Re-assessment of the 250 µg m^{-3} action value

Work Package 1

Testing PM_{10} trigger values at construction sites

King's College London

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Contents

Summary

This study re-evaluates the particulate matter (PM_{10}) action level used in the Best Practice Guidance (BPG) (GLA-LC, 2006) and the Supplementary Planning Guidance (SPG) (GLA, 2014) for construction activities. The action level or trigger concentration of 250 µg m^{-3} measured as a 15 minute mean was based on analysis of a single construction site in 1999. Urban air pollution and measurement techniques have changed since this time.

Pollution measurements from nine construction sites were analysed using modern EU reference instruments. This dataset comprises 1.8 million measurements and is the largest analysis of construction PM_{10} to our knowledge. Construction sites are a clear source of local PM_{10} concentrations and many contribute to local breaches of EU limit values.

A revised trigger concentration of **190 µg m^{-3}** is recommended. This should be measured as an **hourly mean**.

This trigger limit can be used to indicate when PM_{10} from construction activities might be affecting local air quality. It can provide important near-real time feedback to operators enabling them to take rapid and responsive measures to control emissions as part of a dust emissions control plan. The trigger is not based on any health standards and does not indicate a breach of EU Limit Value concentrations or occupational limits, merely the presence of a construction source. This trigger will not be a perfect detector of construction emissions but false detections should be around 0.5% of construction days.

From our nine construction sites the worst case showed the trigger being exceeded on around one day in three. Three construction sites showed triggers being exceeded on more than one day in 12. By contrast, some sites showed no more than the expected false alarm rate. This shows that there is considerable scope for good site management practices to control construction dust. Even by controlling peak concentrations, to ensure that the trigger is not exceeded, local PM from construction might still increase by 4-5 µg m^{-3} as a median over the construction project.

Local PM_{10} from construction can also arise from dust resuspension from the road surface along haulage routes away from construction sites.

The analysis of this uniquely large dataset avoids the need for pre-scheme measurements to characterise urban PM_{10}. However care needs to be taken in rural settings where agricultural activities and local fires can give rise to exceedences of trigger values in the absence of construction activities.

The Greater London Authority's London Atmospheric Emissions Inventory (GLA-LAEI) 2010 included new calculations of emissions from construction activities with both construction activities and exhaust from non-road mobile machinery (NRMM). Investigation of possible effects of exhaust on ambient NO_X and NO_2 was possible at seven construction sites and NRMM exhaust was not detected in measurements made near site. Previous studies of construction in London did not detect NRMM $PM_{2.5}$. From this analysis we cannot determine which source is in error in the GLA-LAEI; the NRMM exhaust estimates or the construction PM_{10} estimate, but there is no evidence to support the ratios of these emissions given in the London inventory.

This first part of the study used evidence from high quality instruments that are used to measure air pollution for EU Directive assessment but these cannot be operated in most construction settings. A separate follow-on study will consider how the recommended trigger should be used with two commercially available instruments that are suitable to make high quality perimeter measurements around construction sites.

Introduction

1.1 Background

The Greater Local Authority (GLA) code of practice for construction emissions and that by the Institute for Air Quality Management (IAQM) have trigger limits to indicate when PM_{10} from construction activities might be affecting local air quality. Developers should respond to breaches of the trigger threshold by stopping work immediately and ensuring best practice measures are in place before restarting. With breaches of the PM_{10} trigger value local authorities can use their powers to prevent the statutory nuisance (GLA, 2014).

As used in the codes of practice, the 250 µg m^{-3} trigger value (15 minute mean) is designed to protect the local population from construction emissions. Anecdotal evidence from construction sites suggest that breaches of the trigger concentration do not always have an obvious cause and some have occurred outside working hours. Breaches of the 250 µg m^{-3} trigger value due to non-construction sources may cause undue concern to people living around the construction site and can be disruptive to construction activities. It is also possible that the 250 µg m^{-3} trigger value is missing some emissions sources from construction that could be controlled by better working practices. Alternative metrics based on hourly increments above a background were implemented at the Olympic Park and lower warning thresholds have been adopted at sites close to sensitive receptors, specifically a 200 µg m^{-3} as 15 minute means or 50 µg m^{-3} as hourly mean increments above the background (GLA, 2014, IAQM, 2012). To our knowledge these alternative metrics have not been assessed across a range of construction sites.

1.2 Where did the trigger value come from?

There are surprisingly few peer reviewed studies of emissions from construction activities. A small number of studies provide emissions estimates for modelling and assessments, and overall levels of construction in an area have also been assessed through calcium particle concentrations in urban air. The trigger value originates from research carried out by King's and published over ten years ago (Fuller & Green, 2004). The measurements used in the study were made between 1999 and 2001 using data from one monitoring site next to a construction project. The study highlighted the way in which construction works next to a monitoring site could lead to a breach of the EU Limit Value for PM_{10} but this very local effect should not imply that a city or urban area had a widespread PM_{10} problem.

Fuller & Green, 2004 analysed measurements from the Marylebone Road site during major refurbishment of the neighbouring University of Westminster during 1999. Measurements were made less than 5 m from the edge of the construction area. The frequency distribution of the 15 minute mean PM_{10} concentrations was compared to measurements in comparable periods before construction (Figure 1). During the preceding two years 15 minute mean concentrations did not exceed 250 µg m^{-3} but this value was exceeded during the construction work. The 250 µg m^{-3} was therefore used as a marker of construction emissions to allow them to be detected at other monitoring sites. The 250 µg m^{-3} was incorporated into construction code of practices as a method of detecting construction emissions distinct from PM from other urban sources. Given the good ability of the trigger to discriminate between construction and non-construction sources in the heavily trafficked Marylebone Road street canyon it should prove a good discriminatory test in less polluted environments. It also does not rely on comparing concentrations before the development with those during the construction period. The 250 µg m^{-3} threshold was not based on any health standards and does not indicate a breach of EU Limit Value concentrations or occupational limits, merely the presence of a construction source.

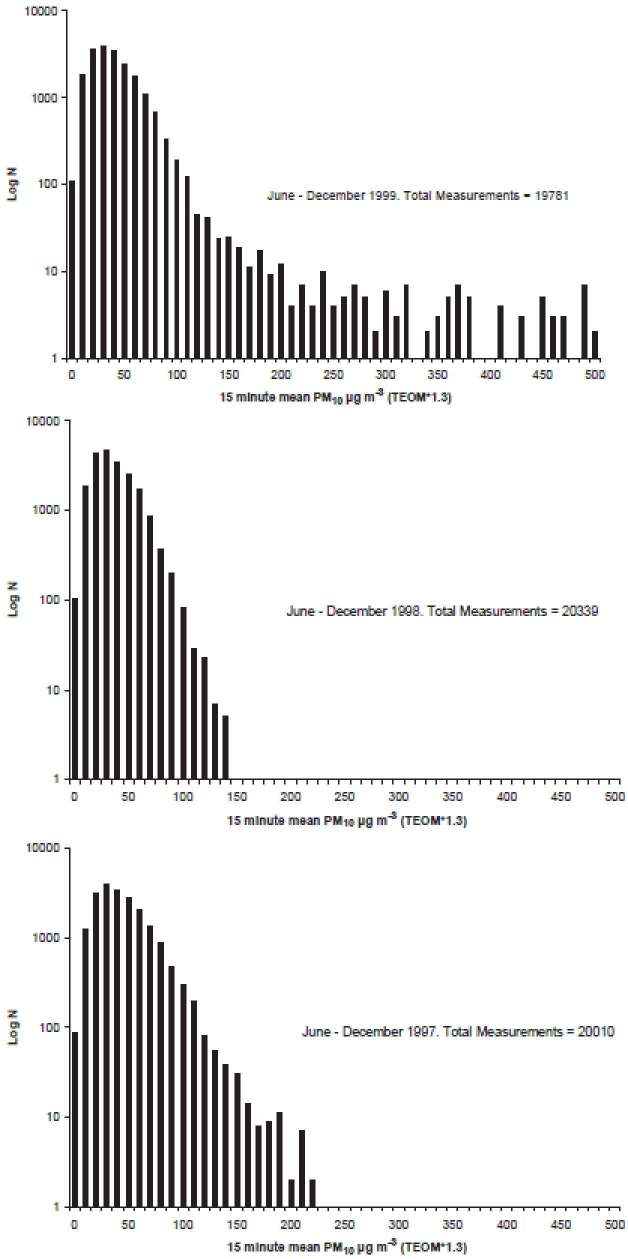

Figure 1. Frequency distribution of 15 min mean PM_{10} concentrations measured at Marylebone Road during the June–December 1999 construction period (top) and comparable periods in 1998 (middle) and 1997 (lower) before the construction took place. Extracted from Fuller and Green (2004).

1.3 Emissions inventory comparisons

The GLA's London Atmospheric Emissions Inventory (LAEI) for 2010 (GLA, 2013) included new calculations of emissions from construction activities. This divided emissions between construction dust and tailpipe emissions from non-road mobile machinery (NRMM); the former being a source of PM_{10} and the later being a source of NO_X and $PM_{2.5}$. On a mass basis for London the emission of NO_X from NRMM was 77 times the emission of PM_{10} from construction dust; $PM_{2.5}$ from NRMM was seven times the emission of PM_{10} from construction dust. These emission estimates gave rise to modelled areas of high concentrations of NO_X, NO_2 and $PM_{2.5}$ in certain areas of London including the City, Docklands and central Croydon due to large scale development projects.

1.4 Aims

Work package 1 of the project aims to:

- Test the efficacy of the 250 μg m^{-3} trigger to discriminate between construction and non-construction PM_{10} events using data from different types of construction projects using new EU reference equivalent PM measurements. The project also aimed to profile the concentration ranges that can be expected in rural, urban and roadside environments in and around London in the absence of construction through a dataset assembled from around ten construction sites.

- Test the efficacy of alternative PM_{10} metrics based on longer averaging times and also those based on incremental concentrations above the urban background. Assessment of the pros and cons of pre-scheme measurements were also included in the scope.

- Seek evidence for the impacts of construction on local concentrations of NO_X, NO_2 and $PM_{2.5}$ where these data were available.

2 Methods

2.1 Identifying the study sites

Ten monitoring sites close to construction projects were identified for analysis through searches on operational records from over 200 PM_{10} monitoring sites operated from King's College London (KCL) since 2004 (the earliest date for EU Reference PM_{10} measurements). These measurement sites are part of the UK Automatic Urban and Rural Network (AURN) and the London Air Quality Network (LAQN), networks used for compliance reporting against the EU Air Quality Directive. The study was designed to include a range of construction sites. It was agreed at the outset that the Marylebone Road 1999 dataset would be included in the analysis to enable continuity with the previous work. The test sites were selected to include a range of settings around London; roadside, urban, inner and outer London. Rural sites were included in the set of study sites since agricultural sources like combine harvesting and burning plant waste can give rise to localised peak concentrations that could confound a trigger based assessment. The sites that have been used in the study are summarized in Table 1. A description of each site and the nearby construction project can be found below.

A. Marylebone Road, Westminster, London, site code: MY1.
The Air Quality Monitoring site (AQMS) Marylebone Road (MY1) was a kerbside site located in central London next to a major arterial road with a daily mean traffic flow of ~85,000 vehicles. During 1999 refurbishment of an adjacent building took place, including demolition and re-roofing (seen in Figure 2). The impact of the construction activity on the PM_{10} measurements was evaluated in Fuller and Green (2004) and this site was included in the project for continuity of the previous assessment with the current methods.

Figure 2. Marylebone Air Quality Monitoring site. The white building in the background was extensively refurbished.

B. A206 Thames Road, Bexley, London, site codes: BX6, BX7, BX8.

The A206 Thames Road in Bexley was re-developed as a dual carriageway between January 2006 and August 2007 (Figure 3). The road improvements involved a 1.8 km section of the A206 Thames Road and were designed to reduce delays on the route and regenerate the area, the second-largest industrial area in London (Bexley, 2002). It was planned that around 25,000 m^3 of material would be brought in to construct the road and around 18,000 m^3 would be excavated. Two monitoring sites were located on opposite sides of the road (Bexley 7 in the east side; and Bexley 8 in the west) and measurements of PM_{10} and $PM_{2.5}$ (by TEOM), NO_X and NO_2 were evaluated in Font et al. (2014). PM_{10} measurements by FDMS were collocated at Bexley 7 and those were coded as Bexley 6.

Figure 3. Construction works during the road widening scheme in Thames Road, borough of Bexley.

C. Shepherd's Bush Greens, Hammersmith and Fulham, London, site code: HF4.

A new layout for Shepherd's Bush Green was implemented between November 2011 and May 2013. The scheme involved earthworks over 3.2 hectares, costing £2.6m. A picture of the evolution of the landscaping works is shown in Figure 4. The AQMS Hammersmith and Fulham 4 (HF4) was a kerbside site located only 10 metres away from Shepherd's Bush Green on the north side.

Figure 4. Picture of the Shepherd's Bush Green in July 2008 (left), April 2012 (middle) and May 2015 (right). Source: https://www.google.com/maps/@51.504698,-0.2246095,3a,75y,92.03h,89.01t/data=!3m6!1e1!3m4!1sluK-iu5Imaawp8rrjuL2ug!2e0!7i13312!8.

D. Upper Thames Street, City of London, site code: CT8.

The monitoring site (CT8) in Upper Thames Street was a roadside site in the City of London located under London Bridge. During September 2014 and March 2015 a ten storey office building on the north side of the road, in front of the monitoring station, was demolished and a new one is being constructed at the time of writing (Figure 5). Therefore post-scheme measurements have not been considered for this site.

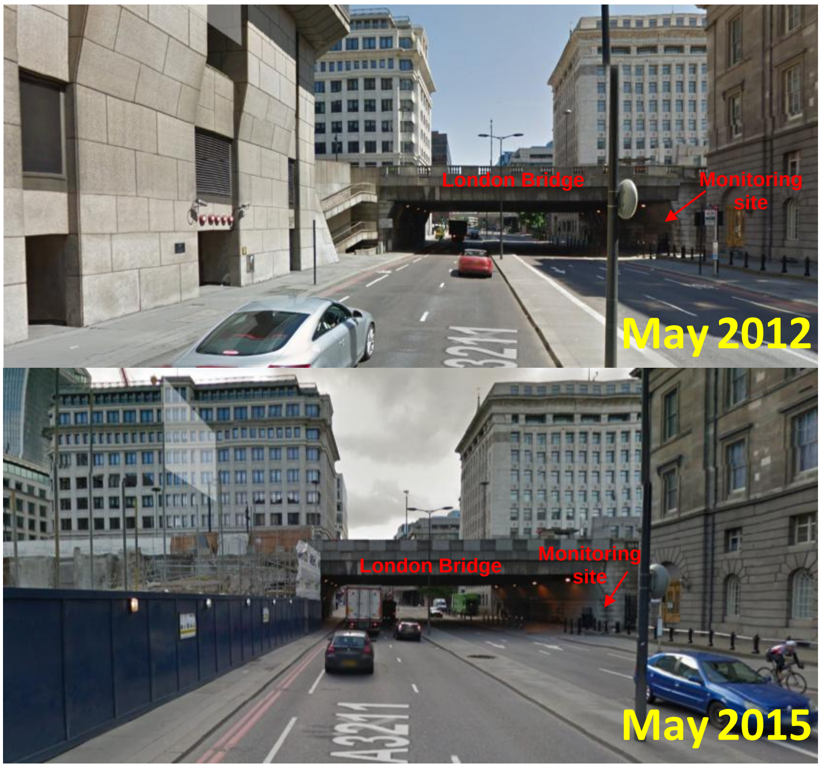

Figure 5. Pictures of the Upper Thames Road in May 2012 (top) and May 2015 (bottom). Source: https://www.google.com/maps/@51.5098174,-0.0878386,3a,75y,100.29h,87.54t/data=!3m6!1e1!3m4!1sjK_yWdkRiFJPPuVeqAcRrg!2e0!7i13312!8i6656

E. Devonshire Place, Eastbourne, site code: EB1

The Devonshire Place monitoring site (EB1) was located in a green square in Eastbourne. A new sub-electrical station was built next to the monitoring site between June and July in 2007 (Figure 6).

