linked to a PC running a simple pattern recognition programme to quantify the grey level. (Relative to the technology required to correctly read the number plates of moving vehicles for London's congestion charging scheme, what is proposed here is very simple.) However, recourse to an electronic reader would not necessarily be required. For example, the tester might be given a reference card containing 3 grey levels, white, 70% and 100% of the pass/fail grey level. It is anticipated that the vast majority of vehicles would produce a filter which contained less than 70% of the pass/fail limit. These could be visually assessed and passed by the tester without recourse to a reader.

A2.4.2.3 Results

A2.4.2.3.1 Noise/background levels

The filter system configured as shown in Figure A2.2 was run for 120 seconds sampling ambient air. The resulting filter showed no staining. The colour of the filters is stable, i.e. they show no drift.

A2.4.2.3.2 Other potential interferences

In terms of other potential interferences it was found that:

- pulses of hot air led to no colouration/staining,
- the presence of NO or NO₂ did not lead to any colouration/staining,
- drawing a liquid droplet aerosol (water) into the system led to no colouration/staining.

A2.4.2.3.3 Results from free acceleration tests on vehicles

The results from detecting the PM produced by free acceleration tests were that filter papers often contained a colouration over the whole area through which exhaust gas is drawn, but with additional black specks in the central area. Because of the shape of the filter holder, shown schematically in Figure A2.2, large "soot" particles, possibly being dislodged from the vehicle's exhaust system or from the instrument's sampling pipe, impact in a tight area around the centre of the filter because they are too large to change their direction of motion. By contrast the smaller soot particles generated in the cylinder of the engine are able to follow the gas flow, leaving a grey stain over the whole filter area through which the gas flows. Therefore the technique appears to provide a degree of size discrimination that could be used to identify poorly conditioned vehicles despite it not giving a measurement for each individual free acceleration.

Filter samples were collected for all vehicles, and were in most cases simultaneously recorded by the Bosch reference meter. Typically a test sequence might comprise:

- load filter but do not insert the exhaust sample probe into the vehicle's tailpipe,
- do 2 free accelerations to precondition the vehicle,
- insert the sample probe into the vehicle's tailpipe and turn on the pump,
- do a further 5 free accelerations, much of whose PM will be drawn through the filter,
- remove the sample probe from the vehicle's tailpipe, turn off the pump and change the filter,
- do 2 more free accelerations to precondition the vehicle,
- insert the sample probe into the vehicle's tailpipe and turn on the pump,
- do a further 2 free accelerations, much of whose PM will be drawn through the filter,

- remove the sample probe from the vehicle’s tailpipe, turn off the pump and switch off the vehicle.

This leads to exposed filter papers whose level of deposit can be assessed based on the 10 categories of greyness (0 – 10%, 10% - 20% etc). The sum of the FAS readings recorded by the Bosch reference meter for the same accelerations can be calculated and a correlation diagram produced. These data are in the last two columns of Table A2.2 which summarises the key data. These data are plotted in Figure A2.3.

Table A2.2 Data from visible assessment of filter paper reflectometry technique

Filter reference code	Run number	Vehicle	Free accelerations recorded on filter	Categorisation of filter paper	Sum of Bosch smoke values (m ⁻¹)
AO 12A	T2-D1-2	Vehicle 1 + silencer	FA 2 - 4	>90% (10)	1.47
AO 12B	T2-D1-2	Vehicle 1 + silencer	FA 6	>90% (10)	0.64
AO 15A	T2-D1-5	Vehicle 1 + poor trap	FA 2 - 4	>90% (10)	0.82
AO 15B	T2-D1-5	Vehicle 1 + poor trap	FA 7	60 – 70% (7)	0.24
AO 18A	T2-D3-7	Vehicle 5	FA 3 - 5	>90% (10)	0.78
AO 18B	T2-D3-7	Vehicle 5	FA 8	70 – 80% (8)	0.31
AO 19A	T2-D3-10	Vehicle 4	FA 3 - 5	>90% (10)	0.98
AO 19B	T2-D3-10	Vehicle 4	FA 8	70 – 80% (8)	0.38
AO 20A	T2-D4-2	Vehicle 1 + good trap	FA 2 - 6	40 – 50% (5)	0.125
AO 20B	T2-D4-2	Vehicle 1 + good trap	FA 8 & 9	10 – 20% (2)	0.05
AO 22A	T2-D4-6	Vehicle 16	FA 2 only	>90% (10)	1.43

Despite this relatively crude method of assessment, the correlation is good. Figure A2.3 shows two important features of the technique:

1. The detection limit is better than an accumulation of 0.025 m⁻¹. Therefore, the accumulation of, for example, three FAS tests, each of which gave a smoke density of 0.01 m⁻¹ would leave an easily measurable deposit.
2. The measurement range of the system is quite limited. For accumulations greater than 0.4 m⁻¹ the filter paper is heavily stained, i.e. appears black, and there is no further discrimination.

This latter feature can be “fine tuned” by varying (i.e. reducing) the quantity of gas that passes through the filter or the number of FAS tests recorded. Reducing the flow by a factor of five, would increase its useable range to 2.0 m⁻¹. However, this would be at the cost of also increasing the detection limit by a factor of 5 to 0.125 m⁻¹.

