Particulate Matter Measurements Made using the Filter Dynamics Measurement System (FDMS), 2005

Prepared for the London Boroughs of Bexley, Ealing and Greenwich

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David Green

Environmental Research Group

King's College London

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Environmental Research Group
King's College London
Franklin-Wilkins Building
150 Stamford St
London SE1 9NN
Tel 020 7848 4044
Fax 020 7848 4045

	Name	Signature	Date
Author	David Green		December 2006
Reviewed by	Gary Fuller		December 2006
Approved by	Gary Fuller		December 2006

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1. SUMMARY

This report details the analysis of particulate matter measurements made in the London Air Quality Network (LAQN) made using the Filter Dynamics Measurement System (FDMS) and compares them to established particulate monitoring methodologies. The FDMS is a relatively new automatic monitoring technique and has proved equivalent to the reference method for PM_{10} and $PM_{2.5}$ in the UK Equivalence Programme. The FDMS system also provides a measurement of volatile particulate matter, which is informative for the understanding of sources of particulate matter and the measurement methodologies.

Monitoring was undertaken at seven locations in London between January 2004 and December 2005. Five sites measured PM_{10} using both the FDMS and TEOM (two of these also measured PM_{10} using the gravimetric method). The two remaining sites measured PM_{10} and $PM_{2.5}$ using the FDMS. Operational issues that affect data quality are discussed and advice is given regarding the best way to minimise data loss.

The measurements made by the FDMS, TEOM and gravimetric instruments were compared to the EU annual and daily limit values during 2004 and 2005. This comparison highlighted differences between the monitoring methodologies. These differences were most marked at the Marylebone Road kerbside site, where the FDMS measurements met the air quality objectives while other methods indicated failure. These differences between gravimetric and FDMS measurements at Marylebone Road increased between 2004 and 2005 and were also identified at an urban background site. The UK Equivalence Programme did not detect such an effect, however, UK Equivalence Programme did not include a heavily trafficked kerbside location and may therefore not be representative of such locations.

The difference between PM_{10} as measured by TEOM and the FDMSBbase measurement was examined. The difference between these two measurements was shown to be proportional to the FDMS's measurement of volatile particulate matter (FDMSPurge). This has provided a method for maintaining measurement continuity if TEOMs are upgraded to FDMS. This continuity calculation respects seasonal and temporal variations in composition of PM_{10} and therefore the difference between the TEOM and FDMS PM_{10} methods.

$$KCL\_TEOM_{FDMS} = FDMSBase + FDMSPurge$$

2. INTRODUCTION

The accurate assessment of PM mass is frequently compromised by the loss of the volatile fraction of PM. This problem is common to most types of PM mass measurement methods, including the Tapered Element Oscillating Microbalance (TEOM). The TEOM instrument is widely used on the Automatic Urban and Rural Network (AURN) and in the London Air Quality Network (LAQN). Its elevated sampling temperature causes it to measure a lower mass concentration than the reference method due to the loss of volatile PM (Allen and Reiss, 1997; Salter and Parsons, 1999; Green et al., 2001; Charron et al., 2003). However, measurements equivalent to those made using the reference method are required for the assessment of the National and European Air Quality Standards (1999/30/EC). This situation is complicated by the requirement to supply up-to-date information to the public, which is only possible using an automatic instrument such as the TEOM. The public information requirements have prevented a change in the monitoring methodology and led to the derivation of a correction factor, which is then applied to the measurements made using the TEOM so that they approximate to the reference method.

The UK Equivalence Programme for Monitoring of Particulate Matter (Harrison, 2006) compared different PM_{10} and $PM_{2.5}$ instruments against the European reference method at four locations in the UK between 2004 and 2005. The results were analysed according to the EC Guidance for the Demonstration of Equivalence (EC, 2005). Several instruments proved equivalent to the European reference method: Partisol 2025, FDMS, Opsis SM200 Beta Attenuation Monitor (BAM), Opsis SM200 sampler (with slope and intercept correction) and the Met One Beta BAM (with correction factor). Importantly, the TEOM did not meet the equivalence criteria and is therefore not suitable for reporting PM_{10} and $PM_{2.5}$ for analysis against the EU limit values.

The FDMS is an upgrade that can be fitted to most TEOM instruments (or supplied new), which will provide results that are equivalent to the European reference method. Local authorities in London have commissioned several of these instruments. This study concerns the measurements of PM made using the FDMS in the LAQN during 2004 and 2005. In particular this report will examine three aspects of the measurements made:

- Data capture and data quality
- The comparability between the measurements of PM_{10} made using the FDMS, TEOM and gravimetric methods.
- The measurement of volatile PM, which is facilitated by the FDMS filter purge measurement cycle.
- Continuity between measurements of PM_{10} made using the FDMS and those made using the TEOM.

3. METHOD

This section outlines the monitoring locations, the methods used, and the treatment of data. It also provides a summary of the data analysis techniques used.

3.1 Monitoring Locations

The monitoring incorporating FDMS instruments in the LAQN during 2004 and 2005 are shown in Figure 1, further details of the monitoring locations are given in Section 7.

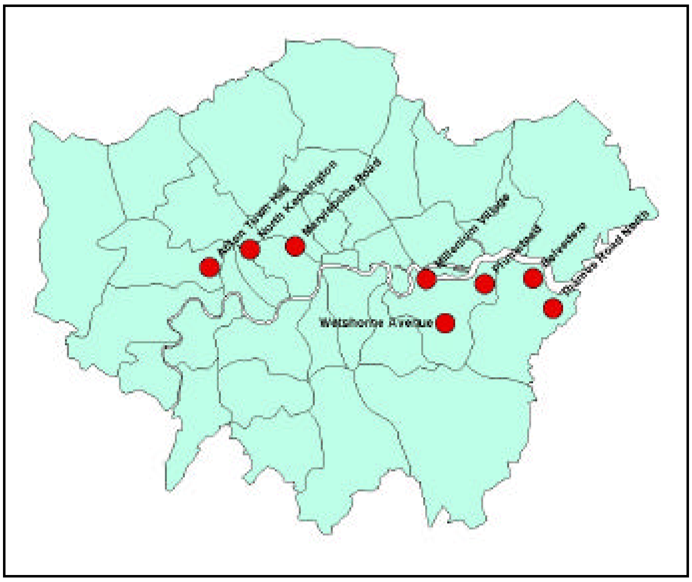

Figure 1: Monitoring site locations

3.2 Monitoring Methods

PM_{10} measurements were undertaken using the R&P TEOM, FDMS and Partisol.

3.2.1 Tapered Element Oscillating Microbalance (TEOM)

The TEOM is a real time particulate mass monitor, its mass measurement method relies on a microbalance, which consists of a hollow glass tapered tube, clamped at one end free to oscillate at the other; an exchangeable filter is placed on the free end. The frequency of oscillation is measured and recorded by a microprocessor at two-second intervals. A schematic of the entire system is shown in Figure 2. The filter and the air stream passing through it are heated to 50 ºC to reduce the interferences from particle bound water and to minimise thermal expansion of the tapered element which may affect the oscillating frequency. This has the widely accepted disadvantage of driving off semi-volatile material such as ammonium nitrate and organic aerosols (Ruppecht E. et al., 1992; Allen and Reiss, 1997; Salter and Parsons, 1999; Soutar et al., 1999; Green et al., 2001; Josef et al., 2001; Charron et al., 2003). However, the TEOM has received US EPA certification as an equivalent method for PM_{10} monitoring (Rupprecht & Patashnick Co., 2003).

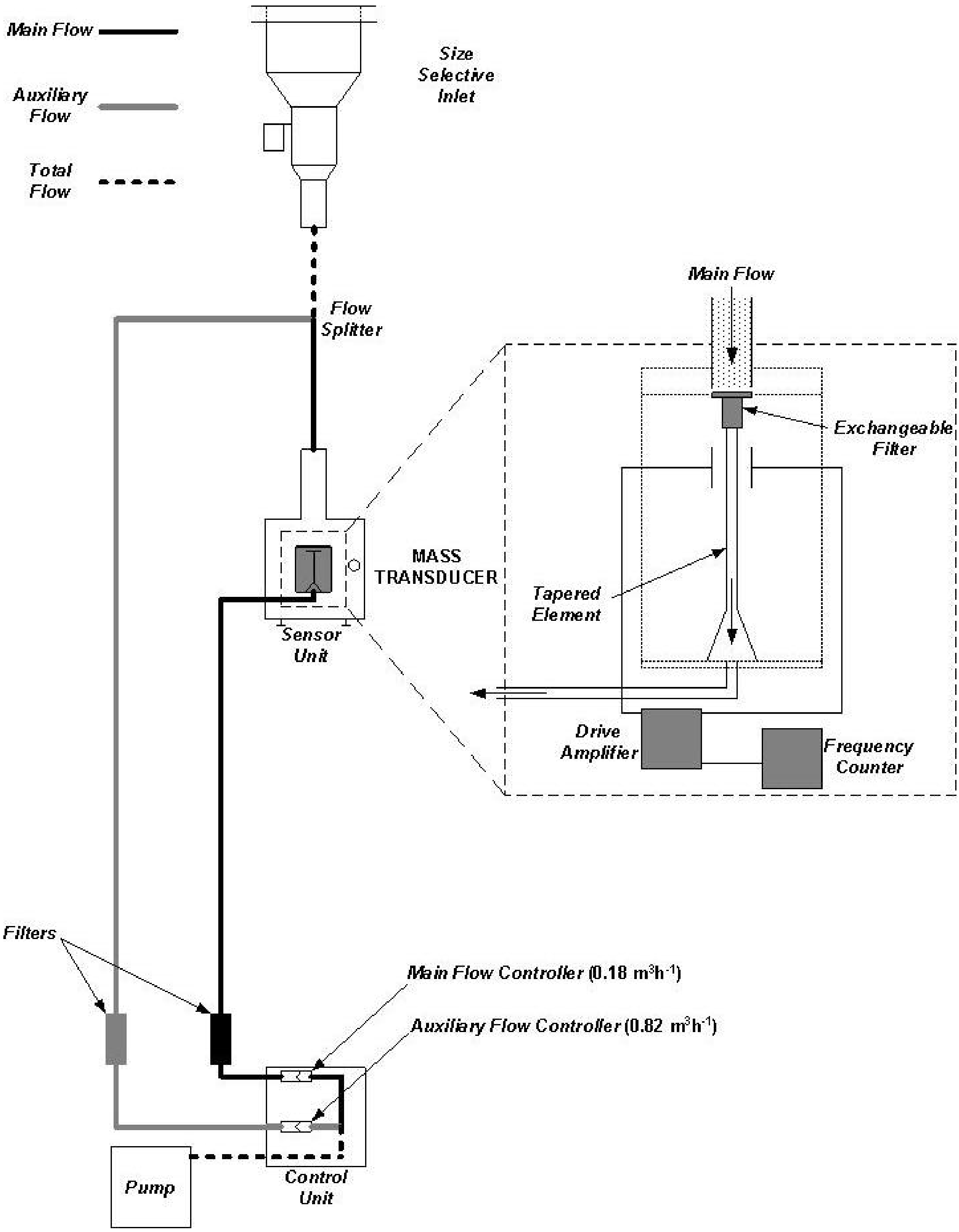

Figure 2: Schematic of the TEOM

3.2.2 The Filter Dynamics Measurement System (FDMS)

The FDMS aims to measure the mass concentration of airborne PM and quantify the mass changes of the filter due to evaporative and condensation processes that will affect the measurements. This system was based on TEOM technology, using the same microbalance. It sampled air through an R&P PM_{10} inlet, and then used a dryer to remove water from the sample; this allowed the mass to be measured at 30 ºC rather than 50 ºC. After passing through the dryer measurement was alternated between two modes (base and purge), switching between them every six minutes, the different configurations of these modes are shown in Figure 3. The change in mass on the filter was measured by the microbalance during both modes.