Figure 6. Location of the Air Quality Monitoring Station (AQMS) in Eastbourne, Devonshire Place, and new electrical sub-station.

F. Streatham Green, Streatham, London, site code: LB6.

A new pedestrian area was built next to Streatham Green at the confluence of Babington Road and Mitcham Lane. The Lambeth 6 monitoring site was enclosed in the construction area. The construction works lasted two weeks in February 2014. A picture of the area before and after the construction project was completed is shown in Figure 7 which also shows the location of the monitoring site.

Figure 7. Streatham Green before (top) and after (bottom) the completion of the pedestrianization of Babington Road with Mitcham Lane. Source: https://www.google.com/maps/@51.4282741,-0.1321411,3a,75y,142.04h,90t/data=!3m8!1e1!3m6!1sPdpR2S9iXafk8Z5s_Jervw!2e0!5s20140901T000000!6s%2F%2Fgeo0.ggpht.com%2Fcbk%3Fpanoid%3DPdpR2S9iXafk8Z5s_Jervw%26output%3Dthumbnail%26cb_client%3Dmaps_sv.tactile.gps%26thumb%3D2%26w%3D203%26h%3D100%26yaw%3D154.06017%26pitch%3D0!7i13312!8i6656

G. Shaftesbury Avenue, Camden, London, site code: CD3

The AQMS in Shaftesbury Avenue was a roadside site located at the junction of the A40 St Giles High Street and Shaftsbury Avenue. Two buildings of up to 15 floors in height with residential and retail use were constructed between 2007 and 2010. Figure 8 shows a picture of the area when the construction activity was taking place (October 2008) and after completion of the project (July 2012); the location of the AQMS Camden 3 (CD3) is also shown.

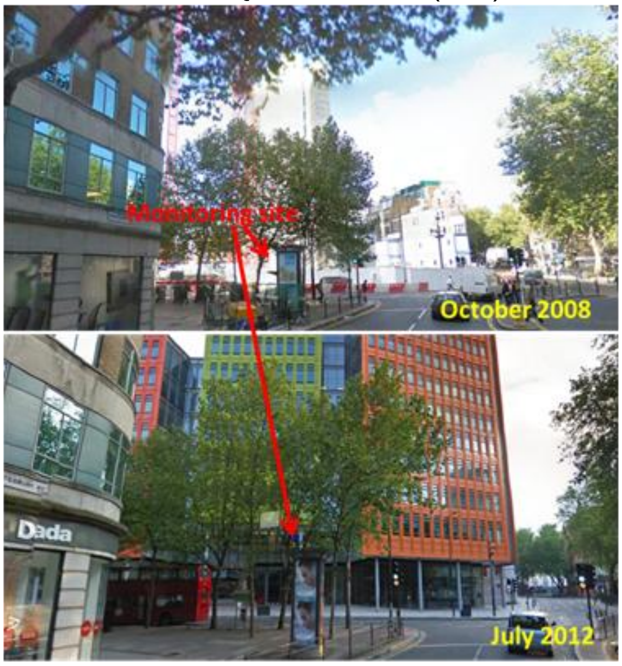

Figure 8. AQMS in Shaftesbury Avenue at the junction with St. Giles High Street during the redevelopment and after completion of the redevelopment scheme. Source: https://www.google.com/maps/@51.5154363,-0.1269035,3a,75y,346.87h,99.89t/data=!3m6!1e1!3m4!1sMO3iYgilICjXS9UWo4HEXw!2e0!7i13312!8i6656

H. Merton Road, South Wimbledon, London, site code: ME2.

The Merton Road AQMS (ME2)was located in a mixed residential and commercial street. Two residential developments took place close by: the demolition of a block of flats and its reconstruction by a housing association, 120 m NW of the AQMS; and the demolition of a large house and the construction of a block of 6 flats, 70 m N of ME2 (Figure 9). The latter involved substantial excavations to create a habitable floor below ground and landscaping.

Figure 9. Two construction projects took place in Merton Road between June 2011 and December 2013. The sites are indicated by the coloured arrows. The AQMS is located south on the left-hand pavement as viewed in above. Source: https://www.google.co.uk/maps/@51.4173792,-0.1925766,3a,75y,168.47h,79.39t/data=!3m7!1e1!3m5!1sSEne8uvSL42N64rvCfFcJA!2e0!5s20140901T000000!7i13312!8i6656

I . Blackheath Hill, Greenwich, London, site code: GR7.

A large housing estate was demolished and rebuilt on the south-side of Blackheath Hill in the borough of Greenwich, London. This took place in phases from 2010 to 2014 onwards (Figure 10). The main road between the construction site and the AQMS GR7 was part of the Mayor's dust suppressant trials between 16^{th} Oct 2011 and 8^{th} Mar 2012 with calcium magnesium acetate being applied to the road on 53 days. Local PM_{10} concentrations were found have decreased by 6 µg m^{-3} during this time (Barratt et al 2012).

Figure 10. Blocks of flats opposite the AQMS and shown in the LH panel in 2008 were demolished and a new housing estate built and shown in the right hand panel in 2014.

J. Rural measurement sites

With regulatory measurements focusing on urban areas, where people are exposed, there have been very few rural air pollution monitoring sites in the UK. No examples of construction projects could be found close to rural monitoring sites but typical concentrations were assessed to determine the applicability of construction dust triggers from urban datasets to rural settings. Two sites from southern England were selected for analysis, the Maidstone – Detling monitoring site, in a field on the North Downs; and a site in Stoke, Medway which is located in a school on the edge of a village. Both locations are in Kent (Figure 11).

Figure 11 The Maidstone - Detling monitoring site (left) and the Rochester- Stoke monitoring site (right).

Table 1. List of construction sites close to an Air Quality Monitoring Site (AQMS). Description of construction activity and air pollutants measured.

Construction activity	Construction site	Dates construction projects	Air quality monitoring site (AQMS) and code	Distance to construction (m)	Air pollutants measured
Refurbishment & external works to building	University of Westminster (London)	Jun - Dec 1999	Marylebone Road (MY1)	~5	PM_{10} (TEOM), NO_X, NO_2
Trunk road widening	A206, Thames Road (London)	Jan 2006 - Aug 2007	Bexley 6, Bexley 7, Bexley 8 (BX6, BX7, BX8)	~10	PM_{10} (TEOM, FDMS), $PM_{2.5}$ (TEOM), NO_X, NO_2
Landscaping, earthworks over 3.2 ha	Shepherds Bush Green (London)	Nov 2011 - May 2013	Hammersmith & Fulham 4 (HF4)	~10	PM_{10} (TEOM), NO_X, NO_2
Demolition of ten storey office building	Upper Thames Street (London)	6 Sept 2014 - 31 Mar 2015	City of London 8 (CT8)	~10	PM_{10} (TEOM)
Construction of electrical sub-station	Devonshire Place (Eastbourne)	3 Feb 2014 - 20 Feb 2014	Eastbourne 1 (EB1)	<5	PM_{10} (TEOM), NO_X, NO_2
New road junction layout and public area	Streatham Green (London)	28 Jan – 14 Feb 2014	Lambeth 6 (LB6)	0, within site area	PM_{10} (BAM)
Demolition & construction of 15 floor office (66Km^2), retail and residential	Central St Giles (London)	2007 to May 2010	Camden 3 (CD3)	~30	PM_{10} (TEOM), NO_X, NO_2
Demolition of house, excavation and construction of flats	Merton Road (London)	June 2011 – Dec 2013	Merton 2 (ME2)	~70-120	PM_{10} (BAM)
Phased demolition of blocks of flats and construction of new.	Blackheath Hill (London)	2010 to 2014	Greenwich 7 (GR7)	>10	PM_{10} (TEOM), NO_X, NO_2

2.2 Measurement instrumentation and methods

Particulate Matter (PM) with aerodynamic diameter < 10 µm (PM_{10}) and <2.5 µm ($PM_{2.5}$) were measured by TEOM-FDMS (Tapered Element Oscillating Microbalance - Filter Dynamics Measurement System); by TEOM and by MetOne BAM (Beta Attenuation Monitors). TEOM-FDMS measurements were considered equivalent to the EU reference method. PM_{10} measurements made by TEOM were converted to reference equivalent using the Volatile Correction Model (VCM) (Green, Fuller, & Baker, 2009) for measurements after 2004. TEOM measurements before 2004 were corrected for losses of semi-volatile particulate and particle bound water by applying the factor TEOM*1.3 (DETR, 1999). $PM_{2.5}$ measurements by TEOM were not corrected to reference equivalent as there is currently no agreed method for this. PM measurements by BAM were corrected to EU Reference equivalent using a factor of 1/1.2 (DEFRA-DA, 2010). The type of PM monitor used in each Air Quality Monitoring Site is summarized in Table 1.

Nitrogen oxides, NO_X (NO + NO_2), were measured by chemiluminiscence and fortnightly calibrations enabled the traceability of measurements to national metrological standards.

The time resolution of PM measurements varied according to the measurement method. PM concentrations measured by TEOM-FDMS and BAM were hourly means. PM measured by TEOMs was available as 15-minute mean concentrations, the same time base as NO_X concentrations.

All instruments (PM and NO_X) were subject to twice yearly audit tests by the National Physical Laboratory or Ricardo-AEA.

2.3 Setting a trigger threshold

Following the approach presented in Fuller and Green (2004), a simple statistical approach was applied to identify the PM_{10} concentrations from fugitive dust caused by building and road works separately from other PM sources. The approach used in Fuller and Green was based on the operational observation that construction works gave rise to short but intense periods of elevated PM_{10} concentrations. The maximum concentrations during construction at Marylebone Road were compared to two non-construction periods in the preceding years. The construction and non-construction periods where matched by time of year to control for the effects of seasonality in the analysis.

For the re-analysis in this project, PM_{10} measurements during construction works close to the Air Quality Monitoring Sites (AQMS) listed in Table 1 were compared to those PM_{10} measurements made during the same period in the preceding and following years (pre and post-scheme, respectively). However, due to some issues with data availability some sites had different pre and post time periods:

- Lambeth 6 (LB6): the pre and the post construction periods were taken two months before and two months after the construction period respectively since data was not available for the year before;
- Merton 2 (ME2): no pre-scheme period was taken into account since monitoring started in June 2011 coincidental with the start of the construction period;
- Hammersmith and Fulham 4 (HF4): the pre and post periods were taken as the six months before and following the project, respectively, since monitoring did not extend so far back in time.
- No post-scheme period was considered for City 8 (CT8) as the construction period continued beyond the time that this study was written;
- For continuity of Fuller and Green (2004), the pre-scheme period for Marylebone Road (MY1) AQMS was extended two years prior to the construction period.
- For those construction sites that operated over several years, each calendar year of construction was considered separately.

For each period of time (pre-scheme, construction period and post-scheme), the 50^{th} (median) 95^{th}, 99.7^{th} and 99.9^{th} percentiles; and the maximum PM_{10} concentration were calculated for the 15-minute and hourly mean concentrations. These percentile values indicate the threshold concentration that has 50%, 95%, 99.7% and 99.9% of the data set below it, respectively. Therefore, as the percentile value increases, the more likely the PM_{10} concentrations are to be associated with periodic peak fugitive emissions from the construction activity.

The calculations were undertaken on hourly and 15 minute PM_{10} means (the latter only for TEOM measurements) for:

1) The entire period of time;

2) Weekday days (Monday to Friday) between 7 am and 5 pm only, in accordance with the times of construction activities, excluding Bank Holidays;

3) The entire period of time removing the background concentration to calculate a local increment. For this, the concentrations of PM_{10}, NO_X and NO_2 measured at Kensington and Chelsea 1 - North Kensington (an urban background site located in central London) were used. $PM_{2.5}$ measurements from North Kensington started in 2008 therefore data from Bexley 2 – Belvedere (suburban background AQMS in SE London) were used instead. Eastbourne 3 was the only site outside London but local background concentrations were available and therefore London's background values were used instead. Local increments were calculated by subtracting background concentrations from those measured at the sites affected by construction projects each hour or 15 minutes as appropriate.

The calculation of the PM_{10} statistics for Bexley 6, Bexley 7 and Bexley 8 excluded those measurements when the wind blew from the NE (45^o to 120^o) to remove the confounding influence of PM_{10} resuspension from an unpaved road located just NE of the AQMS. Further details can be obtained from Font et al. (2014).

2.4 Statistics in rural areas

The 50^{th} (median) 95^{th}, 99.7^{th} and 99.9^{th} percentiles; and the maximum PM_{10} concentration were calculated on annual basis for the 15-minute and hourly mean concentrations for the two monitoring sites located in rural areas outside London: Maidstone – Detling and Stoke. The sites measured PM_{10} by TEOM prior 2010 and 2009, respectively, measuring at a 15 minute mean resolution. After that, the instruments were upgraded to a TEOM-FDMS, reporting mass concentrations on an hourly basis.

2.5 Diurnal and day of week variation in local increments

PM_{10}, $PM_{2.5}$, NO_X and NO_2 hourly increments were averaged to create hour of day and day of week mean concentrations for the construction and non-construction periods for each of the AQMS.

Changes in the mean concentration of PM_{10} compared to that of $PM_{2.5}$ and NO_X could then be used to determine the emissions ratio of construction PM (assumed to be PM_{10}) to that from the exhaust from non-road mobile machinery (NRMM) used in the construction activity.

3 Results and discussion

3.1 PM_{10} from construction sites

Full statistical summaries for each construction location for 15 minute and hourly mean PM_{10} measurements can be found in Table 2 and Table 3, respectively.