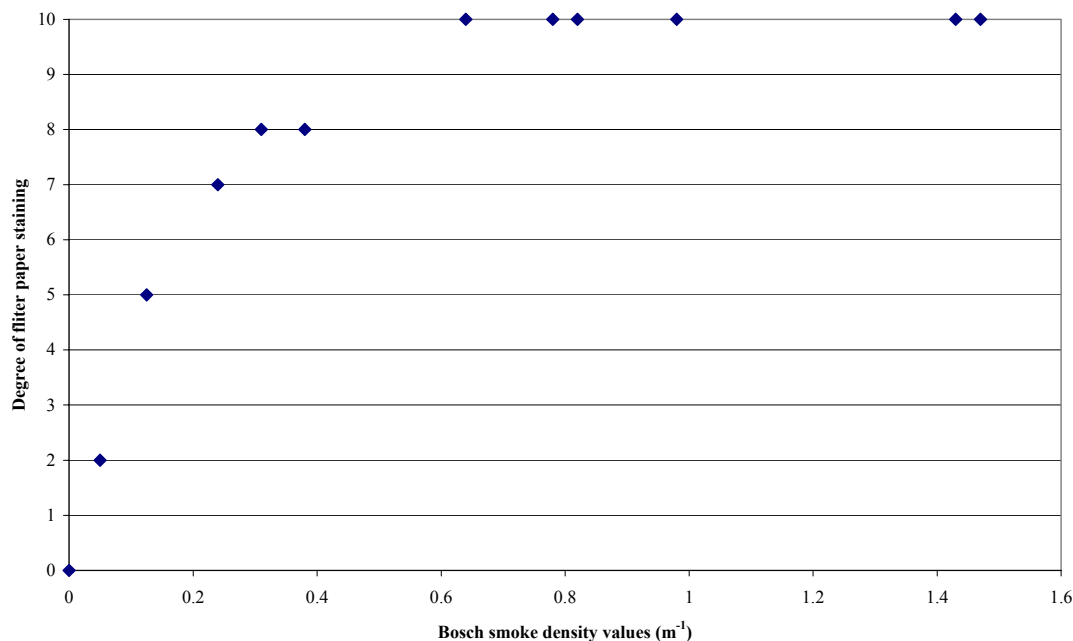


Figure A2.3 Grey level from filter paper reflectometry relative to the sum of the Bosch smoke values

A2.4.3 LIGHT SCATTERING METER

A2.4.3.1 Reasons for selection

The primary focus of this task is the identification of instrumentation that is more sensitive than current smoke meters. Fluorescence spectroscopy is well known to be more sensitive than absorption spectroscopy. By analogy, light scattering meters are expected to be more sensitive than opacimeters. Indeed light scattering instrument specifications typically quote the range 0.1 – 200 mg/m^3 dust concentrations. If the relationship 1.00 m^{-1} smoke density is equivalent to 75 mg/m^3 (derived in Section 3.2.4 of the Phase 2 report of the Low Emissions Diesel research project) then 0.1 mg/m^3 is equivalent to a smoke density of 0.0013 m^{-1} .

A2.4.3.2 Measurement principle and instrument configuration

The instrument assessed was a FW 102 Sick AG Dust Concentration Monitor. This is suitable for environments of 0 – 220 °C. (The original instrument selected for assessment, the Mie Inc PDR 1200, has a similar measurement range but is only suitable for ambient temperatures and therefore had to be substituted.)

The instrument operates by detecting light scattered forwards by dust particles from its original path. Since it is extremely sensitive this principle is suitable for measuring very low particle concentrations. A laser diode directs a beam of modulated light (at the red end of the visible spectrum) through the volume monitored. The light scattered by particles is recorded by a highly sensitive detector. The point of intersection between the transmitted beam and the receiver aperture defines the measuring volume in the gas duct. This is a region around 15 mm long located around midway along the 180 mm long sample probe. The measured scattered light intensity is proportional to the dust concentration.

The underpinning physics is that of light scattering (Mie theory). An important aspect of this is that the intensity of the scattered light is a function of particle size and the interrogating wavelength. Scattering efficiencies reduce markedly when the particle size is less than 30% of the incident light's wavelength. In this instrument the wavelength of the interrogating light was around 670 nm. This would imply that the instrument is poor at "seeing" particles whose diameter is less than around 200 nm. (As will be seen later this is a problem for the challenge of detecting emissions from diesel vehicles.) In a conversation a representative of the manufacturer opined that the instruments range is for particles greater than 500 nm, and has a very low sensitivity for particles whose diameter is less than 200 nm.

The measurement probe contains control circuitry that, amongst other functions, causes the instrument to undertake a cycle check when turned on and after every eight hours of continuous operation. This takes around 200 seconds and comprises:

- contamination measurement on the boundary surfaces,
- span (full scale) point check, and
- zero point check.

The measurement probe is linked to a connection unit which provides an integrated power supply, a purge air supply (to continually flush the probe's optical windows) and other functionality. Signals can be measured either as analogue outputs or via an interfaced PC. This study used the former with the instrument's 4 – 20 mA analogue output being used with its default settings of:

- 4 mA \equiv 0 mg/m³ dust concentration
- 20 mA \equiv 20 mg/m³ dust concentration.

The current was dropped across a 500 Ω resistor, so that the 4 – 20 mA span was visible as a 2 to 10 V range for the data logger. The exact voltages corresponding to 4 and 20 mA were read from the data logger when the instrument performed its cycle check.

The instrument was physically located within the sampling cone of the Celesco 107 diesel exhaust smoke meter, as shown schematically in Figure A2.4a. Figure A2.4b shows the cross-section of the instrument located in the Celesco central measurement section.

A2.4.3.3 Results

A2.4.3.3.1 Noise/background levels

The background noise level of this instrument was measured when it sat in ambient air. This gave a noise level (principally from electronic noise) that corresponded to 0.007 mg/m³. (There is some uncertainty in this because of the instrument's time characteristics.)

A2.4.3.3.2 Effect of NO₂

The light scattering instrument was removed from being within the Celesco sampling cone and placed in a flow tube. Through this was flowed around 600 ppm NO₂ (as quantified using a Horiba MEXA 7100 DEGR gas analyser rack). A very small change in signal was observed, although this might have been caused by factors other than the NO₂, e.g. drift. The size of the signal was around 0.003 mg/m³/100 ppm of NO₂. To put this in context it is around half the background noise level /100 ppm of NO₂.