Base Measurement

The change in mass of the filter was measured by the microbalance after size selection and passing through the dryer. This provided a mass concentration of PM_{10} analogous to that measured by the TEOM the difference being the dryer and the reduced sampling temperature.

Purge Measurement

A purge filter, chilled to 4 ºC, removed particulate matter and volatile organic compounds from the sample stream. This purged air was passed through the microbalance filter and the change in mass of filter measured. This provided a mass concentration due to evaporative and condensation processes on the filter.

A total PM concentration was calculated as:

FDMS mass measurement = base measurement - purge measurement

During the purge measurement mode, the mass lost due to the evaporation of volatile PM tended to exceed the mass gained due to any condensation of gaseous material onto the filter. This resulted in a predominately negative purge measurement and therefore increased the FDMS mass measurement above the base measurement.

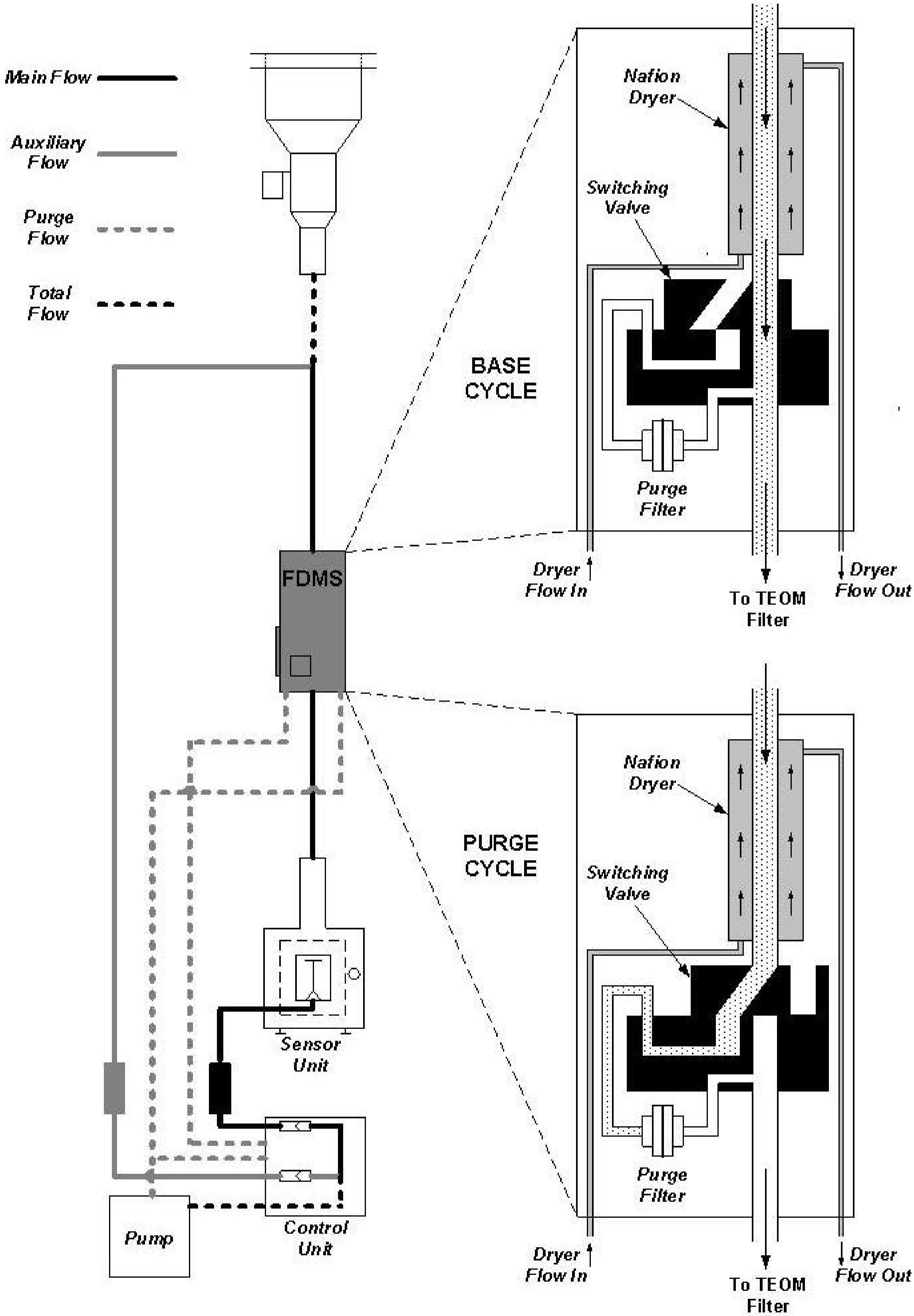

Figure 3: A schematic of the FDMS system. Base cycle (top) and purge cycle (bottom) configurations are shown separately.

3.2.3 Partisol 2025

Sampler systems such as the Partisol 2025 shown in Figure 4 are the basis of the European and US gravimetric reference methods when used in association with defined operating parameters governing the choice of sampler, filter and method of laboratory (EPA, 1997; CEN, 1998; CEN, 2003); The sampler collects particulate matter onto a pre-weighed filter. The filter is then re-weighed under standardised conditions to determine the mass of particulate collected on the filter. Using measurements of sample volume a mass concentration of particulate matter in the air can be calculated.

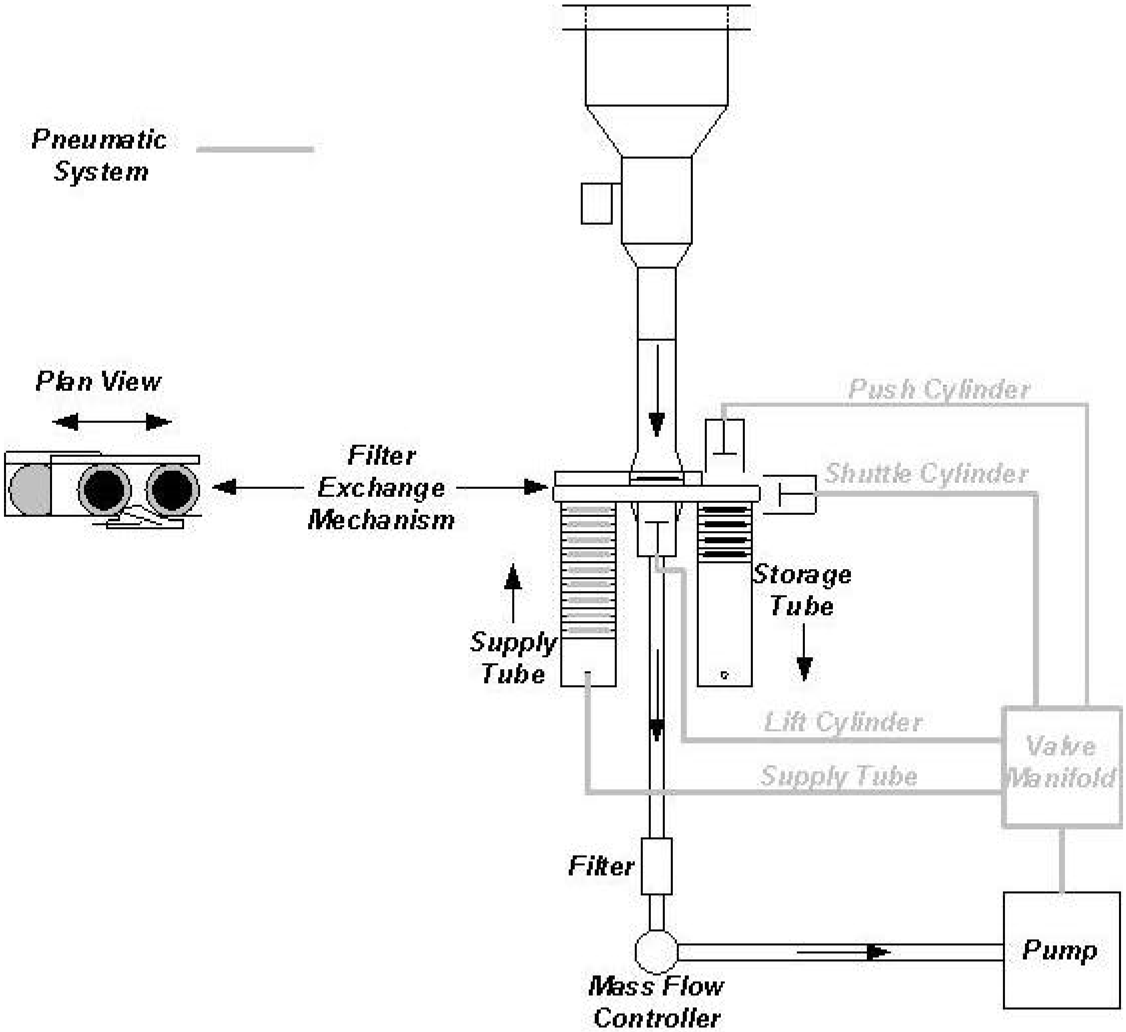

Figure 4: Schematic of the Partisol 2025

Standard Partisol 2025 systems, equipped with a PM_{10} size selective inlet, were used at the Marylebone Road and North Kensington sites. These and other operational issues are summarised in Table 1.

Site	Instrument	Filter Type	Filter Exchange frequency
Marylebone Road	Partisol 2025	Quartz Fibre	2 weekly
North Kensington	Partisol 2025	Quartz Fibre	2 weekly
DEFRA Equivalence Trials	KFG	PTFE coated glass fibre	Daily

Table 1: Summary of the operational parameters of the Partisol instruments used in this study and in the DEFRA equivalence trials

3.3 Data Pre-processing

To enable a valid comparison between the measurement methods two types of adjustments were made to the TEOM measurements. The first corrected for the US EPA Correction Factor in the TEOM (TEOM = 3.0 µg m^{-3} + 1.03 Raw TEOM), which was included to account for the relative underestimation when compared to the US EPA reference method (Ruppecht E. et al., 1992). The second corrected for the reporting conditions of the TEOM, which default to 25 ºC, and 1 atmosphere pressure, and was the US EPA requirement prior to 1997. These are referred to as standard temperature and pressure (STP) and atmospheric temperature and pressure (ATP). The TEOM is reported at ATP unless stated otherwise. The TEOM*1.3 correction factor is applied to TEOM at STP.

The FDMS and gravimetric measurements are always reported at ATP. These adjustments will lead to differences between the measurements examined in this report and those disseminated to the public. Further discussion of the impact of these correction factors and offsets can be found in Green and Fuller (Green and Fuller, 2006).

	TEOM	$TEOM_{STP}$	$TEOM_{ATP}$	TEOM*1.3	FDMS
US EPA Correction Factor	Yes	No	No	Yes	No
STP Correction	Yes	Yes	No	Yes	No
DEFRA 1.3 Correction Factor	No	No	No	Yes	No

Table 2: Summary of correction factors for TEOM and FDMS measurements

4. RESULTS AND DISCUSSION

Measurements of PM_{10} made using collocated TEOM, FDMS and gravimetric instruments are examined in this section.

4.1 Data Capture and Ratification

As these are relatively new instruments, it is important to consider the operational challenges and data capture achieved. The data capture during 2004 and 2005 is shown in Table 3. Data capture was low during 2004 as many of the instruments were installed part way through the year. Data capture rate since installation is therefore shown in brackets. Data capture is also calculated for paired data (when both instruments are operational) and triplicate data (when all three instruments are operational).