Comparing construction with non-construction periods, the impacts of PM10 from construction are not always apparent in the median and 95th percentiles at every construction site. However, CT8 and GR7 observed an increase in their median concentrations of about 14% (CT8) and between 11% and 33% (GR7) compared with the median concentration in the pre-scheme period.

The impact of fugitive emissions from construction is most apparent in the highest 0.3% of the PM_{10} measurements. The greatest high percentile values during construction were measured at Marylebone Road (MY1) and Eastbourne (EB1), with 99.9th percentiles over 480 µg m^{-3} as 15 minute means, reflecting the proximity of the monitoring sites to the construction projects (< 5 m). This suggests that distance between source and receptor is important. The sites that observed the smallest increase in their 99.9th percentile as 15 minute means were CT8, CD3 and GR7 with values less than 205 µg m^{-3} as 15 minute means. For CD3 and GR7 where the construction projects lasted for several years, increases in the 99.9th percentile PM_{10} concentrations were largely limited to the first two years when demolition was likely to have taken place.

The largest separation between monitoring and construction site was at ME2. Here analysis of concentrations by wind speed and direction (not shown) suggest that additional local PM_{10} during the construction period did not arise from within the construction site boundary but from the roadway. It is possible this additional local PM_{10} was caused by resuspension of material tracked from the construction site.

With the exception of CD3, hourly mean concentrations exhibited a similar behaviour to 15 minute means. CD3 observed an increase in the 99.9th percentile of 15 minute means during the construction period which was not apparent in the hourly means.

It appears that measures to avoid peak concentrations at Upper Thames Street and Blackheath Hill projects did not adequately control for increases in the 50th percentile measured in the nearest AQMS (CT8 and GR7, respectively) which increased by around 4-5 µg m^{-3}.

Table 2. Statistical summary for the 15 minute mean PM_{10} measurements at each measurement site using different selection criteria. Measurements have been divided between pre and post construction and also the construction period itself.

Site	Start date	End date	Case	All times 50th p	All times 95th p	All times 99.7th p	All times 99.9th p	All times Max	Construction times 50th p	Construction times 95th p	Construction times 99.7th p	Construction times 99.9th p	Construction times Max	Increments above background 50th p	Increments above background 95th p	Increments above background 99.7th p	Increments above background 99.9th p	Increments above background Max
MY1	01-Jun-1997	31-Dec-1997	Pre scheme	44	93	157	192	225	60	110	170	198	225	15	47	76	94	187
MY1	01-Jun-1998	31-Dec-1998	Pre scheme	38	75	111	125	145	53	89	125	135	145	14	43	66	78	111
BX7	02-Jan-2004	31-Aug-2005	Pre scheme	21	54	124	188	437	25	62	134	207	437	3	21	88	144	367
BX8	02-Jan-2004	31-Aug-2005	Pre scheme	18	45	89	133	650	21	50	92	116	650	0	15	54	92	598
HF4	11-Sep-2011	21-Mar-2012	Pre scheme	32	68	105	127	289	39	74	119	144	289	10	30	59	81	252
CT8	06-Sep-2013	31-Mar-2014	Pre scheme	31	73	127	148	402	45	91	143	186	402	11	47	98	120	385
EB1	24-May-2006	31-Aug-2006	Pre scheme	20	45	87	99	119	22	49	92	103	116	-2	13	30	42	86
CD3	01-Jan-2006	31-Dec-2006	Pre scheme	28	63	113	144	878	34	70	115	136	172	7	25	50	69	846
GR7	01-Jan-2009	31-Dec-2009	Pre scheme	21	52	91	105	114	23	57	105	112	114	3	18	40	50	70
MY1	01-Jun-1999	31-Dec-1999	Construction	41	91	546	788	1657	60	132	790	1129	1657	14	57	518	755	1645
BX7	02-Jan-2006	31-Aug-2007	Construction	22	69	196	281	816	27	93	246	343	816	4	34	157	240	779
BX8	02-Jan-2006	31-Aug-2007	Construction	19	55	131	179	2790	21	67	150	191	2790	1	19	79	128	2775
HF4	22-Mar-2012	30-Sep-2012	Construction	33	103	251	331	616	57	147	336	408	616	15	85	236	319	599
CT8	06-Sep-2014	31-Mar-2015	Construction	36	90	162	205	281	53	113	203	239	281	17	70	142	182	263
EB1	24-May-2007	31-Aug-2007	Construction	16	38	205	488	880	20	55	455	656	880	0	19	162	363	730
CD3	01-Jan-2007	31-Dec-2007	Construction	29	67	121	189	6888	36	76	142	255	1471	9	31	82	154	6875
CD3	01-Jan-2008	31-Dec-2008	Construction	27	60	124	176	680	34	72	154	287	528	6	28	85	153	660
CD3	01-Jan-2009	31-Dec-2009	Construction	28	58	111	158	900	33	68	144	226	900	7	28	77	134	849
CD3	01-Jan-2010	31-Dec-2010	Construction	27	53	103	134	696	33	60	118	160	696	8	26	73	115	668
GR7	01-Jan-2010	31-Dec-2010	Construction	25	56	97	183	575	29	63	111	209	575	7	22	56	139	555
GR7	01-Jan-2011	31-Dec-2011	Construction	28	66	129	141	172	32	72	126	156	172	8	24	49	62	127
GR7	01-Jan-2012	31-Dec-2012	Construction	24	61	103	110	154	28	69	106	115	154	8	26	52	60	99
GR7	01-Jan-2013	31-Dec-2013	Construction	26	62	95	113	538	29	70	112	128	538	7	26	49	62	530
GR7	01-Jan-2014	31-Dec-2014	Construction	23	57	99	114	132	25	59	107	119	132	7	20	40	51	79
MY1	01-Jun-2000	31-Dec-2000	Post scheme	44	90	141	207	1453	66	103	162	549	1453	19	61	106	182	1427
BX7	02-Jan-2008	31-Aug-2009	Post scheme	20	48	98	128	625	24	54	127	190	625	3	19	51	82	608
BX8	02-Jan-2008	31-Aug-2009	Post scheme	17	44	91	107	208	19	48	106	118	191	0	14	46	67	158
HF4	01-Oct-2012	11-Apr-2013	Post scheme	24	54	93	113	164	30	62	109	124	164	5	31	62	75	163
EB1	24-May-2008	31-Aug-2008	Post scheme	16	38	66	95	810	16	38	98	531	810	-1	14	44	71	777
CD3	01-Jan-2011	31-Dec-2011	Post scheme	28	64	122	170	620	32	70	139	181	407	7	24	83	148	579
GR7	01-Jan-2015	31-Dec-2015	Post scheme	22	53	92	107	138	24	58	102	109	138	8	28	59	74	136

Table 3. Statistical summary for the hourly mean PM_{10} measurements at each measurement site using different selection criteria. Measurements have been divided between pre and post construction and also the construction period itself.

Site	Start date	End date	Case	50th p	95th p	99.7th p	99.9th p	Max	50th p	95th p	99.7th p	99.9th p	Max	50th p	95th p	99.7th p	99.9th p	Max
				All times					Construction times					Increments above background				
MY1	01-Jun-1997	31-Dec-1997	Pre scheme	45	92	159	181	217	61	109	167	183	189	15	45	72	81	132
MY1	01-Jun-1998	31-Dec-1998	Pre scheme	38	74	105	119	134	54	88	119	126	134	14	42	59	70	91
BX6	02-Jan-2004	31-Aug-2005	Pre scheme	18	50	90	142	313	21	55	91	120	201	0	16	49	93	173
BX7	02-Jan-2004	31-Aug-2005	Pre scheme	21	54	109	145	337	25	60	120	139	150	3	20	71	108	198
BX8	02-Jan-2004	31-Aug-2005	Pre scheme	18	45	83	131	362	21	48	86	94	311	0	13	44	73	261
HF4	11-Sep-2011	21-Mar-2012	Pre scheme	32	67	102	125	155	38	74	111	147	155	10	29	55	77	118
CT8	06-Sep-2013	31-Mar-2014	Pre scheme	32	71	120	139	157	46	90	140	155	157	11	45	92	108	140
EB1	24-May-2006	31-Aug-2006	Pre scheme	20	44	84	96	105	22	49	87	95	102	-2	11	23	34	40
LB6	28-Nov-2013	27-Jan-2014	Pre scheme	15	41	69	79	92	18	46	80	87	92	-3	10	31	52	74
CD3	01-Jan-2006	31-Dec-2006	Pre scheme	28	62	111	133	256	34	69	107	128	135	7	23	42	54	223
GR7	01-Jan-2009	31-Dec-2009	Pre scheme	21	52	91	105	114	23	57	105	112	114	3	17	38	49	68
MY1	01-Jun-1999	31-Dec-1999	Construction	41	91	523	715	1041	61	138	724	963	1041	14	57	493	690	1017
BX6	02-Jan-2006	31-Aug-2007	Construction	18	61	153	217	468	22	79	184	232	411	1	25	104	167	372
BX7	02-Jan-2006	31-Aug-2007	Construction	22	68	183	251	484	28	92	222	277	327	4	33	141	209	330
BX8	02-Jan-2006	31-Aug-2007	Construction	19	54	118	151	782	21	65	128	148	782	1	18	66	94	769
HF4	22-Mar-2012	30-Sep-2012	Construction	33	103	225	279	332	59	145	279	317	332	15	84	208	264	316
CT8	06-Sep-2014	31-Mar-2015	Construction	36	89	156	179	241	54	109	180	218	241	17	68	129	152	203
EB1	24-May-2007	31-Aug-2007	Construction	16	38	178	354	528	20	61	355	466	528	0	19	129	239	431
LB6	28-Jan-2014	11-Feb-2014	Construction	13	55	278	326	353	15	177	326	344	353	0	35	264	314	340
CD3	01-Jan-2007	31-Dec-2007	Construction	30	65	116	145	2858	36	75	128	159	432	9	29	71	131	2844
CD3	01-Jan-2008	31-Dec-2008	Construction	27	59	111	132	308	35	69	127	138	308	7	25	64	101	288
CD3	01-Jan-2009	31-Dec-2009	Construction	28	56	104	117	441	34	67	116	164	441	7	26	66	84	387
CD3	01-Jan-2010	31-Dec-2010	Construction	27	52	85	100	201	33	59	93	104	201	8	25	61	71	175
ME2	01-Jan-2013	31-Dec-2013	Construction	26	64	129	168	804	31	77	152	219	804	8	31	99	151	787
GR7	01-Jan-2010	31-Dec-2010	Construction	25	56	97	173	575	29	63	109	190	575	7	21	54	125	553
GR7	01-Jan-2011	31-Dec-2011	Construction	28	66	128	141	172	32	72	126	148	172	8	23	48	61	125
GR7	01-Jan-2012	31-Dec-2012	Construction	24	61	103	110	154	28	69	106	112	154	8	25	51	60	85
GR7	01-Jan-2013	31-Dec-2013	Construction	26	62	95	113	538	29	70	112	127	538	7	26	49	62	530
GR7	01-Jan-2014	31-Dec-2014	Construction	23	57	98	113	132	25	59	106	118	132	7	19	38	50	75
MY1	01-Jun-2000	31-Dec-2000	Post scheme	45	90	139	192	901	67	102	161	351	901	19	60	100	203	876
BX6	02-Jan-2008	31-Aug-2009	Post scheme	19	48	92	118	413	22	51	110	143	413	2	16	42	59	395
BX7	02-Jan-2008	31-Aug-2009	Post scheme	20	48	94	127	221	24	53	125	149	221	3	17	45	68	204
BX8	02-Jan-2008	31-Aug-2009	Post scheme	17	43	83	98	114	19	46	92	110	114	0	12	36	51	75
HF4	01-Oct-2012	11-Apr-2013	Post scheme	24	53	90	111	144	30	62	109	114	144	5	31	58	66	106
EB1	24-May-2008	31-Aug-2008	Post scheme	16	36	65	172	349	16	36	176	298	349	-1	12	45	135	312
LB6	12-Feb-2014	12-Apr-2014	Post scheme	17	60	88	108	112	21	69	108	112	112	-3	10	45	52	78
CD3	01-Jan-2011	31-Dec-2011	Post scheme	28	62	113	135	283	33	66	123	145	156	7	22	67	115	244
ME2	01-Jan-2014	31-Dec-2014	Post scheme	23	58	109	171	296	28	68	163	225	296	7	30	91	153	284
GR7	01-Jan-2015	31-Dec-2015	Post scheme	22	53	92	107	138	24	58	101	109	138	7	27	58	72	133

3.2 Evaluation of the PM_{10} trigger

The distribution of the PM_{10} measurements as 15 minute means and as hourly means for the pre-scheme, construction and post-scheme periods for Hammersmith and Fulham 4 (HF4) is shown as an example in the form of a histogram using all data available (Figure 12), using data during construction hours (Figure 13) and increments above the background (Figure 14). Data for the other sites are not represented graphically but data is summarized in Table 3. It is clear that there was an increase in the occurrences of very high PM_{10} concentrations (>250 µg m^{-3}) measured at this AQMS during the construction phase that were not seen in the pre-scheme times (Figure 12a) and not observed in the post-scheme period (Figure 12c,f). The 99.7th and 99.9th percentiles measured during the construction period (251 and 331 µg m^{-3} as 15 minute means; and 225 and 279 µg m^{-3} as hourly means) were not observed in the other periods of time. The impact of fugitive emissions due to construction on PM_{10} concentrations was most apparent in the highest 0.3% of the data. In a similar way, the 99.7th and 99.9th percentiles for the PM_{10} measurements during construction hours and PM_{10} increments above the background were not exceeded outside the construction period (Figure 13 and Figure 14) indicating that the use of these very high percentile concentrations is as a good indicator to mark PM_{10} due to fugitive dust.