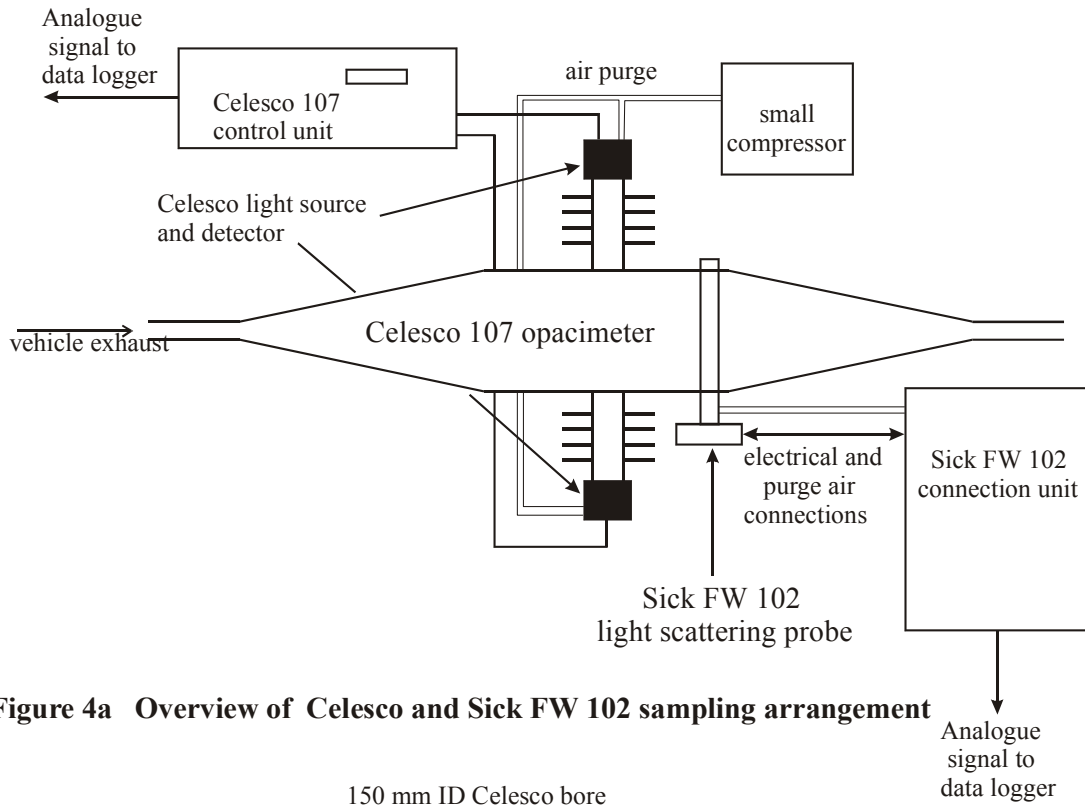


Figure 4a Overview of Celesco and Sick FW 102 sampling arrangement

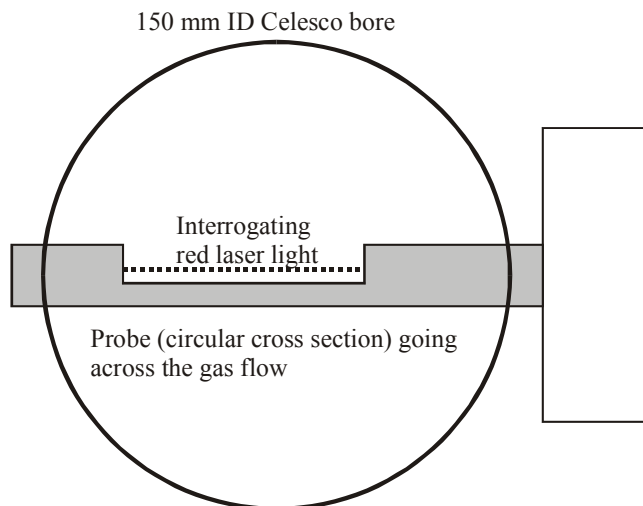


Figure 4b Cross section of light scattering probe within the Celesco's centre section

Figure A2.4 Schematic of sampling configurations of light scattering instrument and Celesco

A2.4.3.3.3 Effect of temperature

This was assessed by blowing clean heated air into the Celesco cone, see Figure A2.4. Temperature excursions of around 65 – 70°, as measured by a thermocouple adjacent to the measurement volume in the Celesco, were produced. This led to changes in the signal from the instrument of 0.08 mg/m³/100° peak to peak.

A2.4.3.3.4 Effect of droplets

This was assessed by blowing a fine water spray, made using a standard compressed air powered paint spray, in front of the inlet cone to the Celesco (see Figure A2.4). Air was being sucked through the instrument by the application of suction to the output cone. The presence of the spray caused a small reduction in the temperature of the air going through the Celesco, some absorbance (as detected by the Celesco) and some light scattering as detected by the Sick FW 102 instrument.

There was no absolute calibration, but this enables the relative size of the signals from the two instruments to be assessed. The data were

	Size of signal recorded by Celesco 107	Size of signal recorded by Sick FW 102
For spray 1	0.029 m ⁻¹	10.9 mg/m ³ (12.7 mA)
For spray 2	0.042 m ⁻¹	11.5 mg/m ³ (13.2 mA)

These data are included in Figure A2.5, alongside the data from vehicle FAS tests. The data lie above the smoke correlation curve, showing that this instrument is more sensitive to liquid droplets than to PM (by around a factor of 7). It is likely that this is a consequence both of differences in particle size distribution (with the water droplets being the larger) combined with the response of the instrument to different sizes, and the higher reflectivity of liquid droplets relative to PM.

A2.4.3.3.5 Results from free acceleration tests on vehicles

The output from the light scattering meter, in both mA and mg/m³, are listed in Table A2.3 alongside the analogous data from the Bosch reference meter and the Celesco. Figure A2.5 presents these data as a correlation graph.

Table A2.3 Data from light scattering meter from free acceleration tests on vehicles

Vehicle	Light scattering meter		Bosch smoke value	Celesco smoke value
	mA	mg/m ³	Smoke density (m ⁻¹)	Smoke density (m ⁻¹)
Vehicle 16	>20	>20	1.37 +/- 0.09	7.63
Vehicle 1	>20	>20	0.53 +/- 0.12	
Vehicle 4	8.8	6	0.34 +/- 0.05	0.87
Vehicle 5	14	12.5	0.27 +/- 0.02	0.59
Vehicle 1 with poor particulate trap	11.4	9.25	0.21 +/- 0.02	0.65
Vehicle 1 with good particulate trap	4.44	0.55	0.026 +/- 0.011	0.054