Site		2004			2005		
		TEOM	FDMS	Gravimetric	TEOM	FDMS	Gravimetric
Acton Town Hall PM_{10}	**All data**	93			**87**	**31** (95)	
	Paired				**20 (64)**		
North Kensington PM_{10}	**All data**	96	**47**	**85**	98	**87**	**82**
	Triplicate	**35**			**70**		
Marylebone Road PM_{10}	**All data**	98	92	**84**	96	91	**87**
	Triplicate	**79**			**79**		
Millennium Village PM_{10}	**All data**		**33** (92)			**0**	
	Paired						
Millennium Village $PM_{2.5}$	**All data**		**0 (0)**			91	
	Paired						
Westhorne Avenue PM_{10}	**All data**		**3** (100)			**68**	
	Paired						
Westhorne Avenue $PM_{2.5}$	**All data**		**3** (100)			**66**	
	Paired						
Belvedere PM_{10}	**All data**	**67** (98)	**58 (83)**		**81**	**54**	
	Paired	**57 (82)**			**38**		
Thames Road North PM_{10}	**All data**	**58 (89)**	**61 (84)**		**75**	**74**	
	Paired	**48 (70)**			**60**		

Table 3: Data capture (%) for the TEOM, FDMS and paired data set during 2004 and 2005. Data capture rates since installation in 2004 are shown in brackets.

Some of the FDMS instruments have low data capture for during 2004 and 2005 for operational reasons; the easons for this data loss have been grouped into the three categories below.

1. Routine operation

Measurements are lost from all instrumentation while essential work such as filter changes, services, repairs and audits are carried out. However, unlike the TEOM the FDMS requires a period of stabilisation following these interventions to allow the adsorption and evaporation from the filters to equilibrate. This period of stabilisation is variable, ranging from 1 to 48 hours. This stabilisation period is most clearly identified using the purge measurement, as shown in Figure 5.

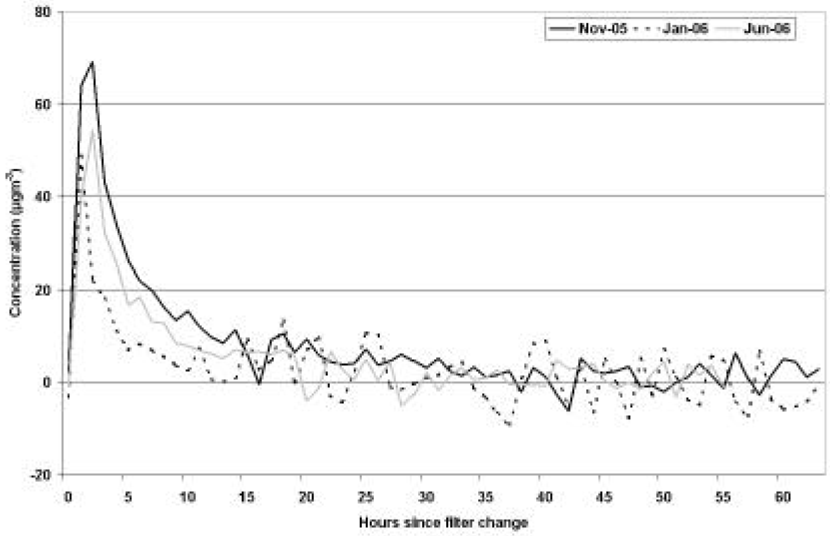

Figure 5: Example of the stabilisation period of the purge measurement following filter change

2. Faults induced by routine operation

Measurements that do not reflect ambient conditions are often encountered following a filter change. Three aspects of the purge filter have been identified as leading to errors in the measurement of the volatile fraction following a filter change:

a. Orientation of the filter holder in the chiller unit.

b. Orientation of the filter in the filter holder.

c. A leak in the filter housing.

All three of these faults can be avoided by correct LSO training and the use of the correct tools.

3. Drier faults

Drier faults are the most common fault occurring on FDMS systems. The drier efficiency is measured by the dew point of the sample leaving the drier and entering the switching valve where it proceeds either to the purge filter or to the microbalance. A warning status appears when the dew point rises above 2 ºC. The efficiency of the drier is highly dependent on the relative pump vacuum, which should remain above 24'' Hg and on the enclosure temperature, which should remain below 22 ºC. The cabin temperature should not be at a low enough temperature to lead to condensation in the sample stream.

4. Unidentified artefact formation

Two of the FDMS instruments in the LAQN (Millennium Village PM_{10} and Belvedere PM_{10}) have been influenced by a positive artefact that is not attributable to any of the issues described above and is not associated with any status alarms on the instrument. This takes the form of a purge measurement of increased magnitude and a base measurement elevated by a similar value, this also increases in magnitude over time; an example is shown in Figure 6. This fault was only identifiable using retrospective analysis as the impact on the base and purge concentrations was small and only identified by comparing these measurements to a collocated TEOM and other FDMS instruments nearby. Measurements affected by this fault have been excluded from analysis in this report, the cause of this fault is still under investigation.

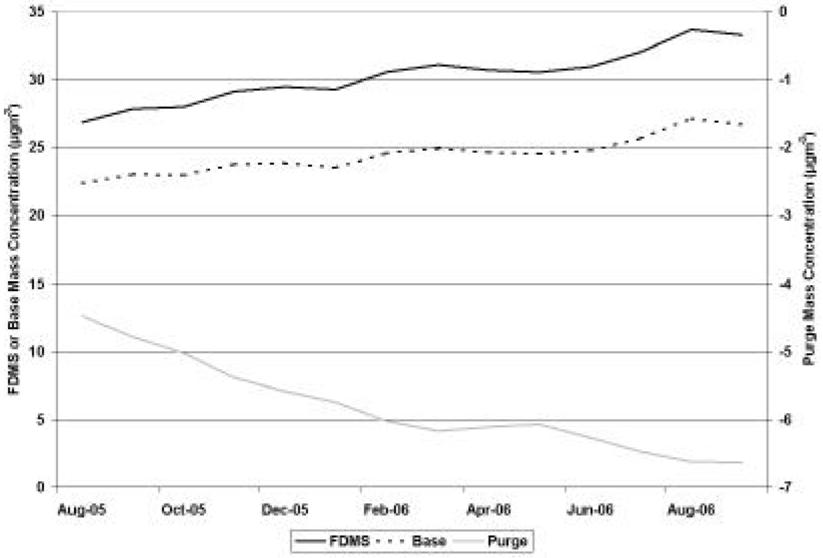

Figure 6: Mass concentrations of the FDMS, base and purge cycles of the FDMS instrument at Millennium Village

4.2 Annual Mean PM_{10} and $PM_{2.5}$ Concentrations

Annual mean PM_{10} and $PM_{2.5}$ concentrations at each site and year, using each available method is shown in Table 4. TEOM measurements were mutilpied by the DEFRA recommended 1.3 factor to assess the EU stage 1 annual limit value and compared to the annual means from the FDMS and the gravimetric instruments. Both the FDMS and the Partisol proved equivalent to the European reference method during the recent UK Equivalence Programme for Monitoring of Particulate Matter. However, it should be noted that the Partisol methodology used in this study and throughout the AURN differs from that used in the UK Equivalence Programme as shown in Table 1. To ensure that the relationship between the mean concentrations were not affected by the data capture shown in Table 3, the annual mean concentrations were also calculated for paired data. When assessing EU limit values, all data mean concentrations were used. When comparing measurements between methods, pared mean concentrations were used.

Site		2004			2005		
		TEOM*1.3	FDMS	Gravimetric	TEOM*1.3	FDMS	Gravimetric
Acton Town Hall PM_{10}	**All data**	**30**			**29**	**26**	
	Paired				31	26	
North Kensington PM_{10}	**All data**	**24**	**22**	**25**	**24**	**23**	**29**
	Paired	23	21	24	23	22	29
Marylebone Road PM_{10}	**All data**	**43**	**32**	**41**	**43**	**32**	**44**
	Paired	43	32	41	43	31	44
Millennium Village PM_{10}	**All data**		**24**			**-**	
	Paired						
Millennium Village $PM_{2.5}$	**All data**		**-**			**19**	
	Paired						
Westhorne Avenue PM_{10}	**All data**		**16**			**25**	
	Paired						
Westhorne Avenue $PM_{2.5}$	**All data**		**9**			**17**	
	Paired						
Belvedere PM_{10}	**All data**	**23**	**21**		**23**	**24**	
	Paired	23	21		22	23	
Thames Road North PM_{10}	**All data**	**33**	**25**		**30**	**25**	
	Paired	34	25		30	24	

Table 4: Annual mean concentration of PM_{10} and $PM_{2.5}$ measured using the TEOM, FDMS and gravimetric methods in µg m^{-3}.

Firstly, it is clear that annual mean concentrations measured during 2004 and 2005 are generally similar. However, there are a few exceptions:

- At Thames Road North, the annual mean TEOM*1.3 is 3 µg m^{-3} lower in 2005. This may be related to changes in emissions from construction close to the instruments.

- The gravimetric mean concentrations at both Marylebone Road and North Kensington are 3 and 4 µg m^{-3} higher during 2005 than they during 2004 respectively; this increase is not reflected in either the TEOM or the FDMS measurements.

The only annual means that breach the 40 µg m^{-3} EU Stage 1 Limit Value were measured at Marylebone Road using the gravimetric method and TEOM *1.3. No FDMS annual mean, even Marylebone Road, exceeded this Limit Value.

There are two further comparisons which can be made using the annual mean concentrations: between the TEOM*1.3 and the FDMS and between the FDMS and the gravimetric measurement. The TEOM*1.3 annual mean concentration was greater than the collocated FDMS measurement at all sites except Belvedere during 2005, where it measured 1 µg m^{-3} lower than the FDMS. This small difference is consistent with the small difference between the TEOM*1.3 and the $FDMS_{ATP}$ at North Kensington, the other urban background site in this study, where the TEOM*1.3 measures 1 µg m^{-3} higher than the FDMS. In contrast, the TEOM*1.3 concentration at the roadside and kerbside sites is 5 - 12 µg m^{-3} greater than that measured by the FDMS. This indicates that the 1.3 correction factor accurately reflects the volatile fraction lost at background locations but substantially overestimates that at roadside locations.

The FDMS annual mean concentrations measured at Marylebone Road and North Kensington are 3 and 9 µg m^{-3} lower than the collocated gravimetric measurements respectively during 2004. During 2005 this difference increases to 7 and 13 µg m^{-3} respectively. This conflicts with the results of DEFRA's UK Equivalence Programme for Monitoring of Particulate Matter, which showed that the FDMS agreed well with the gravimetric method. This difference may have been caused by the differences in the methodology used for the AURN measurements compared to the UK Equivalence Programme as described in Table 1. The daily exchange of filters employed during the UK Equivalence Programme was designed to reduce the loss of volatile material during filter storage. This would therefore increase the gravimetric mass relative to the FDMS, the opposite effect to that seen in London. The filter type is therefore the prime suspect for this disparity, the UK Equivalence Programme used Teflon-coated glass fibre filters while the rest of the DEFRA gravimetric monitoring (including that utilised here) uses quartz filters. Quartz filters are known to adsorb organic gases (Kirchstetter et al., 2001; Eatough et al., 2003) and they were highlighted as having a susceptibility to changes in relative humidity (Brown et al., 2005). Both of these effects could increase the mass of quartz filters relative to the Teflon-coated glass fibre filters systematically, however, they would not induce the temporal change identified in the measurements. Incidentally, both the purge filter and the microbalance filter used in the FDMS instrument are made of Teflon-coated glass fibre.