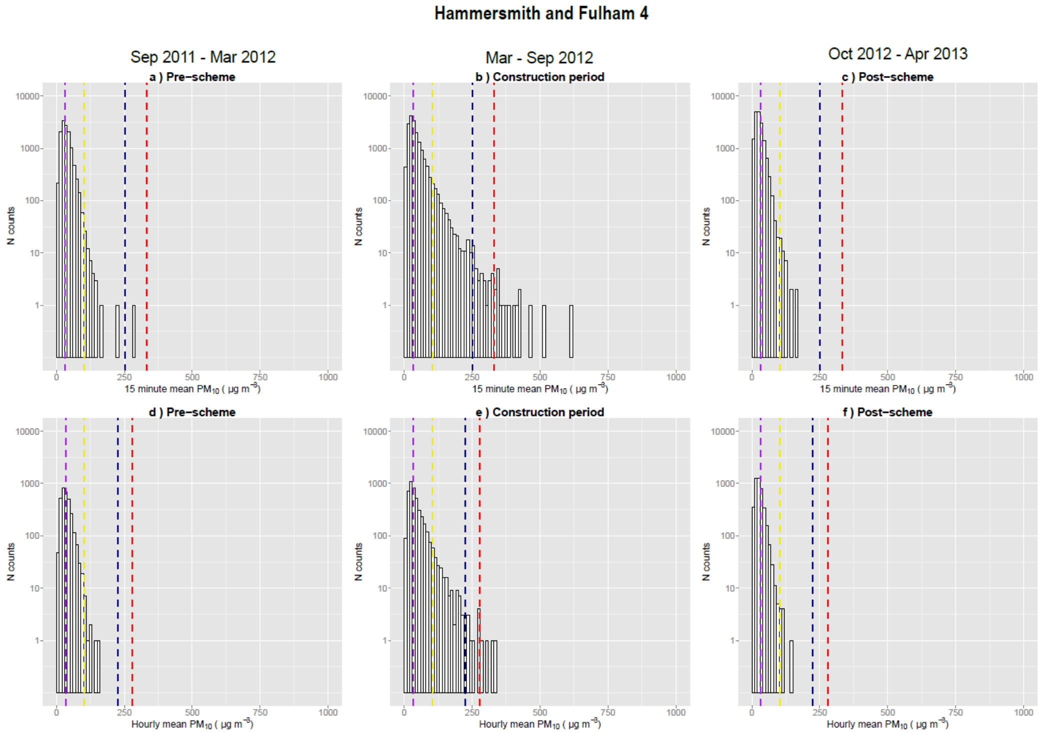

Figure 12. Frequency of 15 minute (a-c) and hourly (d-f) PM_{10} concentrations measured at Hammersmith and Fulham 4 during September 2011 to March 2012 (pre-scheme), march to September 2012 (construction period) and October 2012 to April 2013 (post-scheme). The number of PM_{10} measurements (N counts) have been counted for each 10 µg m^{-3} bin. The 50^{th}, 95^{th}, 99.7^{th} and 99^{th} percentile of PM_{10} measurements during the construction period are represented in purple, yellow, blue and red, respectively, and represented in the pre and post-scheme histograms.

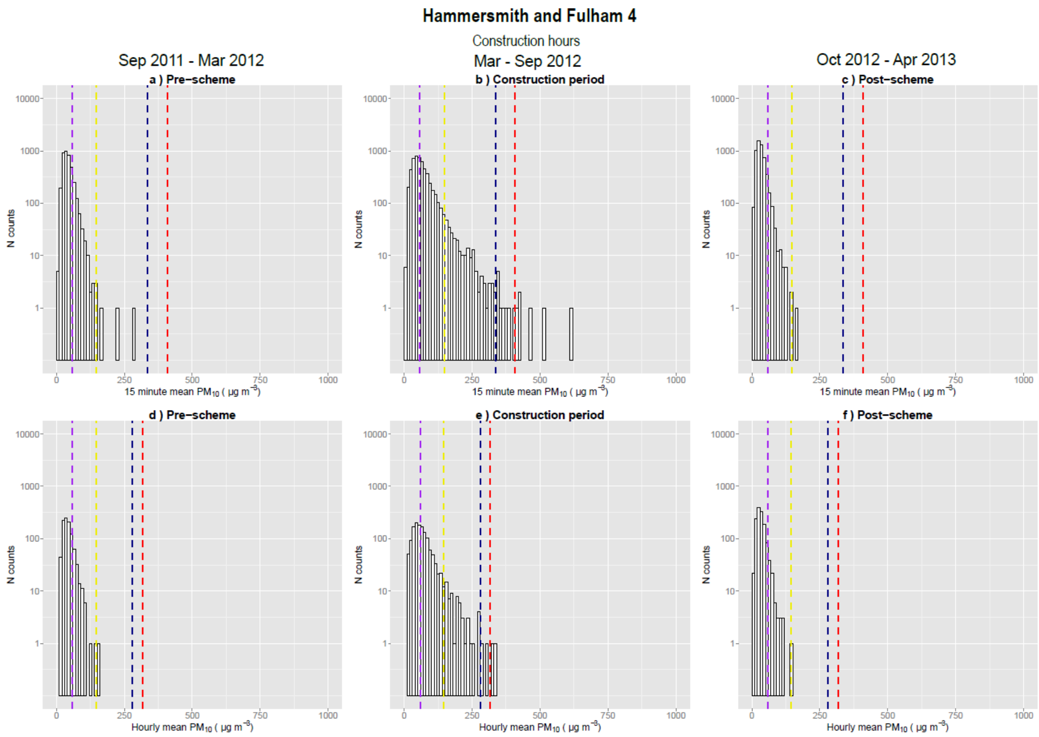

Figure 13. Frequency of 15 minute (a-c) and hourly (d-f) PM_{10} concentrations measured at Hammersmith and Fulham 4 during September 2011 to March 2012 (pre-scheme), march to September 2012 (construction period) and October 2012 to April 2013 (post-scheme) during working hours: Monday to Friday from 7 am to 5 pm (excluding Bank Holidays). The number of PM_{10} measurements (N counts) have been counted for each 10 µg m^{-3} bin. The 50^{th}, 95^{th}, 99.7^{th} and 99^{th} percentile of PM_{10} measurements during the construction period are represented in purple, yellow, blue and red, respectively, and represented in the pre and post-scheme histograms.

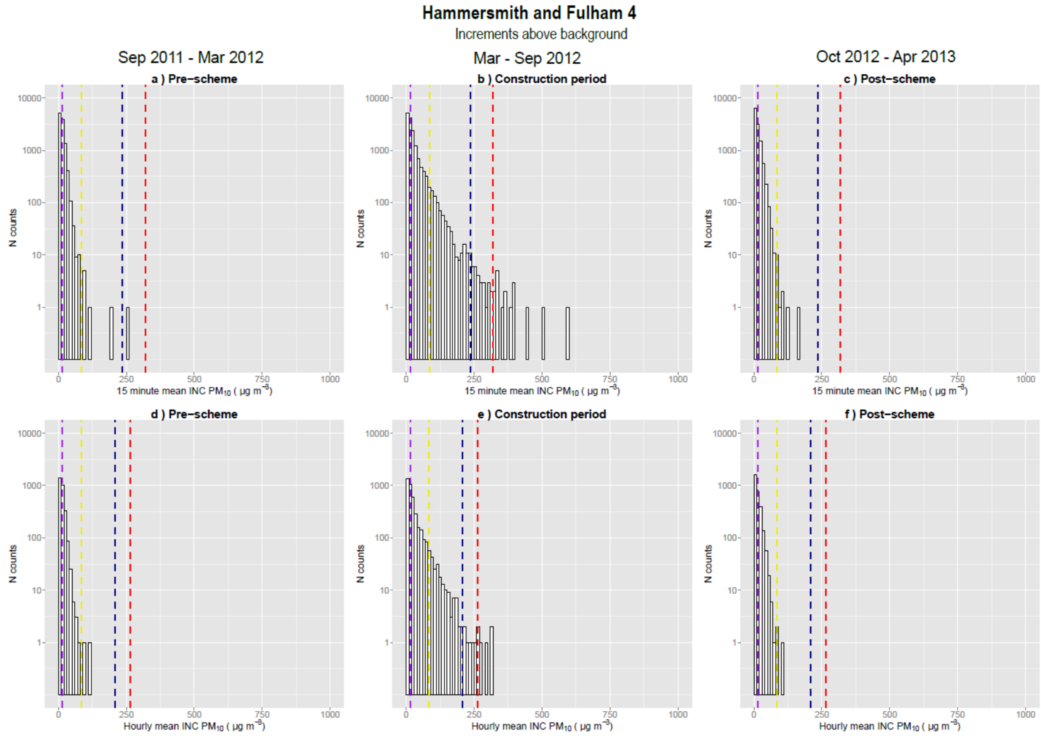

Figure 14. Frequency of 15 minute (a-c) and hourly increments (d-f) of PM_{10} concentrations above background (INC PM_{10}) measured at Hammersmith and Fulham 4 during September 2011 to March 2012 (pre-scheme), march to September 2012 (construction period) and October 2012 to April 2013 (post-scheme). The number of PM_{10} measurements (N counts) have been counted for each 10 µg m^{-3} bin. The 50^{th}, 95^{th}, 99.7^{th} and 99^{th} percentile of INC PM_{10} measurements during the construction period are represented in purple, yellow, blue and red, respectively, and represented in the pre and post-scheme histograms.

Some of the sites used in this study recorded concentrations higher than the 99.9^{th} percentile trigger during non-construction periods. For instance, Figure 15 shows the frequency of PM_{10} concentrations measured at Devonshire Place, in Eastbourne (EB1), during the short construction period (24^{th} May to 31^{st} August 2007) and those for the same period of time for the year before and after (May – August 2006; and May – August 2008) for the 15 minute (a-c) and hourly mean concentrations (d-f).The 99.9^{th} percentile concentration recorded at EB1 (488 µg m^{-3} and 354 µg m^{-3} as 15 minute and hourly means, respectively; all data considered) was not observed in the pre-scheme period but some high PM occurrences took place in the post-scheme period.

The 99.9^{th} percentile was therefore selected to establish a trigger value using PM_{10} concentrations measured at 15-minute and hourly means for the three criteria. This was selected as a balance against setting the threshold based on a single maximum value that would not be representative of other construction sites; but high enough to be representative of the impacts of construction activities. Setting the PM_{10} trigger based on a lower percentile would have led to a high number of misidentifications. Those would lead to unnecessary false alarms on site and unnecessary construction delays due to non-construction PM sources. The use of the 99.9^{th} percentiles set a one in a thousand occurrence of a identifying a construction peak during the non-construction periods. At this percentile a monitoring site without construction PM would be expected to exceed the trigger for between 8 and 9 hours per year unrelated to construction activities.

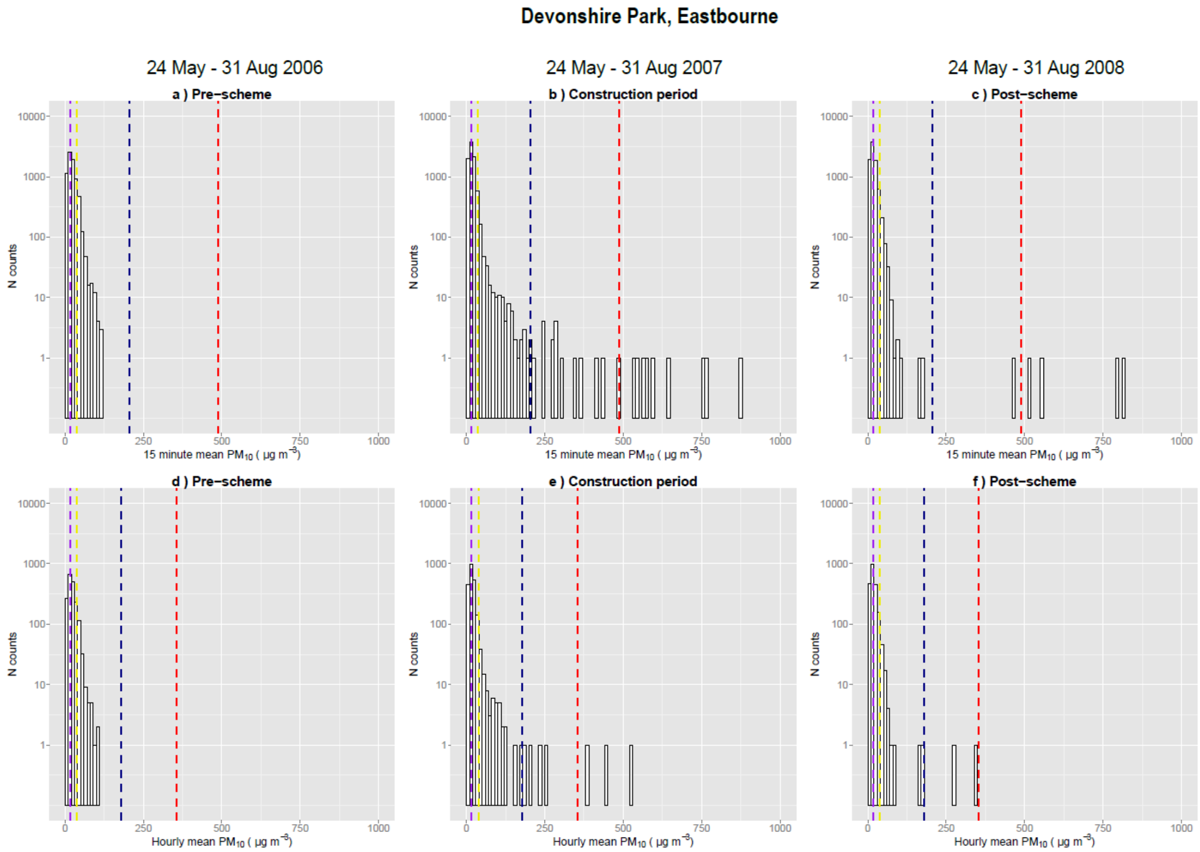

Figure 15. Frequency of 15 minute (a-c) and hourly (d-f) PM_{10} concentrations measured at Devonshire Park, Eastbourne during May to August 2006 (pre-scheme), 2007 (construction period) and 2008 (post-scheme). The number of PM_{10} measurements (N counts) have been counted for each 10 µg m^{-3} bin. The 50^{th}, 95^{th}, 99.7^{th} and 99^{th} percentile of PM_{10} measurements during the construction period are represented in purple, yellow, blue and red, respectively, and represented in the pre and post-scheme histograms.

The 99.9^{th} percentile for the pre-construction, construction and post-construction periods for the 15 minute and hourly means for the three selection criteria (all times; working times; and increments above the background) are shown in Figure 16 to Figure 18. The greatest values for the pre and post scheme 99.9^{th} percentiles were less than 190 µg m^{-3} for both the 15 minute and hourly mean metrics. These were mainly determined by the pre and post scheme measurements at Marylebone Road (MY1), Thames Road (BX6, BX7, BX8), Upper Thames Street (CT8) and Shaftesbury Avenue (CD3). High post scheme measurements were measured in the short dataset at Devonshire Park, Eastbourne (EB1) but this was down weighted in our assessment due to the short dataset. High post-scheme measurements were also measured at Merton Road (ME2) due to high spikes of PM_{10} measured during 10 days in February 2014 with concentrations up to 295 µg m^{-3} which was mostly likely due to construction or local road works. A similar situation arose in the post construction period at Marylebone Road as identified in the work that led to Fuller and Green (2004).

For the vast majority of the time, the 99.9^{th} percentile PM_{10} increments above the background were lower than 120 µg m^{-3} for the pre and post construction periods. Only two of the sites recorded 99^{th} percentile increments > 120 µg m^{-3} during the post construction times, again MY1 EB1 and ME2.

A trigger value of 190 µg m^{-3} is therefore proposed for 15 minute and hourly mean metrics; and a lower maximum of 120 µg m^{-3} is proposed for incremental measurements.