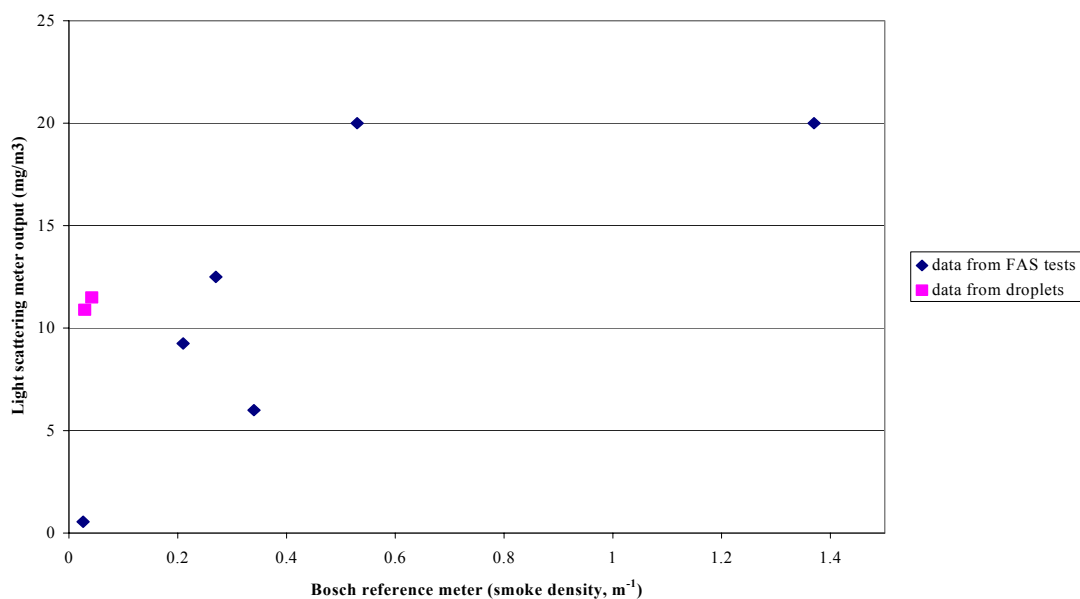


Figure A2.5 Correlation between the Bosch and light scattering meter data from FAS tests

The correlation is moderate, with there being one key outlier, from Vehicle 4, where the size of the signal from the light scattering instrument is anomalously small relative to the signals from both the Bosch and Celesco meters relative to their ratios for other vehicles. Similar data were obtained for several different runs. The difference may occur as a consequence of:

- different peak widths of the PM pulse combined with different time characteristics of the meters,
- different baseline idle smoke levels combined with different time characteristics of the meters,
- the vehicles producing different particle size distributions combined with the meters having different particle size response functions.

There are insufficient data to distinguish between these possibilities.

A2.4.4 QUARTZ CRYSTAL MICROBALANCE

A2.4.4.1 Reasons for selection

The quartz crystal microbalance (QCM) was selected because information from those who have used the instrument, the manufacturer and their agents all suggest that it has a very high sensitivity. Further, the parameter it measures is mass. This is, in principle, directly related to PM deposited on a filter paper, the parameter used for certification at type approval.

There is currently research into future measurement of PM from diesel vehicles for type approval certification. The QCM is one of the instruments that has been assessed in that context. It therefore is prudent to consider its potential also for in-service testing.

A2.4.4.2 Measurement principle and instrument configuration

A quartz crystal can be made to oscillate when excited by an electrical signal of the correct frequency. This frequency can be measured very accurately. This can be used to calculate the passage of time, i.e. is the basis of the familiar quartz clocks and watches.

The frequency also varies with the mass of the crystal, and any mass deposited on it. In a QCM the accurate determination of a crystal's resonant frequency, and its changes with time, are used to infer the mass deposited on the crystal. Modes of operation include:

- using the rate of frequency change to provide a deposition rate, and
- using the change in frequency between that before and after a test to determine the mass deposited during the test (other parameters remaining invariant).

The instrument is so sensitive that it is normally used in conjunction with a diluter, which accurately dilutes the sampled volume. The turn-key system comprises a diluter, the measurement QCM and an associated PC. The PC acts as the controlling interface between the operator and the instrument and also collects, stores and processes data.

A2.4.4.3 Some characteristics of QCM

The above provides some convincing arguments for the possible use of a QCM for in-service testing. Regarding sensitivity, in a typical investigation the deposition rate is displayed on a scale of -50 to 100 $\mu\text{g}/\text{m}^3$ for measurements where the raw exhaust is diluted around 100 times (i.e. its intrinsic sensitivity is a hundred times better for undiluted exhaust).

However, despite these positive aspects which indicate this type of instrumentation should be assessed, there are some drawbacks. At the time of the work (September 2003) there was only one manufacturer of QCM within Europe: Booker Systems. A consequence of this is that in the event of an instrument breakdown there is a dependence on a single company, which is itself very small. Therefore there is a vulnerable dependence on a very small number of key people.

Booker Systems have an agent, who was the company from which the equipment used in this project was hired. However, the newness of the technologies used means that for all but relatively simple failures, the agent has to refer faults back to Booker Systems.

The current cost of a research grade system is around £40,000.

The number of instruments in the field, convoluted with the number of years they have been used is very small. Hence in term of instrumentation product life-cycle, this is currently a very immature instrument.

The QCM measurement itself is, in the vernacular of testing, a destructive method because it involves invasively accumulating a sample. This is like filter paper reflectometry, and is in contrast to non-destructive methods like light scattering and opacity where, barring fouling, measurements can be made continuously. The destructive methods involve additional operations to "reset" the instrument. For filter paper reflectometry this involves the placing and removal of a filter paper in a holder for each test. For the QCM the analogous process is the cleaning of the quartz crystal. This involves unplugging/removing it from the heated sample chamber, very carefully wiping/cleaning it using an appropriate solvent, and then reassembling it. In practice this is not a trivial procedure, even by experienced operators. On the plus side, it would be expected that a number of measurements could be made between each cleaning.

A further drawback of the QCM, which is another consequence of it being a relatively new instrument, is that there remain some scientific questions to be confirmed. One important issue is the relationship between the indicated mass of diesel PM deposited and the loading in the sampled gas. Concern has been expressed by some researchers that drawing through a volume of gas that contained a given quantity of PM leads to a change in frequency that is much less than expected. Possible reasons for this include:

- less than 100% deposition of the airborne mass on the crystal,
- only loose coupling between the deposited PM and the crystal relative to calibration materials.

These factors would not make the QCM unsuitable, but they would mean it required calibrating with diesel PM, and that the instruments sensitivity would be lower than anticipated.

Notwithstanding the above challenges, at the recent (August 2003) 7th ETH conference on combustion generated nanoparticles there was a poster entitled: *Particulate matter mass measurement from a heavy duty diesel engine using 2007 CVS PM sampling in parallel to QCM and TEOM*. Its authors came from Southwest Research Institute, San Antonio, US and the US Environmental Protection Agency. Whilst the poster did not actually give any results from the QCM the presence of this poster indicates that other teams are also assessing the potential use of a QCM for diesel vehicle PM measurement.

A2.4.4.4 Results

In this experimental campaign it was intended to use a QCM instrument owned by AEAT's Aerosol Science Team. Unfortunately this failed prior to the start of the measurements and it could not be repaired.

A replacement instrument was hired from the Agent's for Booker Systems. This instrument too was faulty. Some data were collected but because of the fault they were viewed as too unreliable to be analysed and reported.