4.3 Daily Mean PM_{10} Concentrations Greater than 50 µg m^{-3}

The EU stage 1 daily limit value is 50 µg m^{-3}, not to be exceeded on more than 35 occasions. The number of daily mean concentrations greater than this threshold at each site and year, using each available method is shown in Table 5, this was also calculated for paired data. When assessing EU limit values, all data mean concentrations were used. When comparing measurements between methods, pared mean concentrations are used.

Site		2004			2005		
		TEOM*1.3	FDMS	Gravimetric	TEOM*1.3	FDMS	Gravimetric
Acton Town Hall PM_{10}	**All data**	**24**			**20**	**10**	
	Paired				8	7	
North Kensington PM_{10}	**All data**	**6**	**4**	**12**	**6**	**17**	**26**
	Paired	0	3	4	4	15	20
Marylebone Road PM_{10}	**All data**	**99**	**32**	**67**	**118**	**32**	**85**
	Paired	82	27	63	93	25	74
Millennium Village PM_{10}	**All data**		2			0	
	Paired						
Westhorne Avenue PM_{10}	**All data**		0			24	
	Paired						
Belvedere PM_{10}	**All data**	**4**	**6**		**6**	**11**	
	Paired	2	6		4	4	
Thames Road North PM_{10}	**All data**	**33**	**11**		**21**	**20**	
	Paired	29	9		16	14	

Table 5: Number of Daily mean PM_{10} concentrations greater than 50 µg m^{-3} measured during 2004 and 2005 using the TEOM, FDMS and gravimetric methods.

The only site that exceeded the EU stage 1 daily limit value was Marylebone Road, when measured using the TEOM*1.3 and the gravimetric method in both 2004 and 2005. The FDMS instruments at this site measured 32 daily means greater than 50 µg m^{-3} in both 2004 and 2005. The TEOM*1.3 measured 99 during 2004 and 118 during 2005. The gravimetric method measured 67 during 2004 and 85 during 2005.

As the FDMS at Marylebone Road (one of the most polluted locations where air quality is monitored in the UK) does not exceed the EU stage 1 daily limit value, it is likely that few sites in the UK would continue to breach this limit value if PM_{10} were measured using an FDMS. The inconsistency between the FDMS and the gravimetric method was also highlighted by this comparison. As discussed in the previous section, this may be due to the filter media used by the AURN sites compared to the UK equivalence Programme. Alternatively, as the UK Equivalence Programme did not include a heavily trafficked roadside site similar to Marylebone Road, the equivalence of the FDMS has therefore not been tested in this type of location.

Comparing the variability of the number of daily means greater than 50 µg m^{-3} between 2004 and 2005 is more challenging than comparing the annual mean concentrations as this statistic is strongly influenced by data capture, which was low for some sites during 2004. However, it is worthwhile comparing the 2004 and 2005 results from Marylebone Road, which had a high data capture for both years. When considering the paired data, the FDMS instrument at Marylebone Road measured 27 daily means greater than 50 µg m^{-3} in 2004 and 25 during 2005. However, the TEOM*1.3 measured 82 during 2004 and 93 during 2005, while the gravimetric method measured 63 during 2004 and 74 during 2005. The FDMS therefore showed a consistency in the number of episodes between 2004 and 2005, while both the TEOM*1.3 and the gravimetric method recorded and increase in the number of episodes. This indicates further inconsistencies between the measurement methods.

4.4 FDMS Base and Purge Annual Mean Measurements

As discussed in section 3.2.2, the FDMS measurement is made up of two cycles: base and purge. It is important to examine these measurements separately as they provide useful information regarding the composition of the particulate matter being measured. The previous FDMS report (Green and Fuller, 2004) demonstrated that the base measurement was analogous to the standard TEOM mass measurement but the relationship between collocated instruments was inconsistent. The FDMS purge measurement was shown to be approximately equal to the ammonium nitrate concentration by comparing it to measurements of nitrate in $PM_{2.5}$ made at Marylebone Road. This section examines the annual mean concentrations of these measurements.

Site		2004			2005		
		TEOM	$FDMS_{BASE}$	$FDMS_{PURGE}$	TEOM	$FDMS_{BASE}$	$FDMS_{PURGE}$
Acton Town Hall PM_{10}	**All data**	**19**			**18**	**23**	**-3.2**
	Paired				20	24	
North Kensington PM_{10}	**All data**	**15**	**16**	**-4.5**	**15**	**19**	**-4.0**
	Paired	15	17		15	20	
Marylebone Road PM_{10}	**All data**	**28**	**28**	**-3.9**	**28**	**28**	**-4.4**
	Paired	28	29		28	29	
Millennium Village PM_{10}	**All data**		**21**	**-3.5**			
	Paired						
Millennium Village $PM_{2.5}$	**All data**					**15**	**-4.7**
	Paired						
Westhorne Avenue PM_{10}	**All data**		**15**	**-1.6**		**22**	**-3.0**
	Paired						
Westhorne Avenue $PM_{2.5}$	**All data**		**9**	**-1.1**		**15**	**-2.9**
	Paired						
Belvedere PM_{10}	**All data**	**14**	**18**	**-3.2**	**14**	**20**	**-4.7**
	Paired	14	19		13	20	
Thames Road North PM_{10}	**All data**	**25**	**21**	**-3.7**	**22**	**21**	**-3.5**
	Paired	26	23		21	21	

Figure 7: Annual mean TEOM, FDMS base and FDMS purge concentrations of PM_{10} and $PM_{2.5}$ in µg m^{-3}.

There is little variation in the base concentrations between the 2004 and 2005, this is expected as the FDMS and TEOM*1.3 measurement were also similar for both years. The lower annual mean measured by the TEOM at Thames Road North was highlighted in section 4.2.

As described in section 3.2.2, the FDMS base measurement was made at 30 ºC after passing through the dryer, whereas the TEOM measurement was made at 50 ºC. Some agreement between the two metrics is therefore expected. Examining the paired data, the difference between the TEOM and the FDMS base annual means vary between sites. However, many of the relationships between these two metrics at individual sites are consistent between 2004 and 2005. The FDMS base annual mean is equal to or greater than the TEOM at all sites during 2005. The difference is greatest at Acton Town Hall, North Kensington and Belvedere. The metrics are approximately the same at Marylebone Road and Thames Road North. The exception is at Thames Road North, which records a higher annual mean for TEOM than for the FDMS base, this is possible due to very localised effects of construction work at this site.

The variation in the FDMS annual mean purge concentrations is more difficult to assess, as the concentrations are small and there is no obvious trend. It is useful to consider the analysis presented in the previous report (Green and Fuller, 2004) which showed that one FDMS purge measurement in London can be expected to agree with another ±1.8 µg m^{-3} (2s). None of the annual means from the individual sites differ by more than this threshold. Furthermore, all the annual mean purge concentrations in 2004 and 2005 are within 1.8 µg m^{-3}, except the Westhorne Avenue site during 2004, which had a low data capture.

4.5 Regression Analysis

Reduced Major Axis (RMA) regression analysis was used to demonstrate the relationships between measurements. This method accounts for deviations in both x and y variables due to random measurement error (Ayers, 2000) and was therefore used instead of standard linear regression to provide slopes, intercepts and correlation coefficients for these relationships. All regression analysis results are provided in Table 6 for completeness, however, only pertinent results are discussed in detail.

Site	Independent Variable	Dependent Variable	2004				2005			
			N	Slope	Intercept	R	N	Slope	Intercept	R
Acton Town Hall PM_{10}	FDMS	TEOM					75	0.64	3.3	0.96
	FDMS	TEOM*1.3					75	0.89	8.6	0.96
	$FDMS_{BASE}$	TEOM					75	0.72	2.5	0.97
North Kensington PM_{10}	FDMS	TEOM	151	0.56	3.0	0.86	310	0.54	3.1	0.89
	FDMS	TEOM*1.3	151	0.74	8.0	0.86	310	0.72	8.0	0.89
	$FDMS_{BASE}$	TEOM	151	0.76	1.8	0.93	310	0.68	2.6	0.93
	Gravimetric	FDMS	176	1.00	-2.5	0.90	263	0.94	-3.7	0.89
	Gravimetric	TEOM*1.3	296	0.79	4.4	0.89	307	0.64	5.8	0.83
Marylebone Road PM_{10}	FDMS	TEOM	332	0.78	3.1	0.87	328	0.80	2.5	0.86
	FDMS	TEOM*1.3	332	1.09	8.5	0.88	328	1.11	7.8	0.86
	$FDMS_{BASE}$	TEOM	332	0.87	2.5	0.90	328	0.97	1.5	0.91
	Gravimetric	FDMS	289	0.79	0.6	0.93	303	0.78	-1.8	0.84
	Gravimetric	TEOM*1.3	331	0.80	10	0.79	325	0.84	6.1	0.72
Belvedere PM_{10}	FDMS	TEOM	207	0.64	0.3	0.94	136	0.59	-0.1	0.89
	FDMS	TEOM*1.3	207	0.88	4.5	0.94	136	0.81	4.1	0.90
	$FDMS_{BASE}$	TEOM	207	0.66	3.1	0.94	136	0.61	2.7	0.89
Thames Road North PM_{10}	FDMS	TEOM	167	0.97	4.2	0.90	201	0.73	7.0	0.92
	FDMS	TEOM*1.3	167	1.29	5.7	0.91	201	0.97	9.7	0.92
	$FDMS_{BASE}$	TEOM	167	0.97	4.2	0.90	201	0.73	7.0	0.92

Table 6: RMA regression analysis results of the TEOM, FDMS and gravimetric daily mean concentration data for 2004 and 2005.

Correlation coefficients are high for most analyses. The only R values lower than 0.85 relate to regressions involving a gravimetric instrument; this may reflect the susceptibility of this method to artefacts, both positive (retention of particle bound water and organic gases) and negative (loss of volatile components such as ammonium nitrate and organic compounds). The highest correlation coefficients were found between the FDMS base and TEOM measurements, supporting the analogy between the metrics and the prospect of continuity between the TEOM and FDMS measurement techniques; this is examined further in section 4.7.

There was a good consistency in slope and intercept for most sites between 2004 and 2005. The only intercepts that varied by more than 1 µg m^{-3} and slopes that varied by more than 0.1 were at Thames Road North, possibly due to the change in source strength associated with construction activity during 2004, and those relating to regressions involving a gravimetric instrument, possibly due to the influence of the artefacts described above. As the measurements from Thames Road North appear to be adversely affected by construction activity, this site is excluded when generalising about the relationships between metrics.

The regression analysis of the FDMS and the TEOM*1.3, should indicate how well the 1.3 TEOM correction factor would predict the FDMS measurement and hence the gravimetric method (Harrison, 2006). All RMA regression equations have large intercepts. The Belvedere analysis results in an intercept of approximately 4 µg m^{-3}, while Acton Town Hall, North Kensington and Marylebone Road all have intercepts of approximately 8 µg m^{-3}. This indicates that at low concentrations, when ambient and especially volatile concentrations are low, the 1.3 TEOM correction factor will dramatically over-predict the PM_{10} concentration. Slopes vary between 0.72 and 1.11. The smallest slopes were found at North Kensington and Belvedere, the largest were found at Acton Town Hall and Marylebone Road. This indicates that the 1.3 correction factor overestimates at the highest concentrations, increasing the slope of the line of best fit.

The regression analysis of the gravimetric method and the TEOM*1.3 also indicates how well the 1.3 TEOM correction factor works, this time at predicting the gravimetric measurement. As discussed the correlation coefficients are the lowest for these regressions. The intercepts are large (between 4.4 and 10 µg m^{-3}), similar to the regression analysis of the FDMS and the TEOM*1.3. The slopes vary little between site and year (between 0.72 and 0.83). As with the comparison between the FDMS and the TEOM*1.3, slopes are largest at roadside locations.