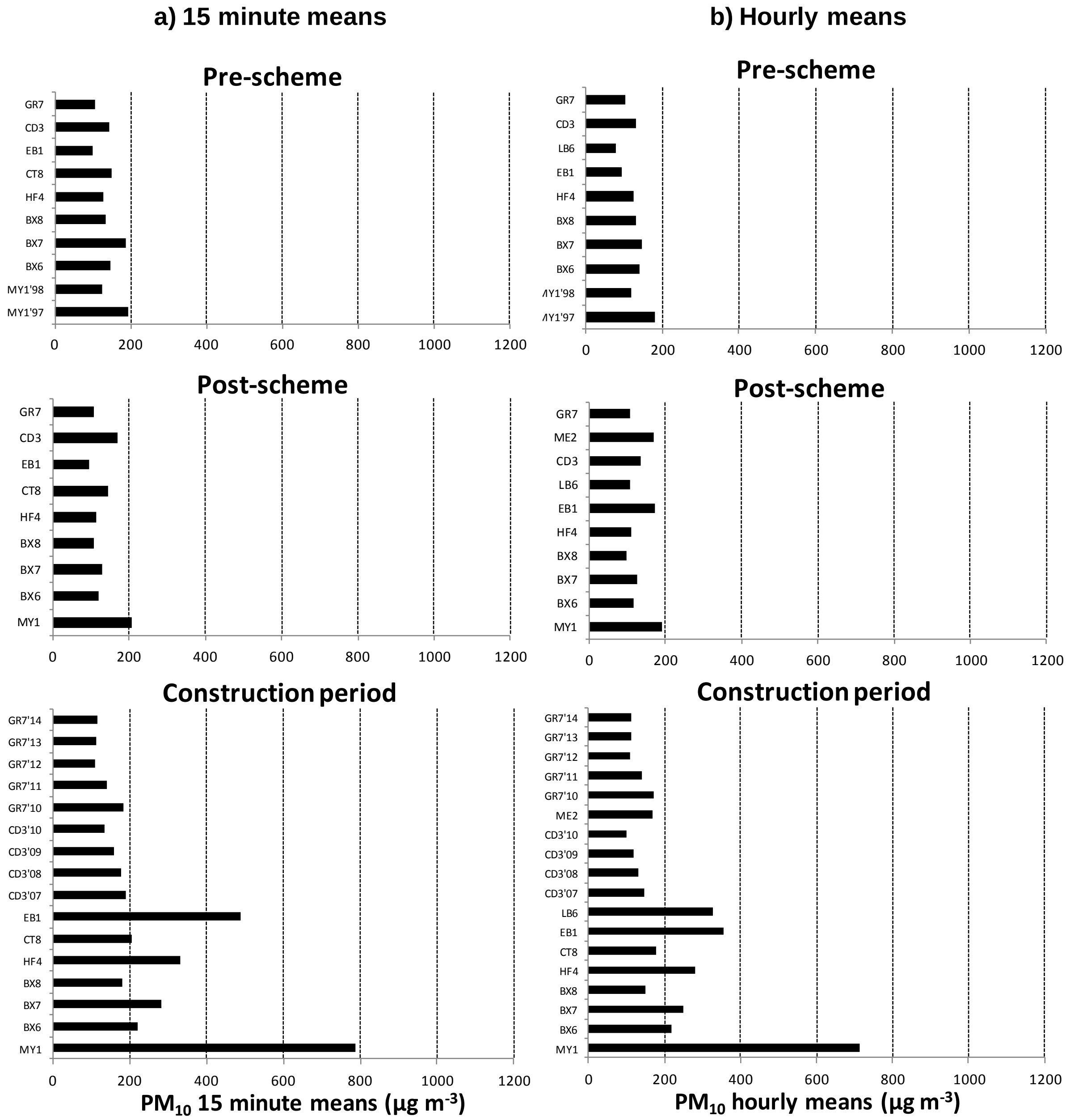

Figure 16. Percentile 99.9 for the a)15-minute means and b) hourly PM_{10} measurements during the pre-scheme, post-scheme and construction periods at the selected monitoring sites.

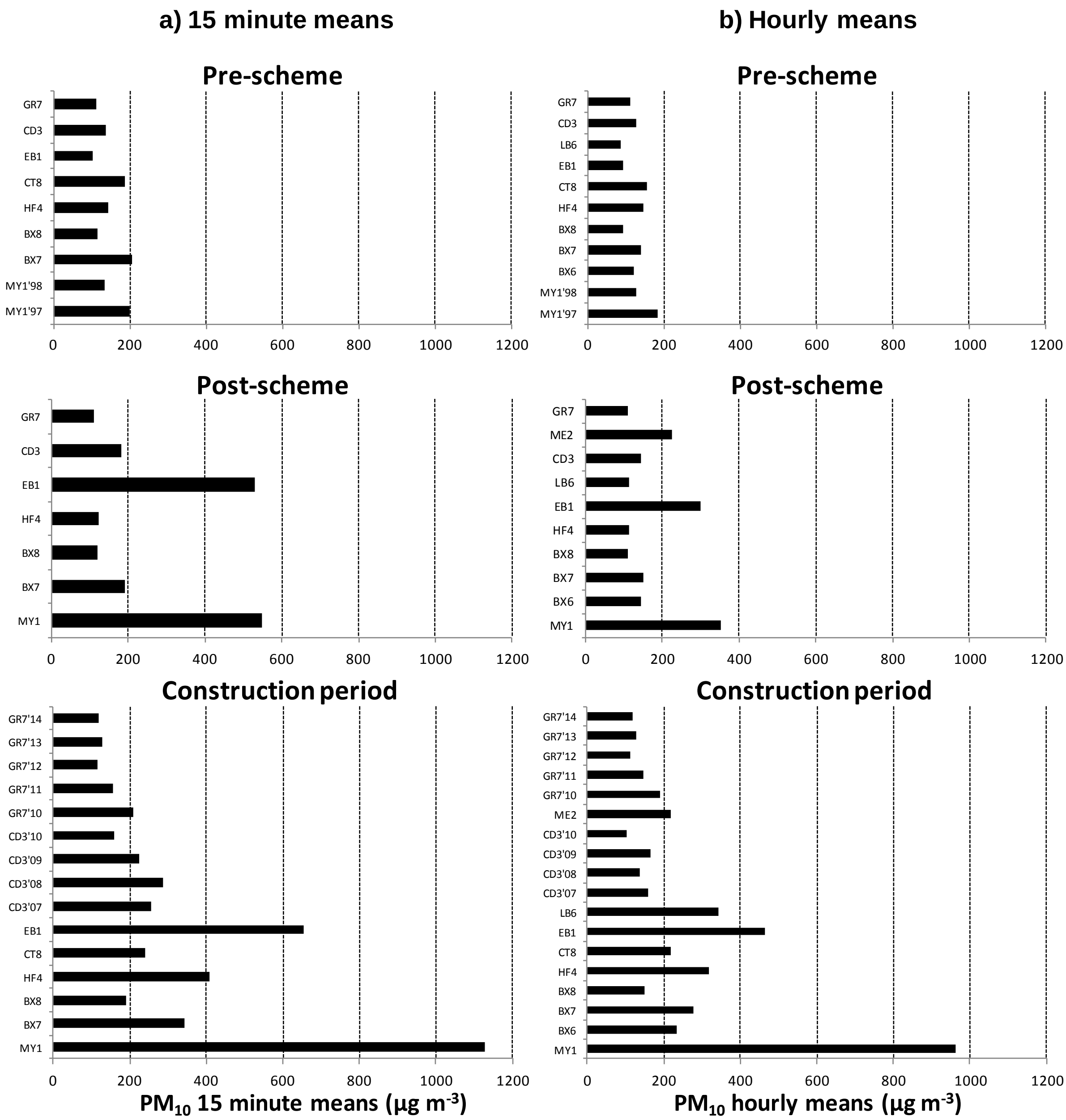

Figure 17. Percentile 99.9 for the a)15-minute means and b) hourly PM_{10} measurements during working hours for the pre-scheme, post-scheme and construction periods at the selected monitoring sites.

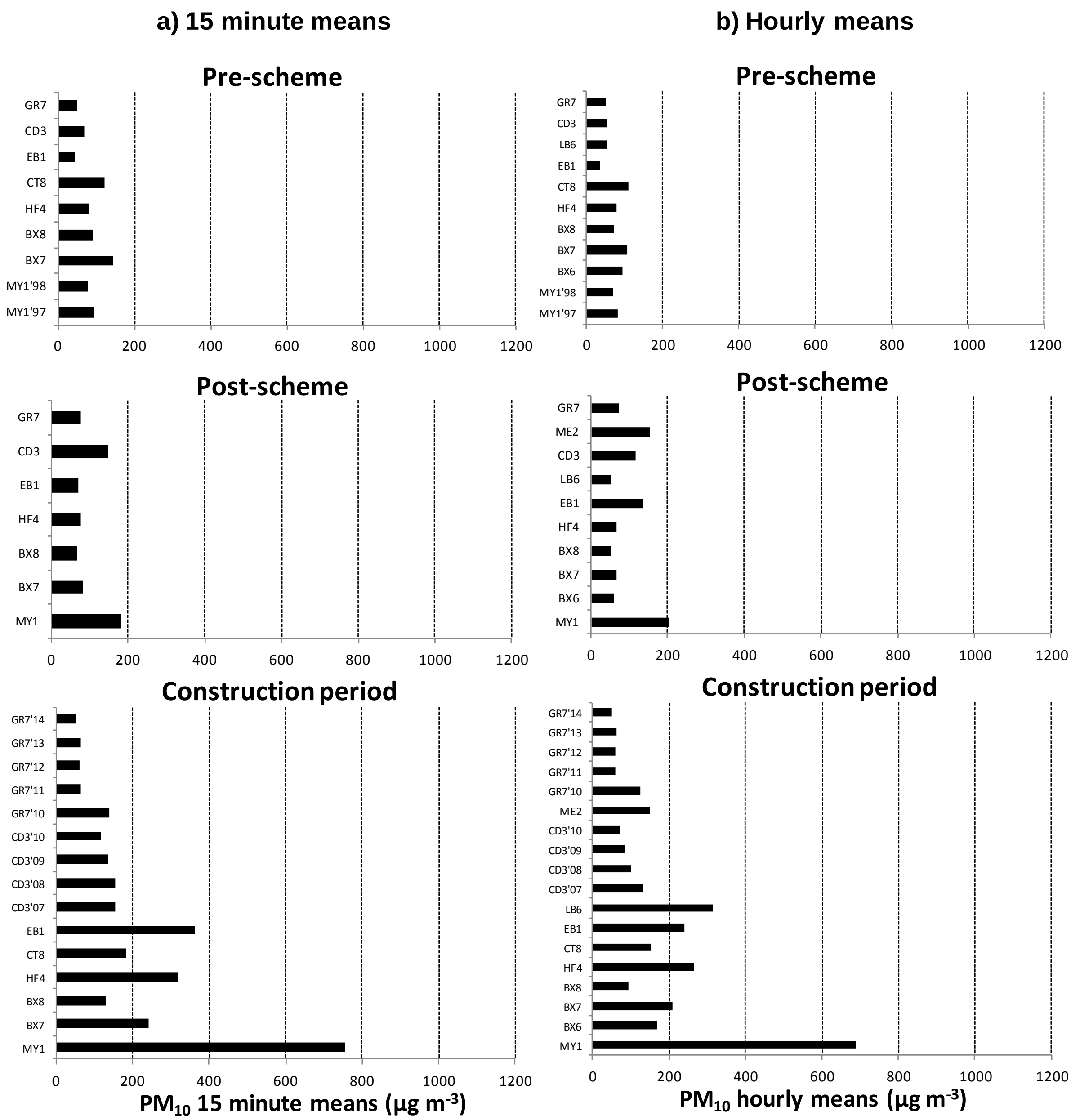

Figure 18. Percentile 99.9 for the a) 15 minute means and b) hourly means of PM_{10} increments above background for the pre-scheme, post-scheme and construction periods at the selected monitoring sites.

The number of hours and days when the proposed PM_{10} triggers were exceeded (190 µg m^{-3} for total PM_{10} concentrations and 120 µg m^{-3} for increments above the background) at each monitoring site for each period of time is summarized in Table 4. The percentage of days that the PM_{10} trigger was exceeded is also shown to normalize the number of exceedences by the length of the construction project time period.

During the construction period the number of exceedences of the proposed triggers was noticeably high at some sites:

- Lambeth 6 (during the construction period the PM_{10} trigger was exceeded 33% of the days),
- Hammersmith and Fulham (10%)
- Marylebone Road (8%).

However, some sites experienced a very low number exceedences of the PM_{10} trigger (all data considered): GR7 (less than 1.1%), CT8 (less than 1%), CD3 (less than 0.8%) and ME2 (0.8%). All these projects involved the demolition and construction of new buildings over long periods of time (> 1 year) with very few hours exceeding the trigger (<9 hours over a year) with the exception of ME2 which recorded 11 hours (10 hours during construction hours).

The majority of trigger exceedences took place during the construction hours suggesting that the very high PM_{10} events were associated with the construction activity itself (demolition, excavation, drilling, etc.) and were not due windblown resuspension of material that might still take place outside the working hours.

Table 4. Number of hour and number of days when the PM_{10} construction trigger was exceeded in the different AQMS during different phases.