In the UK DfT's Particulate Measurement Programme studies were undertaken using the QCM and results were reported. In Phase 1 of Module 3 of the project, a range of instruments were assessed using various vehicle technology test-beds (from a Euro II vehicle to a vehicle fitted with a trap). QCM data exist for this study (Final Report of Phase 1 of Module 3 of the Particulate Measurement Programme: Development of candidate systems – light-duty vehicles, CJ Dickens, EL Payne, AH Reading and EA Feest, AEAT/DDSE/R/ED15003, January 2002). An important caveat is an appreciation of the differences between the measurement requirements for type approval and for in-service testing. The former involves an accurate integrated measurement of the PM emitted from a vehicle during a 20 minute drive cycle. The latter involves an accurate measurement against a pass/fail limit for short tests, lasting a few tens of seconds. Consequently, in-service testing accuracy is much less susceptible to errors from baseline drift.

The studies included the measurement of PM emissions over 3 hot start NEDCs. Table A2.4 contains some useful comparative results.

The report noted: *The coefficient of variance of values recorded for the QCM are also heavily affected by the dilution ratio used. The QCM is very sensitive in a narrow concentration range, but outside this range its performance is not so good. By optimising the dilution ratio it is anticipated that better QCM repeatability could be obtained.*

Table A2.4 Filter and QCM data from PMP Phase 1 study

	Filter	QCM
Euro II vehicle (standard = 80 mg/km)	62 mg/km	52 mg/km
COV for 3 hot starts	7.1%	42.6%
LOD from background measurements	1.9 mg/km	0.57 mg/km
Vehicle fitted with (an inefficient) trap	29.2 mg/km	67.2 mg/km
COV for 3 hot starts	4.6%	63.5%

The paragraph on the QCM in the report’s Conclusions and Recommendations chapter reads: *The QCM was seen to have a better limit of detection than the filter measurement. This could be improved upon by further development and optimisation of the device. The biggest drawback with the QCM is its sensitivity to, and reliance on, correct dilution. The dilution rate required is dependent on the emission levels of the test vehicle. Choosing the wrong dilution could give misleading results. The QCM was also found to give phantom reading (above background) when sampling from the dilution tunnel through a HEPA filter. The QCM has to be set up with care, although further developments by the manufacturer are likely to make the system easier to operate in a type approval situation.*

Hence key aspects that were to be investigated in this study included:

- How has the instrument matured during the 18 months since the PMP Phase 1 study?
- What size signals does the QCM record when exposed to exhaust gas from a FAS test? and
- What size signals do potential interferences (e.g. temperature pulses) give?

Unfortunately these questions remain unanswered.

In late 2003 Sensors Inc, a leading supplier of gas analysers and smoke meters in the automotive aftermarket secured world wide manufacturing and distribution rights to QCM instruments using technology patented by Booker Systems. Whilst they are producing sales leaflets, advertising “Semtech QCM” the instrument is not on their principal web-site. Notwithstanding, ThomasNet® Industrial News Room (a web based source of industrial supplier information published a press release on the Semtech QCM on 13th January 2005 entitled “Particulate analysers are suited for in-use measurements”³. These commercial activities indicate that the QCM was appropriately identified as a sensitive PM instrument potentially suitable for in-service testing. However, the project occurred too early before a robust instrument was available for assessment.

A2.4.5 BOSCH REFERENCE METER

A2.4.5.1 Reasons for selection

This has recently become the UK’s reference diesel smoke meter and as such it gives the “accepted” absolute smoke values from free acceleration tests. Also, characterising its detection limits can be taken as indicative of the actual performance of the better end of the range of current smoke meters (or opacimeters)

³ See web-site <http://news.thomasnet.com/fullstory/28419>

A2.4.5.2 Measurement principle and instrument configuration

The Bosch RT 430 smoke tube measures the reduction in intensity of a green LED source caused by a vehicle's smoke. This is measured in a 430 mm long tube. It contains a number of sophistications. These include:

- clean air purges for the windows through which the light is admitted and leaves the measurement tube
- thermostatic control (to 80°C) to reduce condensation effects
- pressure regulation, and
- light intensity control to compensate for a degree of window fouling.

The output from the instrument is a measurement of opacity, the percentage of light absorbed by the contents of the measurement tube, and this measurement's value is transmitted to an associated PC, via a serial port, at 100 Hz.

One weakness of the system tested is that if there were some baseline drift such that the opacity became negative, i.e. more light was detected than for the initial zeroing action, the opacity reported was 0.00 rather than a negative value (as was reported by the Celesco 107 and the advanced opacimeter). In practice this makes very little difference when assessing smoke peaks of at least 0.2 m^{-1} from free acceleration tests. However, for more fundamental studies, and when assessing the instruments generic characteristics, this did prove a problem.

The UK reference meter comprises the Bosch RT 430 smoke tube as above **plus** bespoke software written by Edit Associates. This takes the data stream from the smoke tube as its primary input. It:

- measures the opacity of the system before and after a sequence of FAS test, i.e. before the exhaust probe is attached to the exhaust pipe and after it has been removed at the end of the test,
- it computes the drift that has occurred during the measurement sequence (expressed in m^{-1}) and indicates whether this is within allowable limits,
- for each FAS test it applies, digitally, a Bessel filter to the opacity data. The sequence of calculations includes:
 - finding the maximum opacity for the filtered data,
 - converting this into smoke density (i.e. from % to m^{-1})
 - measuring the mean gas temperature of the sample chamber,
 - referencing the maximum smoke density to a standard temperature (to 25°C)
 - and finally displaying the smoke value.

For this project software was provided by Edit Associates to enable the raw data to be saved for later analysis.

Samples of vehicle exhaust were taken by connecting the sampling probe directly into the tailpipe.

A2.4.5.3 Results

A2.4.5.3.1 Noise/background levels

Quantifying the background noise level of this instrument is non-trivial because:

- the recorded/displayed opacity is set equal to 0.0% for negative values, and
- although the instrument was read at 100 Hz these data points are not independent.

Statistical analysis of appropriate "background" signals, i.e. clean air, gave a noise level of $0.0021 \text{ m}^{-1} \text{ Hz}^{-0.5}$. Hence for data at 10 Hz this is equivalent to 0.0065 m^{-1} , which corresponds to a detection limit of 0.016 m^{-1} .