As discussed, the relationships between the FDMS base and TEOM measurements are amongst the strongest. Intercepts vary little between 1.5 and 3.1 µg m^{-3}. Slopes vary between 0.61 and 0.97; a slope closer to 1 indicates that they are measuring a similar mass of particulate matter through all concentrations. The smallest slopes were found at North Kensington and Belvedere, the largest were found at Marylebone Road. The uniformity of slope between the metrics therefore appears better at the Marylebone Road, this may be expected as direct vehicle particulate emissions, which would not be lost due to the elevated TEOM sampling temperature, would constitute a larger fraction of particulate in this environment.

Finally, the regression analysis of the gravimetric method and the FDMS, should demonstrate how well the FDMS instrument is at measuring PM_{10} according to the reference method. The intercepts vary between 0.6 and -3.7 µg m^{-3}, they are closer to zero at Marylebone Road than at North Kensington. However, the slopes at North Kensington are closer to parity: 1 and 0.94 in 2004 and 2005 respectively. At Marylebone Road the slopes are 0.79 and 0.78 in 2004 and 2005 respectively. The lack of agreement between these measurements methods was demonstrated when comparing the annual means. Examining the difference in the slopes between sites indicates a site-specific relationship, however the cause for this is unknown.

4.6 Temporal Analysis

Calculating rolling annual mean concentrations for each of the measurement methods at the sites allows a more detailed analysis of the change in concentrations discussed in sections 4.2 and 4.4. Rolling annual means have therefore been calculated between 2004 and 2006, these are the mean of the previous 12 months labelled time ending. A data capture threshold of 75 or 90% is typically used, however the low data capture associated with some of the instruments has necessitated using a 50% data capture threshold.

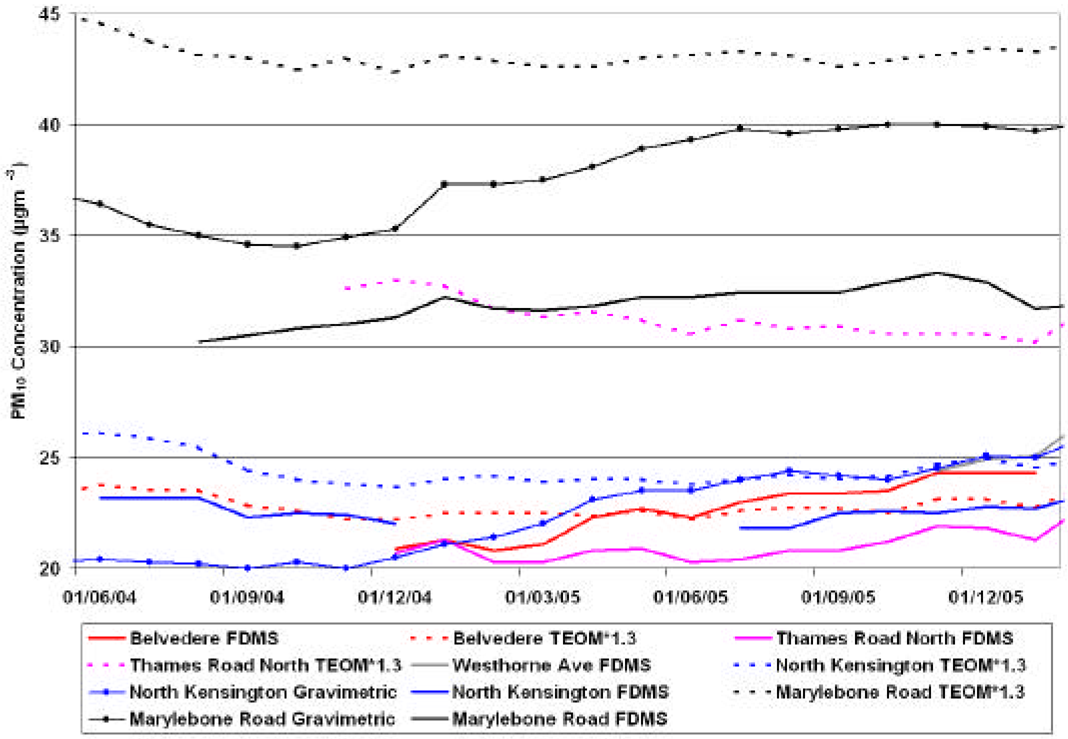

Figure 8: FDMS, TEOM*1.3 and Gravimetric PM $_{10}$ rolling annual means between 1st June 2004 and 31st December 2005

The FDMS, TEOM*1.3 and gravimetric PM_{10} rolling annual means are shown in Figure 8, several trends are evident in this graph. Firstly, the gravimetric PM_{10} concentrations at both Marylebone Road and North Kensington have risen by approximately 5 µg m^{-3} during the period that the FDMS instruments have been operating. At Marylebone Road the FDMS mean concentration has risen by 3 µg m^{-3}, while the TEOM*1.3 concentration has remained stable. At North Kensington the FDMS mean concentration has remained stable, while the TEOM*1.3 concentration has fallen by 1 µg m^{-3}. This is implies either a change in the response of the instruments to the PM_{10}, a change in the composition of the PM_{10} or a systematic artefact in the gravimetric method. Secondly, the Belvedere FDMS increase by 3 µg m^{-3} while the TEOM annual mean increased by only 1 µg m^{-3} over the same period. Therefore by the end of the study period the FDMS measured an annual mean 1 µg m^{-3} higher than the TEOM*1.3, whereas at the start of the study period it measured an annual mean 1 µg m^{-3} lower. This may be an indication of the start of the artefact formation fault discussed at the start of section 4. Thirdly, the Thames Road North FDMS rises by 1 µg m^{-3}, while the TEOM*1.3 falls by 2 µg m^{-3}. However, this may be due to changes in local emissions at this site. The changes to the FDMS and TEOM annual means are small so should be considered alongside the uncertainty in the measurements; the between sampler uncertainty in TEOM and gravimetric daily means has been estimated at 0.54 µg m^{-3} as a daily mean (Harrison, 2006).

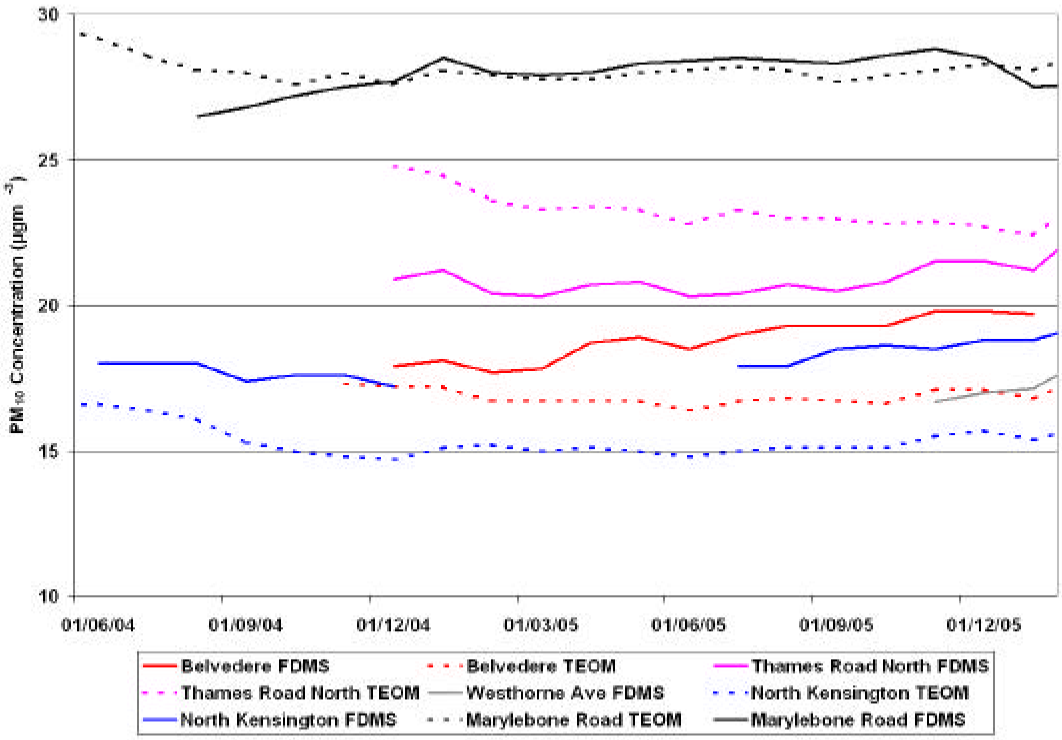

Figure 9: FDMS base and TEOM rolling annual means between 1st June 2004 and 31st December 2005

The FDMS base and TEOM rolling annual means are shown in Figure 9, similar trends to some of those described above can be seen in these analogous measurements. The measurements made using the two instruments at Belvedere diverge, after the start of 2006 data from the FDMS showed symptoms of the artefact formation discussed at the start of section 4 and was deleted during ratification. The FDMS base and TEOM measurements at Thames Road North converge, possibly due to the removal of the localised influence of the construction activity.

The FDMS purge rolling annual means are shown in Figure 10. All the annual mean purge measurements agree within the 1.8 µg m^{-3} demonstrated as an expected daily mean variation in the previous report (Green and Fuller, 2004). However, there appears to be a step change in the concentration measured at North Kensington after the dryer unit was replaced, nevertheless, it remains within the 1.8 µg m^{-3} limit and there were no additional measurements to compare it with at the time. $PM_{2.5}$ FDMS purge measurements have also been included in Figure 10. Collocated PM_{10} and $PM_{2.5}$ purge measurements at Westhorne Avenue appear to agree well, however, low data capture has resulted in a disparity with measurements at other sites. The Marylebone Road $PM_{2.5}$ nitrate measurement, was shown in Green and Fuller (2004) to agree very well with the PM_{10} FDMS purge measurements from Marylebone Road. This is also shown in Figure 10 and the FDMS purge measurements from many of the sites continue to agree well with this measurement.

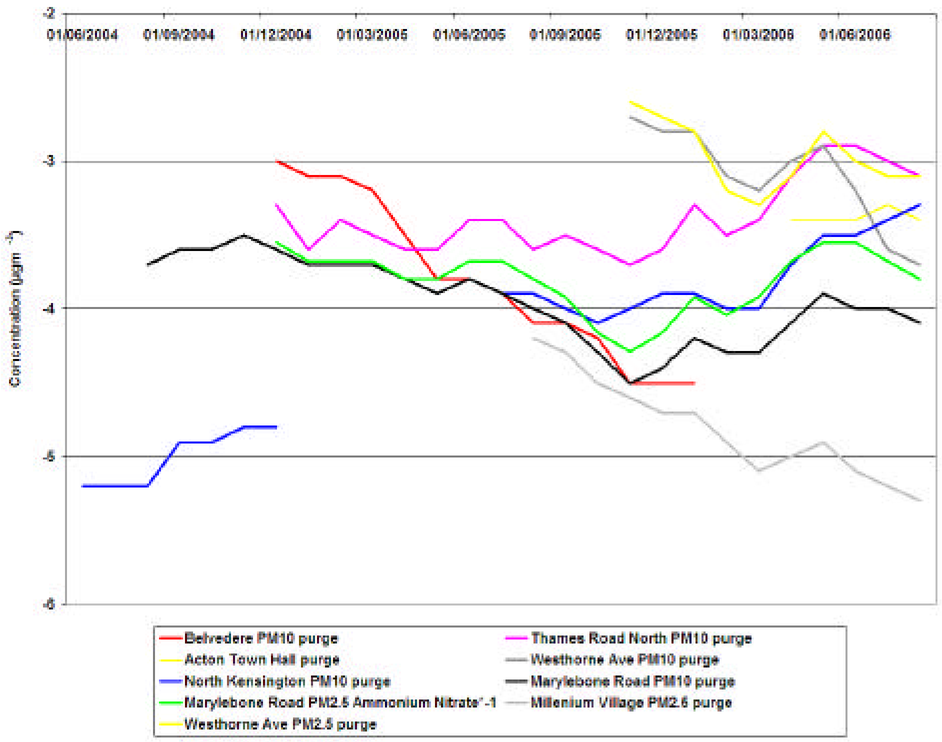

Figure 10: FDMS purge rolling annual means and Marylebone Road NH_4NO_3 x -1 between 1st June 2004 and 31st December 2005