Site	Start date	End date	Case	*N* hours	*N* days	% days	*N* hours	*N* days	% days	*N* hours	*N* days	% days
				All Times			Construction times			Increment Above BG		
MY1	01-Jun-1997	31-Dec-1997	Pre scheme	2	1	0.5	0	0	0	2	2	0.9
MY1	01-Jun-1998	31-Dec-1998	Pre scheme	0	0	0	0	0	0	0	0	0
BX6	02-Jan-2004	31-Aug-2005	Pre scheme	5	2	0.3	1	1	0.2	4	2	0.3
BX7	02-Jan-2004	31-Aug-2005	Pre scheme	4	1	0.2	0	0	0	6	3	0.5
BX8	02-Jan-2004	31-Aug-2005	Pre scheme	6	2	0.3	1	1	0.2	5	2	0.3
HF4	11-Sep-2011	21-Mar-2012	Pre scheme	0	0	0	0	0	0	0	0	0
CT8	06-Sep-2013	31-Mar-2014	Pre scheme	0	0	0	0	0	0	2	2	1.0
EB1	24-May-2006	31-Aug-2006	Pre scheme	0	0	0	0	0	0	0	0	0
LB6	28-Nov-2013	27-Jan-2014	Pre scheme	0	0	0	0	0	0	0	0	0
CD3	01-Jan-2006	31-Dec-2006	Pre scheme	2	2	0.5	0	0	0	1	1	0.3
GR7	01-Jan-2009	31-Dec-2009	Pre scheme	0	0	0	0	0	0	0	0	0
MY1	01-Jun-1999	31-Dec-1999	Construction	56	18	8.4	55	18	8.4	66	20	9.3
BX6	02-Jan-2006	31-Aug-2007	Construction	15	9	1.5	9	7	1.2	24	14	2.3
BX7	02-Jan-2006	31-Aug-2007	Construction	29	15	2.5	21	11	1.8	58	28	4.6
BX8	02-Jan-2006	31-Aug-2007	Construction	6	2	0.3	1	1	0.2	6	2	0.3
HF4	22-Mar-2012	30-Sep-2012	Construction	33	19	9.8	31	18	9.3	83	41	21.2
CT8	06-Sep-2014	31-Mar-2015	Construction	4	2	1.0	4	2	1.0	21	11	5.3
EB1	24-May-2007	31-Aug-2007	Construction	6	5	5.0	5	4	4.0	7	5	5.0
LB6	28-Jan-2014	11-Feb-2014	Construction	6	5	33.4	6	5	33.4	10	7	46.7
CD3	01-Jan-2007	31-Dec-2007	Construction	5	3	0.8	2	2	0.5	9	7	1.9
CD3	01-Jan-2008	31-Dec-2008	Construction	3	1	0.3	1	1	0.3	3	1	0.3
CD3	01-Jan-2009	31-Dec-2009	Construction	3	3	0.8	3	3	0.8	4	4	1.1
CD3	01-Jan-2010	31-Dec-2010	Construction	1	1	0.3	1	1	0.3	2	2	0.5
ME2	01-Jun-2011	31-Dec-2013	Construction	11	8	0.8	10	7	0.7	25	14	1.5
GR7	01-Jan-2010	31-Dec-2010	Construction	8	4	1.1	3	2	0.5	9	5	1.4
GR7	01-Jan-2011	31-Dec-2011	Construction	0	0	0	0	0	0	1	1	0.3
GR7	01-Jan-2012	31-Dec-2012	Construction	0	0	0	0	0	0	0	0	0
GR7	01-Jan-2013	31-Dec-2013	Construction	1	1	0.3	1	1	0.3	1	1	0.3
GR7	01-Jan-2014	31-Dec-2014	Construction	0	0	0	0	0	0	0	0	0
MY1	01-Jun-2000	31-Dec-2000	Post scheme	6	3	1.4	5	2	0.9	10	6	2.8
BX6	02-Jan-2008	31-Aug-2009	Post scheme	2	2	0.3	2	2	0.3	3	3	0.5
BX7	02-Jan-2008	31-Aug-2009	Post scheme	2	2	0.3	2	2	0.3	5	5	0.8
BX8	02-Jan-2008	31-Aug-2009	Post scheme	0	0	0.0	0	0	0	0	0	0
HF4	01-Oct-2012	11-Apr-2013	Post scheme	0	0	0.0	0	0	0	0	0	0
EB1	24-May-2008	31-Aug-2008	Post scheme	2	1	1.0	2	1	1.0	4	1	1.0
LB6	12-Feb-2014	12-Apr-2014	Post scheme	0	0	0.0	0	0	0	0	0	0.0
CD3	01-Jan-2011	31-Dec-2011	Post scheme	1	1	0.3	0	0	0	7	7	1.9
ME2	01-Jun-2014	31-Dec-2015	Post scheme	6	4	0.7	6	4	0.7	22	9	1.6
GR7	01-Jan-2015	31-Dec-2015	Post scheme	0	0	0	0	0	0	1	1	0.3

Focusing on the PM_{10} increments, the construction activities represented a substantial source of PM_{10} in LB6 and HF4 with measurements exceeding the 120 µg m^{-3} threshold for 47% and 21% of the days. Using the PM_{10} increment trigger value by removing background concentrations led to an increase in the number of exceedences for those sites with very low exceedance rate such as CT8 site (from 4 hours to 21 hours) and at ME2 (from 11 hours to 25 hours).

It is also important to quantify the possible false alarms, the times when ambient concentrations exceed the trigger but it was not linked to construction activities. The mean percentage of days that exceed the trigger threshold during the pre and post-scheme periods was less than 0.4% considering all data available with the exception of MY1 and CD3 where sites exceeded on 0.5% of the days in the pre-scheme periods; and in the post-scheme periods MY1, EB1 and ME2 exceeded the trigger threshold on 1.4%, 1% and 0.7% of days respectively. The average percentage days of exceeding the PM_{10} increment trigger of 120 µg m^{-3} was 0.7% outside the construction periods. These percentages were higher than the expected false alarms (0.1%) rate based on 15 minute or hourly measurements. This suggests that the trigger exceedences were separated in time across different days rather than clustered on a small number of hours on a small number of days.

The additional breaches of EU Limit value concentrations are of regulatory importance. Table 5 shows the number of days when the short-term (daily) mean EU limit value concentration of 50 µg m^{-3} was exceeded. Table 5 also shows the number of exceedences at the North Kensington background site (BG) during the same time period and the difference between the construction sites and the background site, i.e. the PM_{10} attributable to local sources at the construction monitoring site. This difference will be due to a variety of local sources including the construction but also traffic for instance. Changes in the difference between the construction sites and the background site during the construction and non-construction periods would denote the impact from construction, assuming other local sources to be unchanged.

An increase in days breaching the EU Limit Value concentration was measured around all of the construction sites except EB1 and LB6 although the data set for these sites was very short; and at CD3. Care has to be taken when this metric is compared across different construction sites. Due to its threshold nature even a small increase in local PM can lead to more breaches of the EU limit value concentration (daily mean of 50 µg m^{-3}) in polluted central locations compared with less polluted outer London locations.

Table 5. Number of days with daily mean PM_{10} concentrations > 50 µg m^{-3} for each period of time.

Site	Pre-scheme	Pre-scheme BG	Difference	Construction	Construction BG	Difference	Pre-scheme	Pre-scheme BG	Difference
MY1 (pre '97)	85	18	**67**	81	12	**69**	98	3	**95**
MY1 (pre '98)	44	7	**37**	81	12	**69**	98	3	**95**
BX6	26	21	**5**	57	23	**34**	32	18	**14**
BX7	44	21	**23**	89	23	**66**	41	18	**23**
BX8	34	21	**13**	72	23	**49**	42	18	**24**
HF4	13	4	**9**	49	3	**46**	4	5	**-1**
CT8	19	5	**14**	38	0	**38**	16	0	**16**
EB1 **	1	1	**0**	1	0	**1**	1	0	**1**
LB6 **	0	2	**-2**	0	0	**0**	4	3	**1**
CD3'07	28	12	**16**	31	18	**13**	27	15	**12**
CD3'08	28	12	**16**	20	12	**8**	27	15	**12**
CD3'09	28	12	**16**	13	6	**7**	27	15	**12**
CD3'10	28	12	**16**	4 *	2	**2**	27	15	**12**
ME2	-	-	-	67	16	**51**	30	0	**30**
GR7'10	12	6	**6**	18	2	**16**	11	0	**11**
GR7'11	12	6	**6**	41	15	**26**	11	0	**11**
GR7'12	12	6	**6**	26	6	**20**	11	0	**11**
GR7'13	12	6	**6**	29	9	**20**	11	0	**11**
GR7'14	12	6	**6**	18	3	**15**	11	0	**11**

* Annual data capture < 90%

** Data period too short

BG = Background site (North Kensington)

3.2 Concentrations in rural areas

The rural sites outside London measured periods of very high PM_{10} concentrations. The 99.9th percentile exceeded the 190 µg m^{-3} trigger in various years at Maidstone – Detling (2003, 2007 and 2008). Stoke did not measure concentrations as high as 190 µg m^{-3} but the maximum concentration in 2003 was 175 µg m^{-3}. That indicates there are multiple sources of PM_{10} in rural areas which lead to very high measured concentrations. Concentration peaks at Maidstone-Detling have been traced to wood burning for heating and bonfires in a nearby large garden. Concentration peaks at Stoke were mainly during late summer and early autumn which could suggest agricultural activity, such as harvesting, as the source.

Table 6. Statistics for the PM_{10} concentrations measured at the rural sites in Kent.

		15 minute means					Hourly means				
AQMS	Year	50th perc	95th perc	99.7th perc	99.9th perc	Maximum	50th perc	95th perc	99.7th perc	99.9th perc	Maximum
Maidstone-Detling	2003	19	50	138	258	1093	19	49	141	233	860
Maidstone-Detling	2004	16	41	66	78	402	16	41	66	77	278
Maidstone-Detling	2005	17	45	79	91	431	17	45	78	88	229
Maidstone-Detling	2006	16	44	71	93	1203	16	43	69	91	904
Maidstone-Detling	2007	15	44	95	276	967	15	44	95	315	644
Maidstone-Detling	2008	14	40	99	222	667	14	40	100	213	591
Maidstone-Detling	2009	15	36	67	77	96	15	36	65	76	94
Maidstone-Detling	2010	–	–	–	–	–	11	26	57	90	117
Maidstone-Detling	2011	–	–	–	–	–	11	40	84	216	752
Maidstone-Detling	2012	–	–	–	–	–	12	38	80	103	1282
Maidstone-Detling	2013	–	–	–	–	–	18	47	66	99	256
Stoke	2003	21	55	115	175	698	21	55	109	172	421
Stoke	2004	18	44	71	97	240	18	43	69	88	167
Stoke	2005	17	48	88	99	877	17	48	84	95	745
Stoke	2006	16	45	80	100	443	16	44	76	98	292
Stoke	2007	17	47	91	106	214	17	46	89	100	128
Stoke	2008	17	42	85	103	298	17	42	80	99	156
Stoke	2012	–	–	–	–	–	13	38	70	77	191
Stoke	2013	–	–	–	–	–	15	40	64	69	89
Stoke	2014	–	–	–	–	–	14	42	82	90	95

– No data, TEOM upgraded to TEOM-FDMS

3.3 Detection of NRMM exhaust emissions

Air pollution from construction is not confined to PM_{10} but also includes $PM_{2.5}$ and NO_X/NO_2 from non-road mobile machinery (NRMM) exhaust. In contrast to PM_{10}, which was characterised by high peak concentrations, similar peaks were not seen from NRMM emissions. This likely reflects the different emissions patterns; PM_{10} peaks being due to short-term dusty activities and the NRMM emissions being from the longer-term use of machinery and plant through the working day. We therefore adopted a different analytical approach.

Air pollution varies according to variations in the type and intensity of sources and also the weather which affects dispersion, deposition and chemistry. Sources that vary in a regular pattern can be detected by looking at mean diurnal and day of week cycles when the daily differences due to weather should exert a random effect that is reduced by averaging. The impact of construction emissions in ambient air quality was evaluated using this approach by quantifying the mean increment of air pollutants during the construction working hours in comparison with the pre and post schemes.

Figure 19 shows the mean hourly variation of PM_{10} concentrations above background measured at Marylebone Road (MY1) during the construction and non-construction periods. This clearly shows the impact of construction emissions on ambient concentrations. Mean PM_{10} concentrations were up to 50 µg m^{-3} above the pre-scheme levels during working hours (7 am to 5 pm) Monday to Friday. PM_{10}

increments measured during Saturdays and Sundays were similar to those measured in the pre and post-scheme periods suggesting that there was no construction activity during the weekends. As an aside a long-term increase in PM_{10} from traffic is also evident when pre and post construction periods are compared. This is consistent with the source apportionment work undertaken in Fuller & Green, 2006.

Conversely, the NO_X and NO_2 increments above background measured during the construction time were similar to those measured in the pre and post-scheme times. Assuming construction NO_X and NO_2 arise from NRMM; it appears that no NRMM emissions were detected at this site.

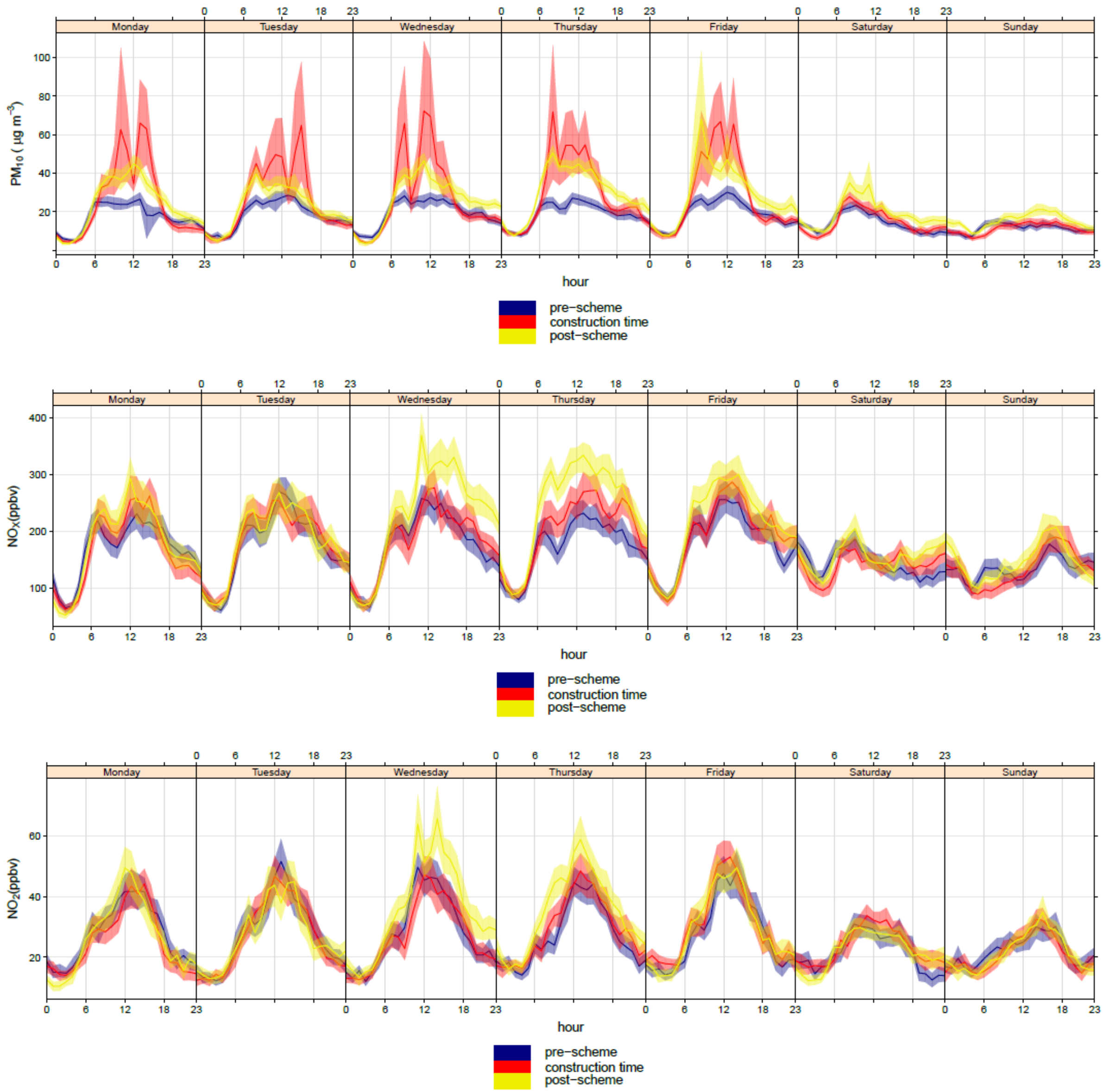

Figure 19. Mean hourly increments above background of PM_{10}, NO_X and NO_2 measured at Marylebone Road for each day of the week for the pre-scheme, construction and post-scheme periods.