A2.4.5.3.2 Effect of NO₂

Injecting around 550 ppm of NO₂ into the Bosch smoke meter led to a false peak because this brown gas absorbs some of the light being transmitted through the smoke tube. Overall it was found that NO₂ does provide a measurable interference of $+ 0.006 \pm 0.002 \text{ m}^{-1} / 100 \text{ ppm NO}_2$.

A2.4.5.3.3 Effect of temperature

Clean heated air was blown into the Bosch smoke tube. No measurable effect was observed. Consequently and such interference was found to be $< 0.010 \text{ m}^{-1} / 100^\circ$.

A2.4.5.3.4 Effect of droplets

The Bosch smoke tube obtains its sample from the pressure of the vehicle's exhaust flow forcing some gas through the sample tube into the instrument. The analysed smoke is combined with purge air etc and exits via a vent. Gentle suction adjacent to the vent led to a significant flow into the instrument. Droplets were made using the same standard compressed air powered paint spray that was used to assess the other instruments. The spray was blown across in front of the instrument's inlet, the normal 1.5 m long exhaust sample pipe having been removed.

The assessment was to take groups of three readings from ambient air (with the suction applied), then three more in the presence of the spray, and then a final three background readings. This sequence was carried out twice. No significant change was seen in the presence of the spray in either case, although a small drift (up to 0.03 m^{-1}) was seen during the course of the measurements. Consequently, the effect of a water droplet spray was found to be less than 0.015 m^{-1} .

This is lower than was found for the Celesco and light scattering instruments. This is to be expected because the Bosch smoke tube is thermostatically controlled to around 80°C , whereas the other two instruments were assessed at around 25°C . It is believed that the elevated temperature in the Bosch meter causes evaporation of the fine droplets, leading to negligible signal. This same design feature would reduce the susceptibility of the Bosch reference meter to interference from hydrocarbon-based droplets.

A2.4.5.3.5 Results from free acceleration tests on vehicles

The Bessel filtered smoke density values reported by the Bosch reference meter have been used as the definitive measure of the vehicle smoke pulses produced during this work. For most vehicles, where FAS values were greater than 0.2 m^{-1} , automatic triggering of the meter was possible. However, manual triggering was used for the cleanest vehicles, and when recording data on potential interferences.

A2.4.6 CELESCO 107 SMOKE METER

A2.4.6.1 Reasons for selection

This research opacimeter was selected because it non-destructively measures smoke in an instrument that can be close-coupled to a vehicle's exhaust in conjunction with any other sampling instrument. Runs were usually grouped such that measurements were made by all three instruments on the same vehicle.

The format used was typically:

- i) take baseline measurements using the Bosch reference meter,
- ii) take measurements using the advanced opacimeter,
- iii) take measurements using the filter paper relectometry instrument,
- iv) take second set of baseline measurements using the Bosch reference meter.

Whilst the stability of the vehicle can be **inferred** from the results from the Bosch meter for activities i) and iv), this meter cannot measure this directly. In contrast, the collection of data from the Celesco meter for all four tests can **demonstrate** the constancy of the FAS emissions, or quantify variations.

A2.4.6.2 Measurement principle and instrument configuration

A schematic of the instrument is shown in Figure A2.4a (where it is seen that the Celesco was also used as a mounting frame for the light scattering instrument's measurement probe). The measurement principle is the quantification of light from a green LED that is absorbed by the PM in vehicle exhaust as it flows through the interrogating beam. However, relative to the Bosch smoke tube and the advanced opacimeter, in this instrument the light beam is perpendicular to the gas flow direction, rather than along it. Consequently, if a vehicle produces a very short duration puff of smoke the residence time of this in the Celesco's measurement volume is shorter than for the other two instruments, and the maximum opacity recorded is higher. The electronics and display capabilities of the Celesco are appropriately fast to capture such an eventuality.

The optical path-length over which the smoke's opacity is measured is 146 mm (cf 430 mm for both the Bosch smoke tube and the advanced opacimeter). The actual separation between the lenses associated with the LED and the detector is much greater than this (around 400 mm) but purge air is flowed through these two arms to keep the lenses free from PM.

An analogue signal from the Celesco was logged by the test cell's logger, together with a number of temperatures and the vehicle's engine speed.

A2.4.6.3 Results

A2.4.6.3.1 Noise/background levels

Quantifying the background noise level of this instrument is easy because the recorded/displayed opacity is allowed to go negative relative to a zero point. For a configuration where a quiescent background was sampled at 20 Hz statistical analysis of the "background" signal gave a noise level of 0.0018 m^{-1} . This corresponds to a noise level of $0.0004 \text{ m}^{-1} \text{ Hz}^{-0.5}$. Hence for data at 10 Hz this is equivalent to 0.0013 m^{-1} , which corresponds to a detection limit of 0.0032 m^{-1} .

A2.4.6.3.2 Effect of NO₂

The Celesco was prepared for assessing the effect of NO₂ by masking off the arms containing the lenses, through which purge air flows during normal operation, to prevent either purge air diluting the calibration NO₂ gas, or the calibration gas extending beyond the normal volume. Also, discs were placed either side of the measurement beam to limit the volume of calibration gas required.

Injecting around 620 ppm of NO₂ into the Celesco 107 smoke meter led to a marked increase in opacity because this brown gas absorbs some of the green LED's light.

Overall it was found that NO₂ does provide a measurable interference of $+ 0.009 \pm 0.0005 \text{ m}^{-1} / 100 \text{ ppm NO}_2$.

This is larger than was found for the Bosch reference meter ($+ 0.006 \pm 0.002 \text{ m}^{-1} / 100 \text{ ppm NO}_2$). This difference is believed to be caused by the differing spectral characteristics of the interrogating light used by the two instruments.

A2.4.6.3.3 Effect of temperature

Clean heated air was blown into the Celesco smoke tube. As the temperature was rising a measurable decrease in opacity was observed. This is probably a consequence of refractive index gradients caused by the introduction of hot air (the Schlieren Effect). A rise of 100° in around 20 seconds (as measured by a 1 mm diameter stainless steel clad thermocouple) caused a signal of around $0.010 \text{ m}^{-1} / 100^\circ$.

A2.4.6.3.4 Effect of droplets

This was assessed by blowing a fine water spray, made using a compressed air powered paint spray, in front of the inlet cone to the Celesco (see Figure A2.4a). Air was being sucked through the instrument by the application of suction to the output cone. The presence of the spray caused a small reduction in the temperature of the air going through the Celesco and some absorbance. The value of this was up to 0.035 m^{-1} .