An important consideration when examining the measurements of the FDMS instruments was whether they agreed with the collocated TEOM and gravimetric instruments and whether the relationship between them changed over time. Examining the rolling annual mean concentrations was a clear method of demonstrating a consistency in these relationships, this was an important method for highlighting the unidentified artefact formation discussed at the start of section 4. The relationship between the FDMS PM_{10} rolling annual mean and the TEOM*1.3 is shown in Figure 11. The FDMS annual mean varies between 63% of the TEOM*1.3 (Thames Road North, December 2004) and 105% (Belvedere, December 2006). At all of the sites this percentage increased during the study period, although this has stabilised or fallen in the provisional measurements for 2006. This change in the relationship is likely to have been caused by an increase in volatile particulate matter during the period and is supported by the increased rolling annual mean ammonium nitrate concentration measured at Marylebone Road and shown in Figure 10. The relationship between the FDMS base rolling annual mean and the TEOM is also shown in Figure 11. The FDMS base annual mean varies between 84% of the TEOM (Thames Road North, December 2004) and 122% (North Kensington, December 2006) and tracks the relationship between the FDMS PM_{10} and the TEOM*1.3. This demonstrates that the relationship between the FDMS base and the TEOM is influenced to some degree by the concentration of volatile particulate matter (ammonium nitrate). Therefore, any continuity factor or relationship developed between the FDMS base and TEOM will be related to the concentration of ammonium nitrate; a fixed continuity factor is therefore not appropriate. This issued is discussed in section 4.7.

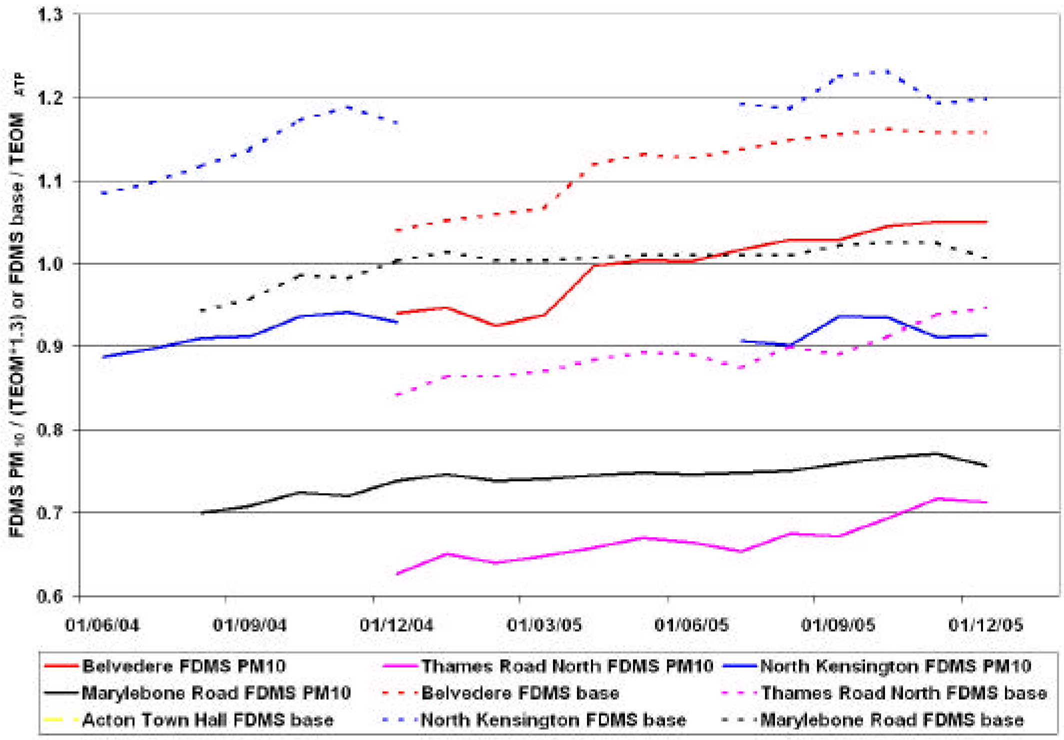

Figure 11: The relationships between the FDMS PM_{10} rolling annual means and the TEOM*1.3 and those between the FDMS base rolling annual means and the TEOM between 1st June 2004 and 31st December 2005

4.7 Continuity Between TEOM and FDMS

The issue of continuity between the TEOM and the FDMS has become very important following the UK Equivalence Programme for Monitoring of Particulate Matter (Harrison, 2006), and the consequent possibility of TEOM instruments being replaced with FDMS. For instance, if the TEOM at a monitoring site is replaced with an FDMS instrument, any concentration changes need to be attributed to either measurement changes or environmental factors. The use of the FDMS base measurement to provide the continuity link between the TEOM and the FDMS measurement has been explored in both the previous report (Green and Fuller, 2004) and in the UK Equivalence Report (Harrison, 2006). Green and Fuller (2004) showed that there was a different relationship between the FDMS base measurement and the TEOM at different sites, while the UK Equivalence Report recommended that the TEOM*1.3 was equivalent to a the FDMS base + 5.826 µg m^{-3}, or TEOM = (FDMS base + 2.061 µg m^{-3}) / 1.36. The regression analysis in section 4.5 also showed that the relationships between the FDMS base measurement and the TEOM differed by site and by year, the pertinent results of this analysis are shown in Table 7. The temporal analysis in section 4.6 also indicated that the relationship was influenced to some degree by the concentration of volatile particulate matter. A simple correction factor is therefore unlikely to account fully for this and alternative methods need to be explored.

Site	2004				2005			
	N	Slope	Intercept	R	N	Slope	Intercept	R
Acton Town Hall					75	0.72	2.5	0.97
North Kensington	151	0.76	1.8	0.93	310	0.68	2.6	0.93
Marylebone Road	332	0.87	2.5	0.90	328	0.97	1.5	0.91
Belvedere	207	0.66	3.1	0.94	136	0.61	2.7	0.89
Thames Road North	167	0.97	4.2	0.90	201	0.73	7.0	0.92

Table 7: RMA regression analysis results of the FDMS Base (independent variable) and TEOM (dependent variable) daily mean concentration data for 2004 and 2005.

The daily mean FDMS base and TEOM PM_{10} measurements from North Kensington are shown in Figure 12, this demonstrates the excellent relationship between the TEOM PM_{10} and the FDMS base measurements. However, the difference between the two daily mean concentrations is often greater than 10 µg m^{-3}, this is of concern when assessing the EU daily mean limit value. As discussed, this difference appears to be related to the FDMS purge measurement, the relationship between FDMS purge and the difference between the FDMS base and TEOM PM_{10} measurements is shown in Figure 13. An inverse relationship between the two is clear, especially when the difference between the two instruments is large. It therefore appears that the FDMS base measurement is equal to the TEOM measurement plus a function of the FDMS purge measurement.

Why this difference is related to the purge measurement is not clear. It is likely that this is due to the difference in temperature (50 ºC for the TEOM, compared to 30 ºC for the FDMS). Components of PM_{10} that are volatile at 50 ºC but not 30 ºC will therefore be lost from the TEOM but not from the FDMS. These components are likely to be semi volatile compounds: ammonium nitrate, water or organic compounds.

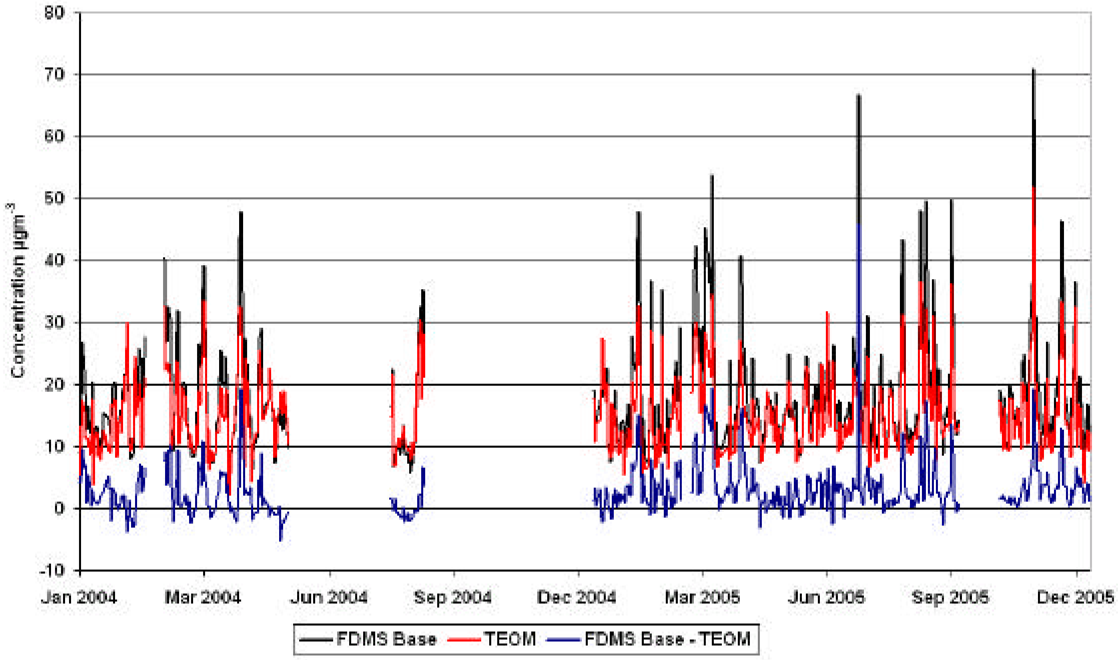

Figure 12: FDMS base and TEOM daily mean concentrations and the difference between them measured at North Kensington between January 1st 2004 and 31st December 2005

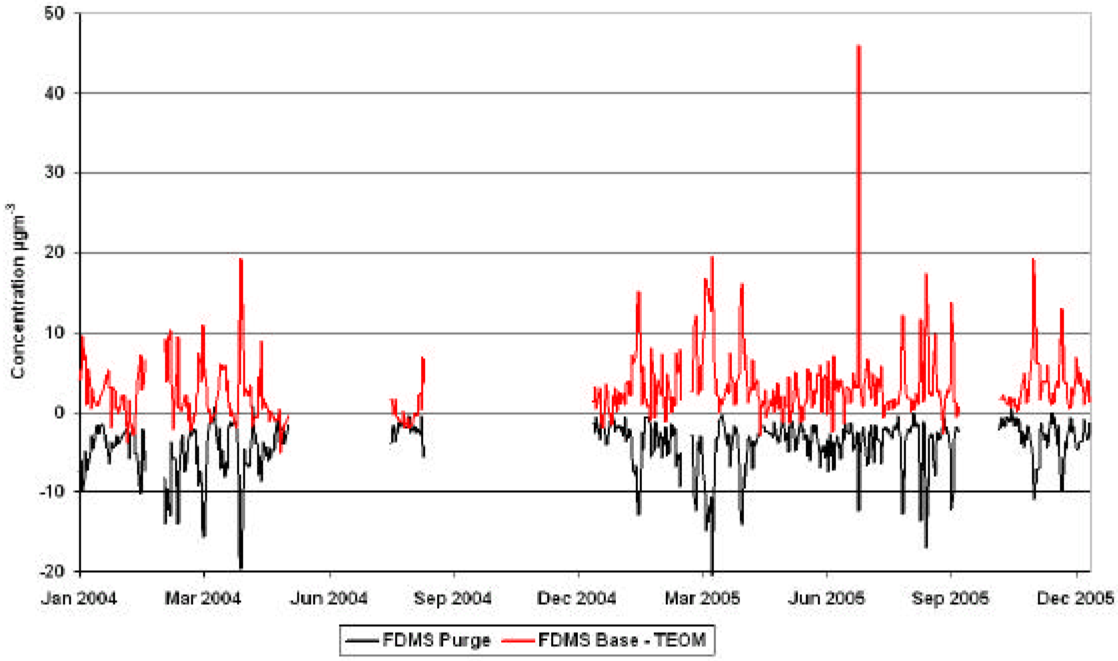

Figure 13: The difference between FDMS base and TEOM daily mean concentrations and the FDMS purge daily mean concentration measured at North Kensington between January 1st 2004 and 31st December 2005

Figure 14 shows a scatter plot of the FDMS purge measurement and the difference between the FDMS base and TEOM daily mean concentrations. One outlier is not shown on this graph, a short-term peak on 17th July 2005 measured by the FDMS and the TEOM but the TEOM measurements are not available from the Air Quality Archive. The relationship is linear, with an approximately 1:1 relationship, but shows a degree of scatter. This relationship is mirrored at the other sites shown in Figure 15. However, there is more scatter in the relationships at both Marylebone Road and Thames Road North, especially at low concentrations. Nevertheless, the

1:1 linear relationship is still clear and provides the basis for a model for reconstructing the TEOM mass measurement from the FDMS base and purge measurements.