Figure 20 shows the PM_{10} increment above background levels for the road widening scheme at Thames Road North Site (BX7) compared with that measured in the pre and post scheme periods. For this construction project it was observed that construction works also took place on Saturdays from 7 am to 12 pm. PM_{10} increments above background were up to ~15 µg m^{-3} higher during the construction period in comparison with the pre and post scheme times. Conversely, the NO_X and NO_2 increments during the construction time were similar to that measured before the construction activity. Higher concentrations in NO_X and NO_2 were measured after the completion of the road widening scheme associated with a larger number of vehicles using the widened road, notably during rush hour peaks (see further details in Font et al., 2014). This monitoring station also measured $PM_{2.5}$ concentrations and, as with NO_X and NO_2 increments, no increase in $PM_{2.5}$ was found during the construction works as might be expected from emissions inventory estimates of NRMM emissions.

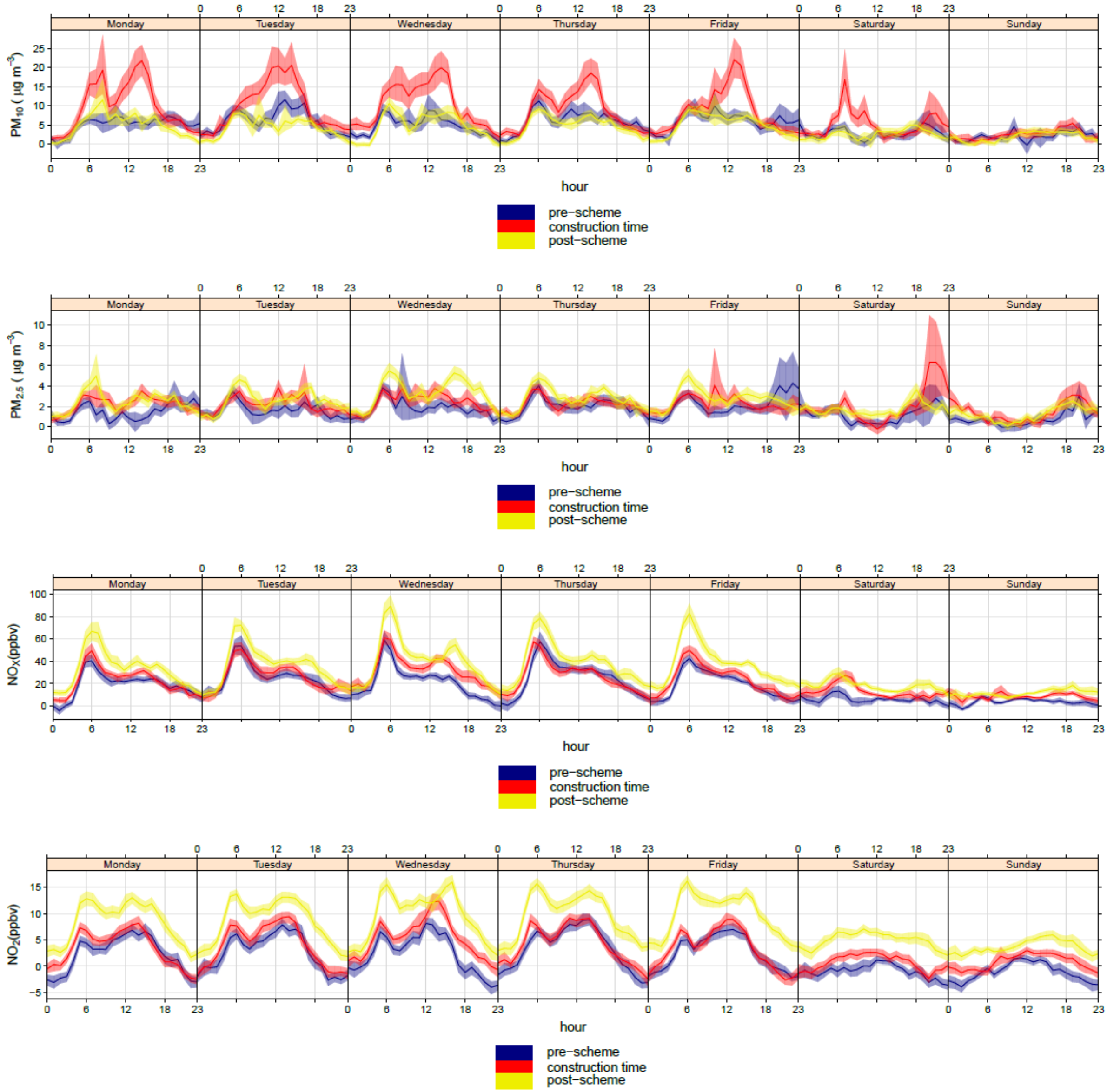

Figure 20. Mean hourly increments above background of PM_{10}, $PM_{2.5}$, NO_X and NO_2 measured at Bexley 7 for each day of the week for the pre-scheme, construction and post-scheme periods.

The time variation plots for all available species for the monitoring sites used in this study can be found in the Supplementary Material. Similar features as those observed to those at Marylebone Road and Bexley Thames Road for PM_{10} ambient concentrations during the construction period were observed at all sites except Merton 2. As per Marylebone Road and Bexley Thames Road, NO_X and NO_2 concentrations did not change during construction so no evidence of emissions from NRMM were found in these sites. An important exception was HF4 where NO_X and NO_2 concentrations increased during the construction period when compared with the non-construction periods. However, PM_{10} concentrations during the construction period were higher during Saturday mornings but NO_X and NO_2 concentrations were not. That suggests that the increase in NO_X and NO_2 at this site were due to changes in local traffic patterns and not due to emissions from NRMM.

The overall conclusion may be drawn that while PM_{10} emissions from construction can be related to increments on ambient measurement during construction hours compared to non-construction periods, the same relationship is not apparent for NO_X and NO_2 emissions from NRMM on ambient measurements.

4. Conclusions

This project set out to reassess the trigger values given in the Greater London Authority (GLA) code of practice for construction emissions and that by the Institute for Air Quality Management (IAQM). These are used as trigger limits to indicate when PM_{10} from construction activities might be affecting local air quality providing important near-real time feedback to operators enabling them to take rapid and responsive measures to control emissions. However the current 250 µg m^{-3} trigger value (15 minute mean) was based on a single study at Marylebone Road in 1999 (Fuller and Green 2004). Alternative metrics based on hourly increments above a background were implemented at the Olympic Park and lower warning thresholds have been adopted at sites close to sensitive receptors, specifically a 50 µg m^{-3} as hourly mean increments above the background (GLA, 2014, IAQM, 2012) but we are not aware that these have been tested.

The trigger values were examined using measurements from nine construction sites covering a range of construction activity and locations, mainly within London. Measurements were made with modern EU reference equivalent instruments in contrast to the older method used in Fuller and Green (2004). This dataset comprises 1.8 million measurements and is the largest analysis of construction PM_{10} to our knowledge.

Peak concentrations proved a good indicator of emissions of PM_{10} from construction with emissions being most apparent in the top 0.3% of concentrations. Most of the construction projects gave rise to the highest PM_{10} concentrations measured as 99.9^{th} percentile. There was no consistency in the type of construction that gave rise to high peak concentrations suggesting the need to manage PM_{10} in all types of construction. Similarly the majority of construction sites experienced an increase in the number of days when the daily mean PM_{10} EU limit Value concentration was exceeded. The greatest high percentile PM_{10} during construction was measured at monitoring locations very close (~5 m or less) to construction activity suggesting that distance between source and receptor is important, but this study did not test for a maximum distance where construction affected local PM_{10} concentrations.

Rather than base triggers on the maximum concentration, which might be unrepresentative, the 99.9^{th} percentile of measurements during non-construction periods was chosen as a basis for the new trigger concentration. Following analysis of this metric we propose the following three triggers as indicators of fugitive PM_{10} from construction sites:

- 190 µg m^{-3} (15 minute mean)
- 190 µg m^{-3} (hourly mean)
- 120 µg m^{-3} (hourly mean) as an increment above background

Given the practicalities of making contemporaneous site and background measurements we would recommend a trigger based on measurements at the construction site only.

For the avoidance of repeated triggered alerts from emissions of very short duration we would suggest that the hourly mean metric is used.

From our nine construction sites the worst case showed the trigger being exceeded on around one day in three. Three sites showed triggers being exceeded on more than one day in 12. By contrast, other sites showed no more than the expected false alarm rate. This shows that there is considerable scope for good site management practices to control construction dust.

Based on non-construction periods, an hourly mean trigger value of 190 µg m^{-3} would generate false alarms (indicating construction dust when none is present) on an average of 0.4 % of days.

Even by controlling peak concentrations, to ensure that the trigger is not exceeded, local PM from construction might still increase by 4-5 µg m^{-3} as a median over the construction project.

There is evidence that additional local PM_{10} during the construction periods can also arise from the roadway in addition to that from within the construction site boundary. This was mostly likely caused by resuspension of material tracked from the construction site. This is supported by results from London Mayor's dust suppression trails (Barratt et al, 2012). Haulage therefore also needs to be considered in any site management plan trial.

The use of short-term trigger concentrations as basis of a construction dust management programme avoids the need for pre-scheme measurements to characterise urban PM_{10}. However care needs to be taken in rural settings. Measurements from the two long-term rural measurement sites in southern England show that mean concentrations are lower than those in urban areas but agricultural activities and local fires can give rise to exceedences of trigger values in the absence of construction activities.

The Greater London Authority's London Atmospheric Emissions Inventory (LAEI) 2010 included new calculations of emissions from construction activities including both construction activities and exhaust from NRMM. On a mass basis this indicated that the emissions of NO_X from NRMM were 77 times the emissions of PM_{10} from construction dust and $PM_{2.5}$ emissions from NRMM were seven times the emissions of PM_{10} from construction dust. This being the case, NO_X and NO_2 ambient concentrations during construction times would be expected to be much greater than PM_{10} concentrations. Analysis of the seven construction sites with NO_X and NO_2 measurements co-located to PM_{10} did not detect greater concentrations that could be attributed to construction NRMM exhaust. It is not possible to say if the NRMM NO_X emissions or the construction PM_{10} in the LAEI is in error but no evidence was found to support the emissions ratios in the inventory. This was consistent with previous studies of the construction periods at Marylebone Road and Thames Road (Fuller and Green, 2004; Font et al 2014) that did not detect NRMM $PM_{2.5}$, NOx nor NO_2. It is clear from these results that the emissions inventory ratios are incorrect but we cannot conclude that NRMM emissions are zero. It is likely that the detection of NRMM emissions from construction was confounded by the presence emissions from London's diesel powered traffic. Fuller et al. (2014) had difficulty quantifying emissions from diesel powered trains in London for this reason. By contrast Faber et al. (2015) did detect NRMM emissions in tests around construction sites in a less polluted suburban environment but these were much less than the emission ratios inferred from the current London inventory. Studies of air pollution around construction sites outside London would enable better quantification of NRMM emissions.

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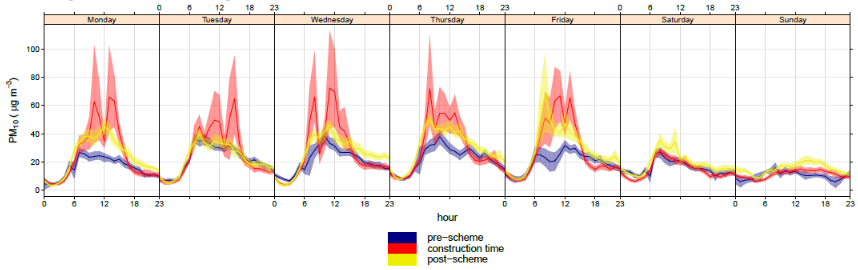
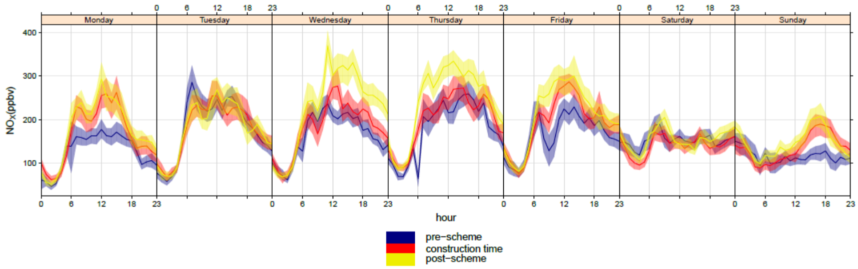
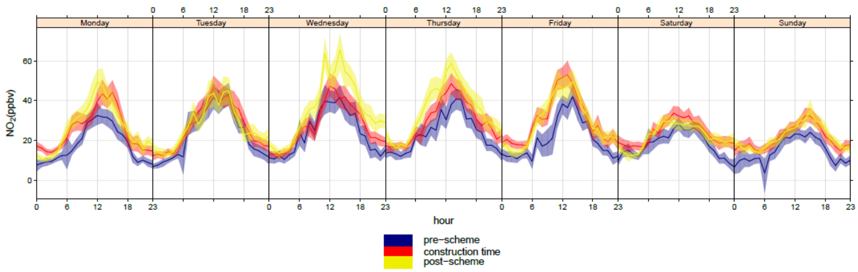
Supporting material - Time variation plots

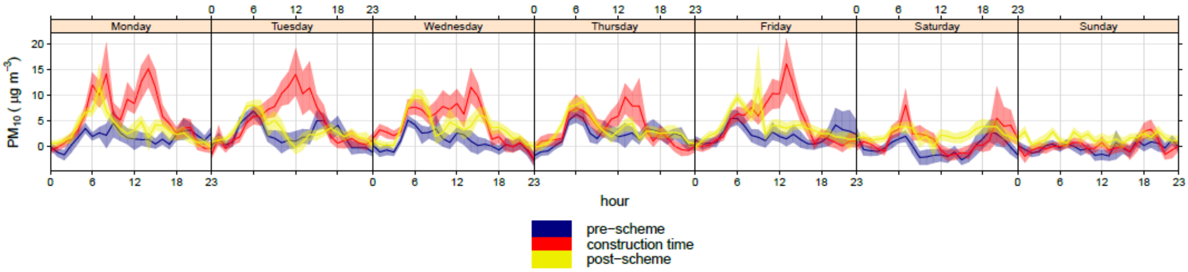
MY1. pre-scheme period: June to December 1997



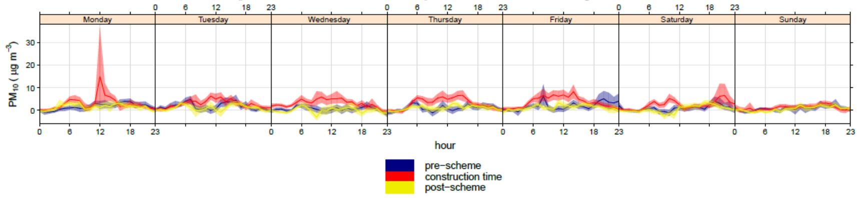


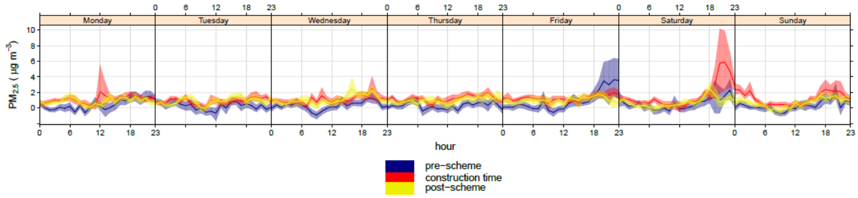


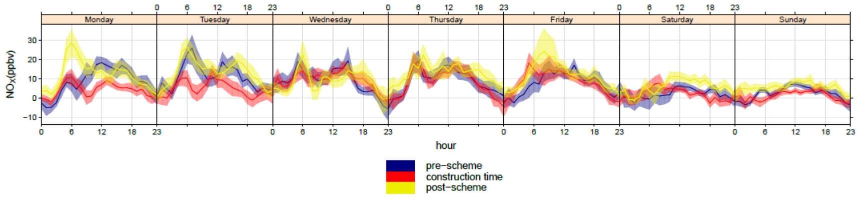
BX6. Construction period: January 2006 to August 2007.