There was no absolute calibration, but this enables the relative size of the signals from the two instruments to be assessed, as discussed in the section on light scattering instrumentation.

A2.4.6.3.5 Results from free acceleration tests on vehicles

The smoke density values recorded by the Celesco 107 reference meter were noted. Generally there was good agreement between these and the smoke density values displayed by the Bosch reference meter, though the Celesco gave higher smoke densities because it measures across the smoke flow, and because its data were not filtered.

A2.5 Conclusions

A2.5.1 GENERAL COMMENTS

The potential of various measurement principles for the quantification of particulate emissions produced by low emitting diesel engines has been assessed. The results are summarised in Table A2.5.

Table A2.5 Summary of results from different measurement instrumentation

	Advanced opacimeter	Filter paper reflectometry	Light scattering	Bosch reference meter	Celesco 107 smoke meter
Background noise level	$0.55 \times 10^{-3} \text{ m}^{-1} \text{ Hz}^{-0.5}$	<10%	$7 \mu\text{g}/\text{m}^3$	$2.1 \times 10^{-3} \text{ m}^{-1} \text{ Hz}^{-0.5}$	$0.4 \times 10^{-3} \text{ m}^{-1} \text{ Hz}^{-0.5}$
LOD	$4 \times 10^{-3} \text{ m}^{-1}$	10%, $2.5 \times 10^{-3} \text{ m}^{-1}$	$18 \mu\text{g}/\text{m}^3$	$16 \times 10^{-3} \text{ m}^{-1}$	$3.2 \times 10^{-3} \text{ m}^{-1}$
Effect of NO ₂	$1(\pm 0.2) \times 10^{-3} \text{ m}^{-1} / 100 \text{ ppm NO}_2$	None	$3 \mu\text{g}/\text{m}^3 / 100 \text{ ppm NO}_2$	$6(\pm 2) \times 10^{-3} \text{ m}^{-1} / 100 \text{ ppm NO}_2$	$9(\pm 0.5) \times 10^{-3} \text{ m}^{-1} / 100 \text{ ppm NO}_2$
Effect of hot air	$< 1 \times 10^{-3} \text{ m}^{-1} / 100^\circ$	None	$80 \mu\text{g}/\text{m}^3 / 100^\circ$	$< 10 \times 10^{-3} \text{ m}^{-1} / 100^\circ$	$-10 \times 10^{-3} \text{ m}^{-1} / 100^\circ$
Effect of water droplets	$< 1 \times 10^{-3} \text{ m}^{-1}$	None	$350 \mu\text{g}/\text{m}^3 / 10^{-3} \text{ m}^{-1}$ on the Celesco	small, $< 0.015 \text{ m}^{-1}$	Up to $35 \times 10^{-3} \text{ m}^{-1}$
Diesel smoke	Calibrated against Bosch meter	See Figure A2.3	See Figure A2.5	Reference values	

In terms of the outputs measured when exposed to diesel smoke:

- the Bosch reference and Celesco 107 meters are calibrated by their manufacturers and provide reference values,
- the advanced opacimeter's output was calibrated against the Bosch reference meter,
- the filter paper reflectometry was also calibrated against the Bosch reference meter and a 10% grey level was found to be caused by accumulated FAS values of $25 \times 10^{-3} \text{ m}^{-1}$,
- the light scattering meter's signals were calibrated against the Bosch reference meter,
- no new data were collected for the QCM.

It can be difficult to appreciate the sensitivity of these systems from the raw data of Table A2.5. To put the data into context, the current pass/fail limits are 3.0 and 2.5 m^{-1} for Euro I and II vehicles, with the limit reducing to 1.5 m^{-1} for Euro IV vehicles. Typical FAS values that were measured in this project for appropriately maintained Euro III vehicles were in the range 0.2 to 0.5 m^{-1} . The PM emissions standards for light-duty vehicles will reduce by a further factor of 2 on going to Euro IV (in 2005) but for heavy-duty vehicles the reduction on going from Euro III to Euro IV is a factor of 5. A similar pro-rata reduction in FAS smoke would lead to anticipated FAS values of $0.05 - 0.1 \text{ m}^{-1}$ for vehicles close to the type approval standard in the future.

However, it is likely that the use of particulate traps will become increasingly prevalent, particularly for Euro IV and later specification heavy-duty vehicles. The PM emissions from such vehicles are expected to be so low so as to be very challenging to measure, **and will probably be well below the type approval standard**. The requirement for in-service testing is not to measure these emissions per se but to detect **defective** vehicles. Consequently, assuming that some vehicle manufacturers do use particulate traps to meet new PM emissions standards, although the FAS peak from a correctly operating vehicle may be significantly less than 0.05 m^{-1} , the meter sensitivity required to identify malfunctioning vehicles is anticipated to be no lower than 0.05 m^{-1} . (This is 30 times less than the revised pass/fail limit for Euro IV vehicles and 60 times less than the current standard.)

The FAS peaks that were produced from Vehicle 1 when fitted with an efficient particulate trap were around 0.025 m^{-1} . Figure A2.6 shows the raw output from the four measurement instruments that gave continuous readings for a series of 10 free accelerations. This clearly shows the “visibility” of the small signals above the instruments’ noise level.

It is important not to over interpret the data in the figure because, despite the steps taken to try and plot the data on comparable scales, it is probable that there are calibration errors at this very low end of the smoke scale.

Further, the data for the Bosch meter is, unfortunately, misleading. During the measurements there was a downward baseline drift. The “real” obscuration values became small and negative and are superimposed on the noise. However, the instrument reports all negative obscurations as 0.00. Consequently the Bosch data in Figure A2.6 does not include the instrument noise.