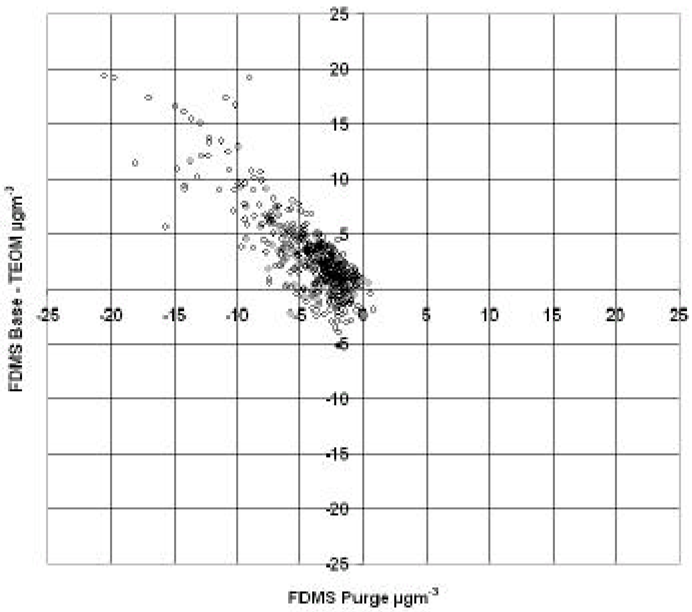

Figure 14: Correlation between (FDMS base – TEOM) and the FDMS purge daily mean concentration measured at North Kensington between January 1st 2004 and 31st December 2005. One outlier is not shown.

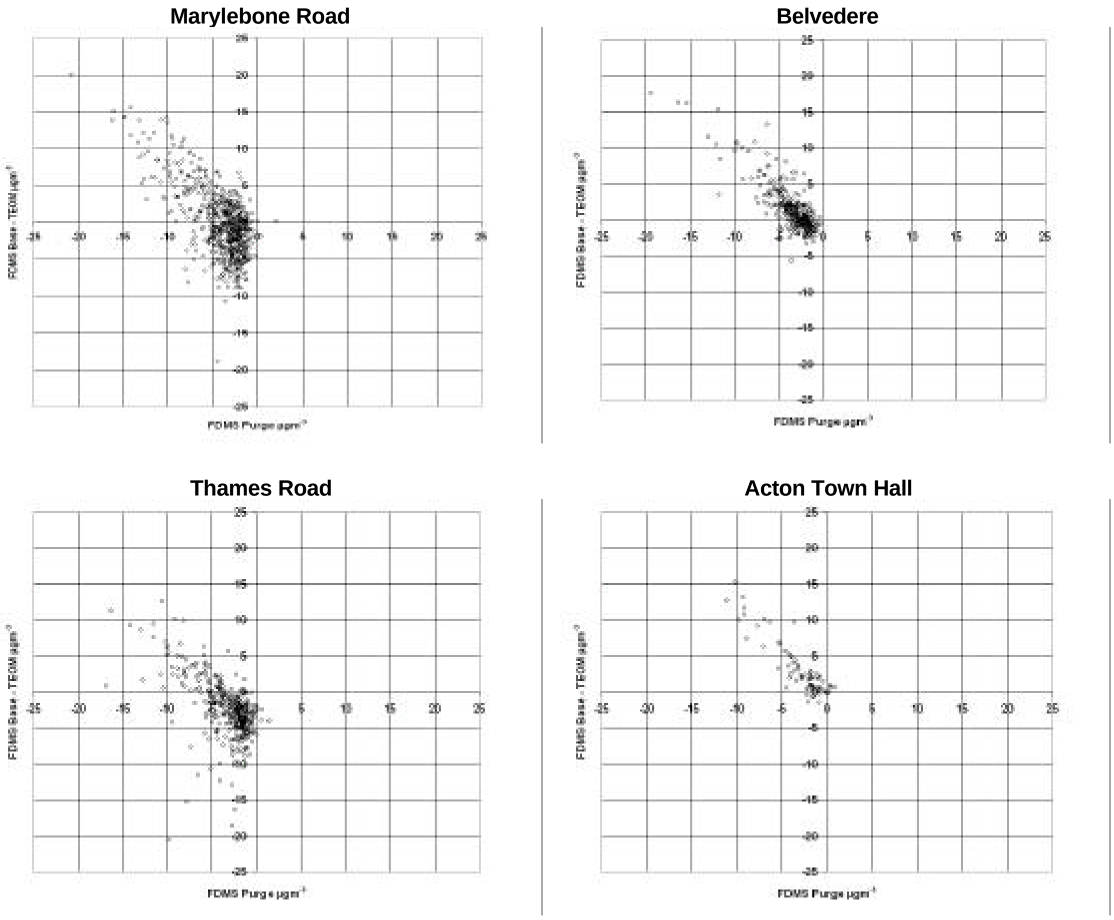

Figure 15: Correlation between (FDMS base – TEOM) and the FDMS purge daily mean concentration measured at Marylebone, Belvedere, Thames Road North and Acton Town Hall between January 1st 2004 and 31st December 2005.

The following equation is therefore used to reconstruct the TEOM mass concentration from the FDMS base concentration and the FDMS purge concentration:

$$KCL\_TEOM_{FDMS} = FDMSBase + FDMSPurge$$

To test how well this equation works, $TEOM_{FDMS}$ concentrations were calculated and compared to the collocated TEOM annual means measurements and the number of 24 hour means greater than 50 µg m^{-3}. $TEOM_{FDMS}$ concentrations were also calculated using the UK Equivalence Report recommended correction factor using the following equation:

$$DEFRA\_TEOM_{FDMS} = \frac{(FDMSBase + 2.061)}{1.360}$$

The results of this analysis are shown in Table 8, which includes measurements made during the UK Equivalence Programme to provide a wider concentration range for regression analysis. The results are also shown in Figure 16. Two sites (Marylebone Road and Thames Road) appear to be outliers and are highlighted. In most locations and years the KCL model predicts the annual mean concentration and the number of daily means greater than 50 µg m^{-3} better than the correction factor, however some of the differences are small.

		TEOM		KCL _$TEOM_{FDMS}$		DEFRA_$TEOM_{FDMS}$	
		Annual Mean	Daily means >= 50 µg m^{-3}	Annual Mean	Daily means >= 50 µg m^{-3}	Annual Mean	Daily means >= 50 µg m^{-3}
Acton Town Hall	2005	20	3	20	6	18	2
North Kensington	2004	15	0	12	0	14	0
	2005	15	2	15	3	15	4
Marylebone Road	2004	28	48	25	27	22	11
	2005	28	60	23	23	22	14
Belvedere	2004	17	2	15	2	15	1
	2005	16	3	14	1	15	1
Thames Road North	2004	25	23	18	10	18	4
	2005	22	12	17	9	17	6
Birmingham*	Instrument Pair 1	13	0	12	0	13	0
	Instrument Pair 2	13	0	12	0	13	0
Teddington*	Instrument Pair 1	15	0	14	0	15	0
	Instrument Pair 2	14	0	14	0	15	0
Bristol*	Instrument Pair 1	19	3	17	4	17	3
	Instrument Pair 2	18	3	18	4	17	3
East Kilbride*	Instrument Pair 1	8	0	8	0	10	0
	Instrument Pair 2	8	0	8	0	9	0

Table 8: Analysis of reconstructed TEOM measurements from the FDMS base measurement ($TEOM_{FDMS}$) using the FDMS purge measurement and the UK Equivalence Programme Report recommended correction factor. * Measurements from the UK Equivalence Programme.

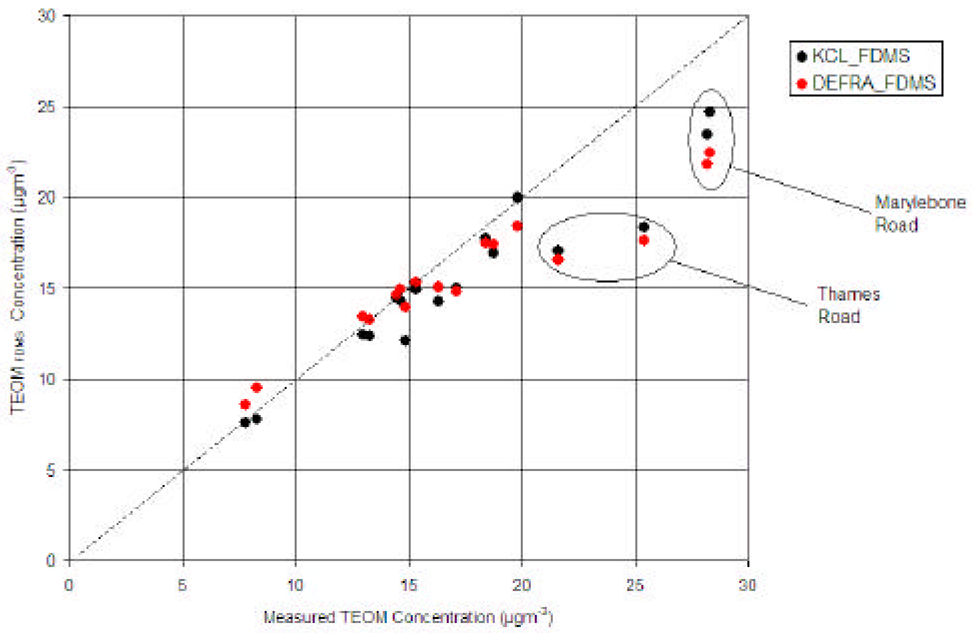

Figure 16: Scatter plot of measured annual mean TEOM PM_{10} concentration and reconstructed TEOM measurements from the FDMS base measurement ($TEOM_{FDMS}$) using the FDMS purge measurement (KCL_TEOM_{FDMS}) and the UK Equivalence Report recommended correction factor ($DEFRA\_TEOM_{FDMS}$)

		Slope	Intercept	R
All sites	KCL_TEOM_{FDMS}	0.78	1.96	0.96
	$DEFRA\_TEOM_{FDMS}$	0.60	5.05	0.95
Excluding Thames Road	KCL_TEOM_{FDMS}	0.83	1.35	0.98
	$DEFRA\_TEOM_{FDMS}$	0.65	4.57	0.98
Excluding Thames Road and Marylebone Road	KCL_TEOM_{FDMS}	0.96	-0.43	0.97
	$DEFRA\_TEOM_{FDMS}$	0.78	2.80	0.98

Table 9: RMA regression analysis results of the TEOM PM_{10} concentration and reconstructed TEOM measurements from the FDMS base measurement ($TEOM_{FDMS}$) with and without Thames Road and Marylebone Road

The RMA linear regression equation for all data pairs and excluding the Thames Road site and both the Marylebone Road and Thames Road data pairs are shown in Table 9. The Thames Road site has been identified as an outlier in Green and Fuller 2004, and in this report, probably due to the very localised effects of construction work at this site. The reason that Marylebone Road diverges from the 1:1 relationship is less clear. It may be due to an unknown artefact of the specific instruments (either TEOM or FDMS), a difference induced by the slightly different locations of the instruments (although equidistant from the road, the inlets are two metres apart) alternatively it may also be a genuine ambient effect that is only seen at heavily trafficked roadside sites. Until more instruments are deployed in such environments it is difficult to draw firm conclusions.