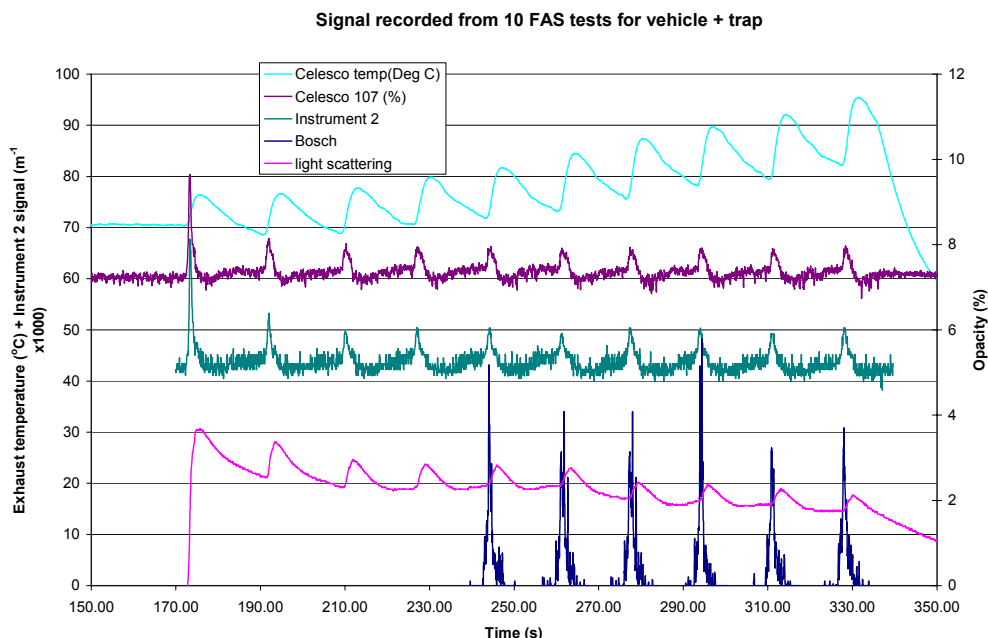


Figure A2.6 Raw response from instruments to FAS peaks of 0.025 m^{-1}

Figure A2.7 shows data from 3 peaks for the Celesco, advanced opacimeter and Bosch meters. Background noise, recorded in a separate experiment where the instrument sampled on clean air, has been added to the Bosch signal.

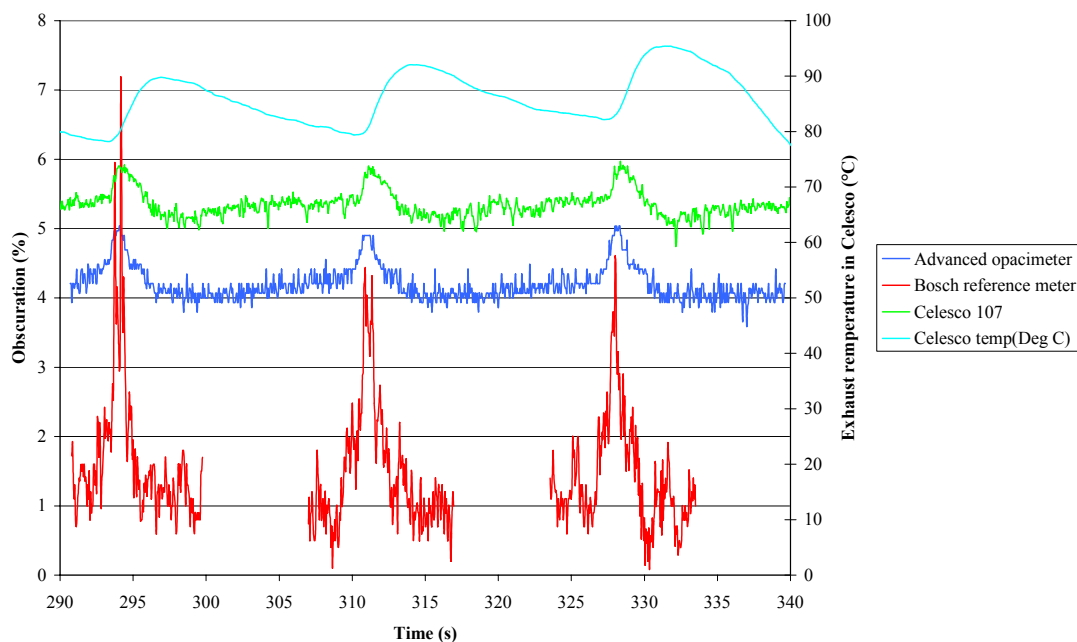


Figure A2.7 Expanded data from 3 accelerations, with edited Bosch response

The principal message to be taken from these two figures is that signals can be clearly seen from smoke peaks 120 times less than the current 3.0 m^{-1} pass/fail limit from the three obscuration based meters. For the filter paper reflectometry technique, filter reference AO 20B was exposed to two FAS tests from the above vehicle, and the resulting paper was found to contain staining between 10 and 20% (see Table A2.2) which is clearly identifiable and indicates that this technique also has a high sensitivity.

Given the smoke levels actually produced during FAS tests from Euro III vehicles, and the reductions in the type approval standards from Euro III to Euro V, the target range for the smoke levels anticipated from the next two generations of vehicles is $0.05 - 0.10 \text{ m}^{-1}$. The pass/fail limit of an appropriate in-service test would be greater than this. The majority of the instrumentation assessed in this phase of the project has been shown to have sufficient sensitivity to be considered as potential candidates for measuring the PM emissions from these next generations low emitting diesel vehicles.

A2.5.2 PRIORITISATION OF INSTRUMENTS

From the preceding discussions it can be deduced that neither the QCM nor the light scattering instrument are currently instrumentation that can be recommended for consideration for the in-service testing of diesel exhaust during a FAS test.

The filter paper reflectometry and advance opacimeter have both been shown to have higher sensitivities than the Bosch reference meter (by factors of 4 and 6.4, respectively from Table A2.5). The two approaches are quite different, one measuring an accumulation of PM whilst the other measures smoke in real time. Both approaches have their merits and drawbacks.

It is noted that the current meter specification given in the type approval test specification (Directive 99/69/EC) is based on real time smoke measurements. It is also noted, particularly in the context of decentralised testing, that to change instrument type requires training and other setting up costs significantly beyond those incurred when upgrading an instrument to its latest model. These considerations bias against the filter paper reflectometry approach.

The crucial question is: **What instrument specification is required in the future?** If has been noted several times that the role of the instrument **is not** to measure how cleaner vehicles perform, but to measure vehicles exhaust smoke relative to a pass/fail limit. Consequently, consider a vehicle fitted with a particulate filter whose real FAS peak is, for example, 0.02 m^{-1} , that is tested using the standard (not RPC) emissions test. The meter used is required to have adequate precision and accuracy to gauge whether the vehicle's emissions are greater than, or below, the 3.0 m^{-1} pass/fail limit. Hence **current meters are totally adequate for this task**. From 2008, when the pass/fail limit is reduced to 1.5 m^{-1} for Euro 4 vehicles, the current meters remain totally adequate for this task.

If, however, the pass/fail limit for some vehicles was reduced to, for example, 0.3 m^{-1} , then the suitability of current meters would become more marginal, and a more sensitive meter might be required.