Nevertheless, the KCL model performs better than the UK Equivalence Report recommended correction factor under all circumstances, the slopes are closer to 1 and the intercepts are closer to zero. This is especially true at the higher and lower concentrations (Marylebone Road and East Kilbride respectively) as the purge measurement reflects an attribute of particle volatility, which is causing the difference between the two instruments, rather than a function of the total particulate mass. The KCL model will therefore be sensitive to site and seasonal variations that correction factors based on the total particulate mass will not. However, it would be prudent to continue some collocation studies to assess and changes in the relationship.

5. CONCLUSIONS

The need to measure PM_{10} concentrations that are equivalent to the gravimetric method in real time is major challenge for air quality monitoring networks; the FDMS instrument offers a proven means to meet this. As these instruments are installed in new monitoring sites and retrofitted to established monitoring sites, our understanding of FDMS measurements grow. During the first two years of their operation in the LAQN several difficulties were encountered and in some cases this impacted on data capture. A widening network of instruments, coupled to routine analysis has improved our understanding and enabled the rapid identification and repair of faults.

Comparison of measurements made using the FDMS, TEOM*1.3 and gravimetric instruments with the EU annual and daily limit values has revealed how a change in monitoring methodology will impact on compliance with national and EU legislation. For instance, Marylebone Road is one of the most polluted locations where PM_{10} measurements are made. Assessing the PM_{10} concentration using TEOM*1.3 (which is the current recommendation to provide a gravimetric equivalent measurement) during 2005 led to an annual mean of 43 $\mu g\ m^{-3}$ and 99 breaches of the daily limit value. The gravimetric measurements resulted in an annual mean of 44 $\mu g\ m^{-3}$ and 74 breaches of the daily limit value. Whereas, the FDMS measurements provided an annual mean of 31 $\mu g\ m^{-3}$ and 25 breaches of the daily limit value. Similar differences between gravimetric and FDMS measurements were seen at North Kensington, although the magnitude of these differences was lower. At both sites the difference between the instruments increased between 2004 and 2005. Therefore, using an FDMS to measure PM_{10} concentrations can result in a site meeting the air quality objectives while other methods indicate failure.

The two measurement cycles (base and purge) of the FDMS provide a better knowledge of the components of PM. In particular, the purge measurement offers an understanding of the volatile fraction and how this is consistent across London.

Ensuring that future measurements of PM_{10} made using the FDMS can be compared to historic measurements made using the TEOM was a subject for the UK Equivalence Programme for Monitoring of Particulate Matter; which recommended the application of a fixed correction factor. The collocated FDMS and TEOM instruments at North Kensington, Marylebone Road, Belvedere and Thames Road provided an ideal opportunity to test this correction factor. Analysis of the measurements made at these sites also revealed an association between the FDMS purge measurement and the difference between the FDMS base measurement and the TEOM. This provided an alternative method of reconstructing TEOM measurements from the FDMS base and purge measurement made using the FDMS (TEOM = FDMSBase + FDMSPurge). Examining the annual mean concentrations across a range of sites showed that this KCL method was an improvement on the DEFRA method at the highest and lowest concentrations, as it accounts for the volatile fraction by measurement rather than as a percentage of the total mass.

6. ACKNOWLEGEMENTS

The analysis in this report would not have been possible without the monitoring equipment and funding provided by the London Boroughs of Bexley, Greenwich and Ealing. Further monitoring equipment and infrastructure was provided by Westminster City Council, the Royal Borough of Kensington and Chelsea and the Department for Food and Rural Affairs and the Devolved Administrations.

7. SITE LOCATIONS

Details of all the sites used in this study are shown in the following sections.

Marylebone Road

Marylebone Road is a kerbside monitoring site in central London shown in Figure 17, grid reference 528120 182000, and is affiliated to the AURN. Marylebone Road is a major route in and out of Central London, running north-east to south-west and carries approximately 90,000 vehicles per day. The tall buildings on either side form a broad street canyon and 40m across. The monitoring cabin is located 1m from the kerb on the southern side of the road.

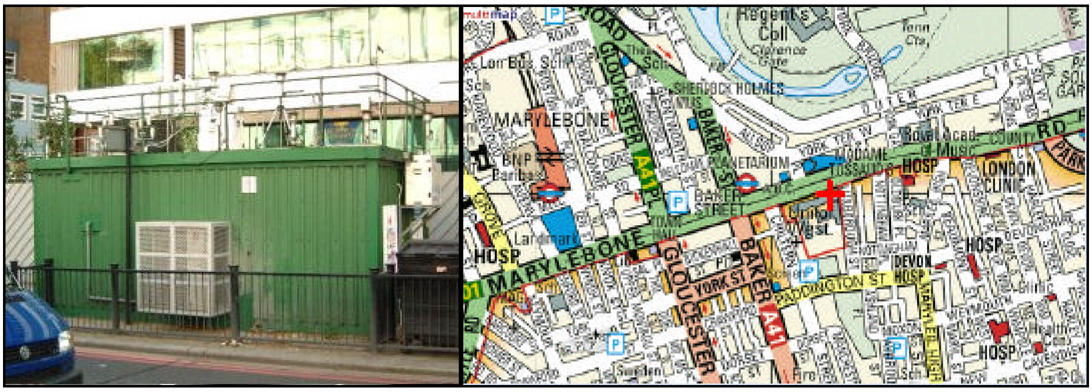

Figure 17: Marylebone Road site picture and location

North Kensington

North Kensington is an urban background monitoring site to the north and west of central London shown in Figure 18, grid reference 524040 181740, and is affiliated to the AURN.

Figure 18: North Kensington site picture and location

Millennium Village

Millennium Village is an urban background monitoring site to the south east of London shown in Figure 19, grid reference 540175 179000.

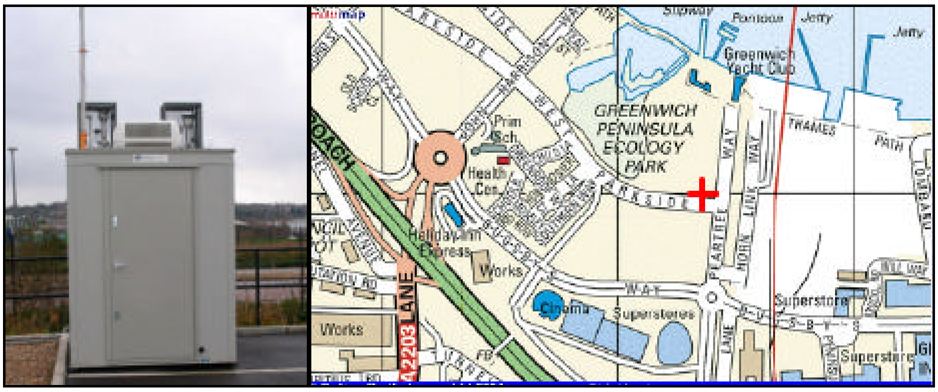

Figure 19: Millennium Village site picture and location

Westhorne Avenue

Westhorne Avenue is a roadside monitoring site to the south east of London shown in Figure 20, grid reference 541883 175016.

Figure 20: Westhorne Avenue site picture and location

Belvedere

Belvedere is a suburban monitoring site to the south east of London shown in Figure 21, grid reference 550000 179070.

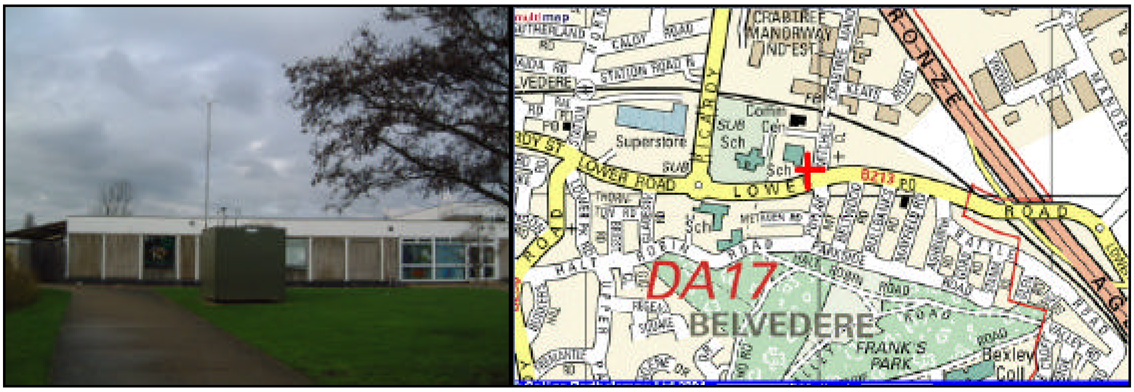

Figure 21: Belvedere site picture and location

Thames Road North

Thames Road North is a roadside monitoring site to the south east of London shown in Figure 22, grid reference 551862 176380. This site has been installed to monitor the changing pollution concentrations that result from the forthcoming conversion of the close by road to a dual carriageway.

Figure 22: Thames Road North site picture and location

Acton Town Hall

Acton Town Hall is a roadside monitoring site to the west of London shown in Figure 23, grid reference 520300 180050. This is a busy road with a junction nearby; two and three storey buildings form a street canyon.

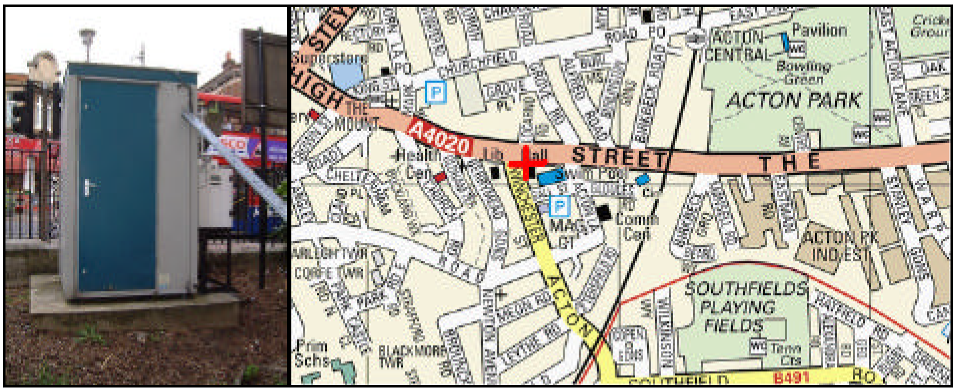

Figure 23: Acton Town Hall site picture and location

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