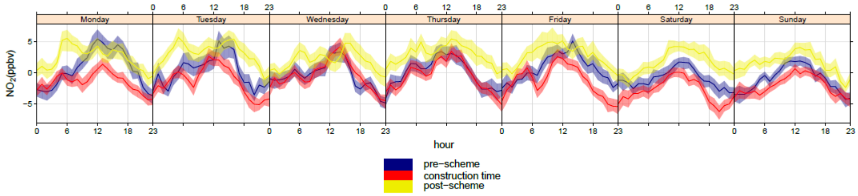


BX8. Construction period: January 2006 to August 2007.

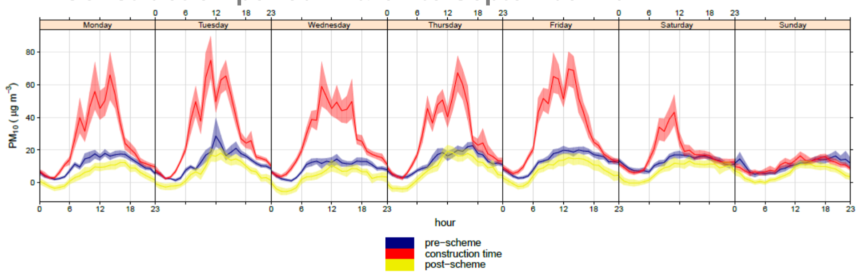


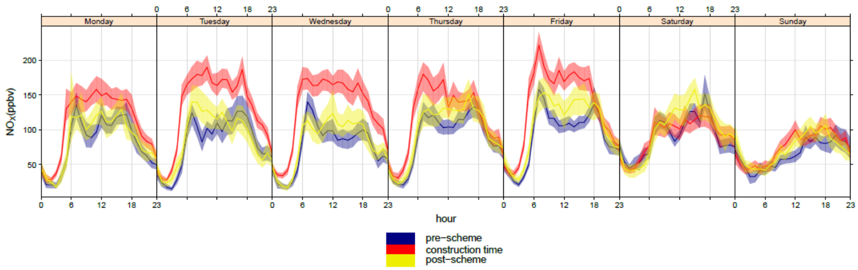


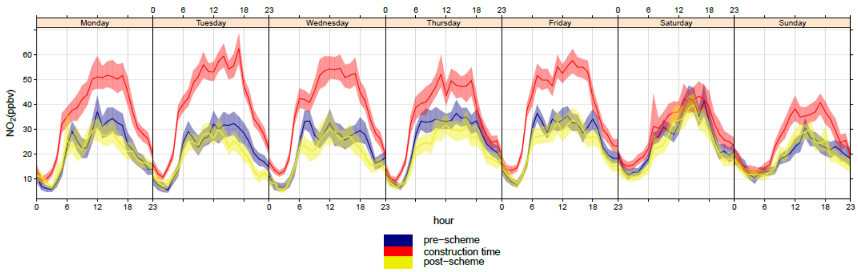




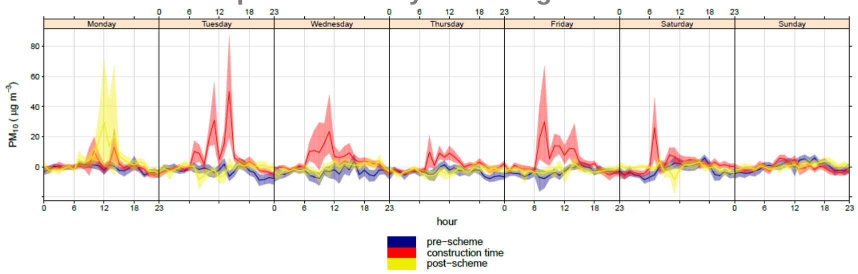
HF4. Construction period: March to September 2012

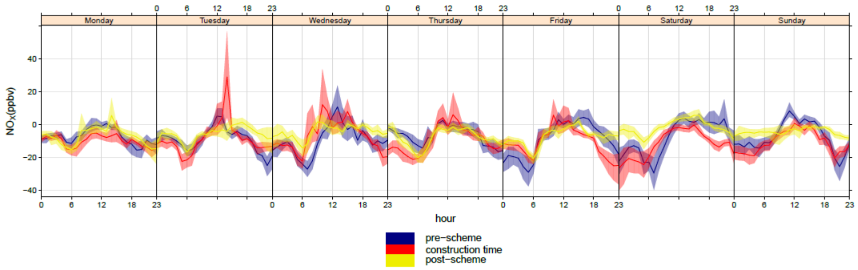


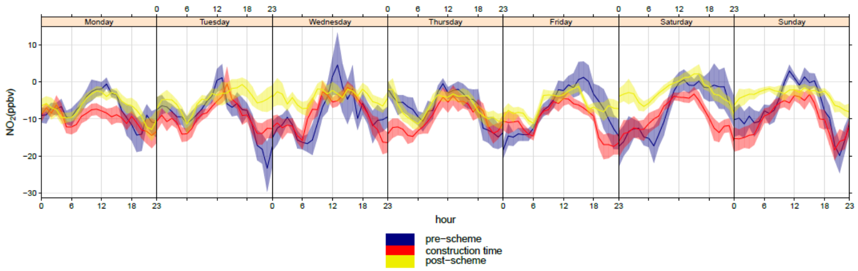




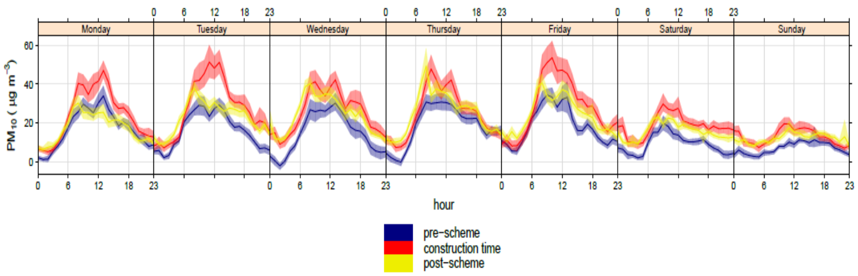
EB1. Construction period: 24 May to 31 August 2006



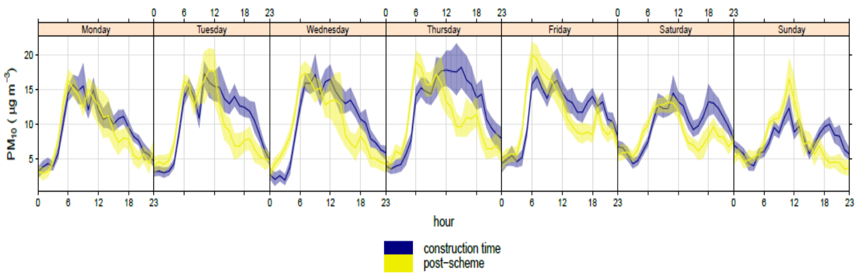




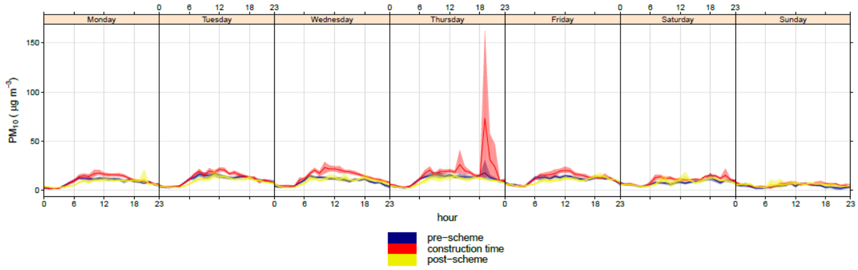
CT8. Construction period: March 2014 – September 2015

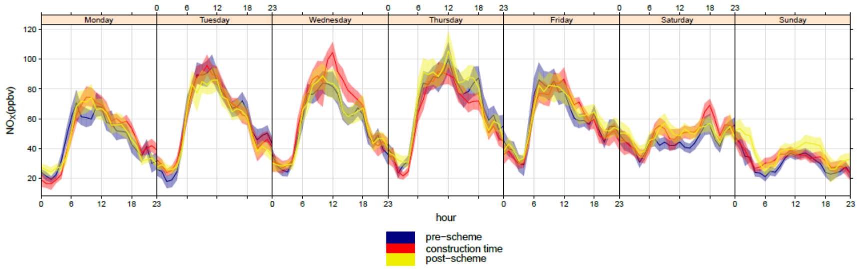


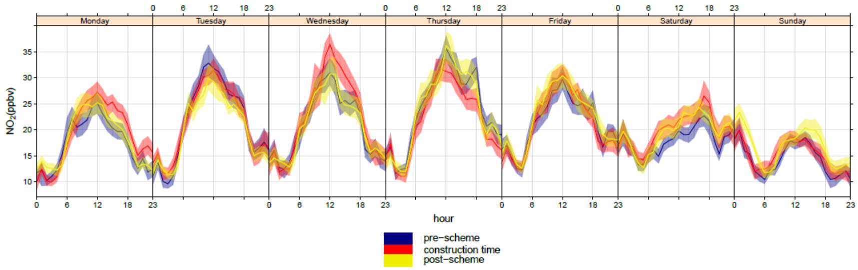
ME2. Construction period: June 2011 – December 2013



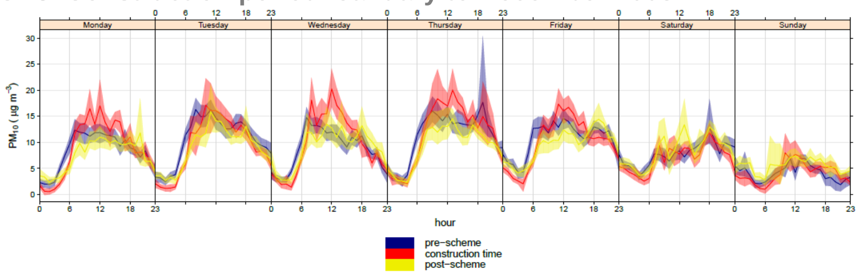
CD3. Construction period: January to December 2007.

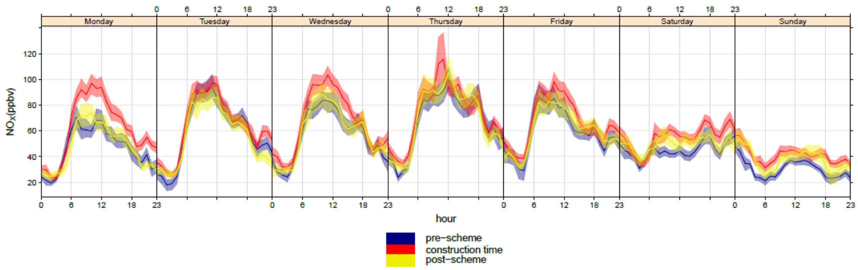


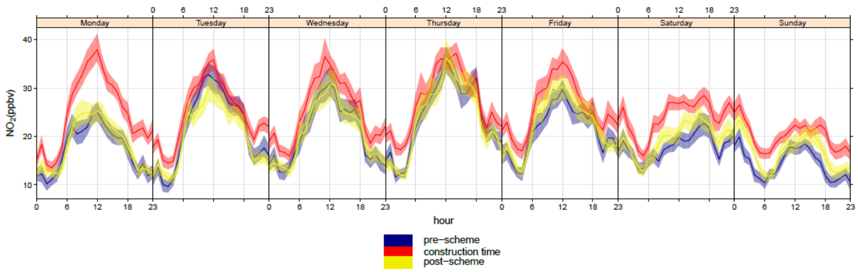




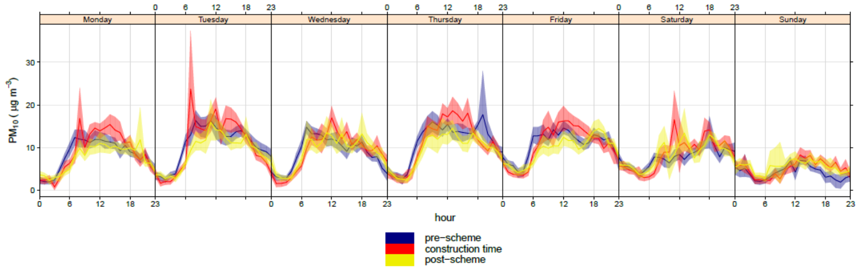
CD3. Construction period: January to December 2008.

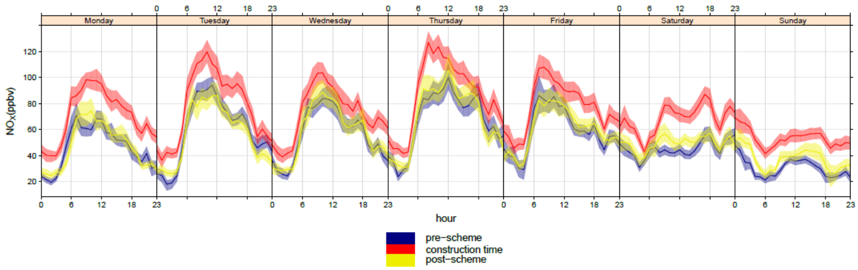


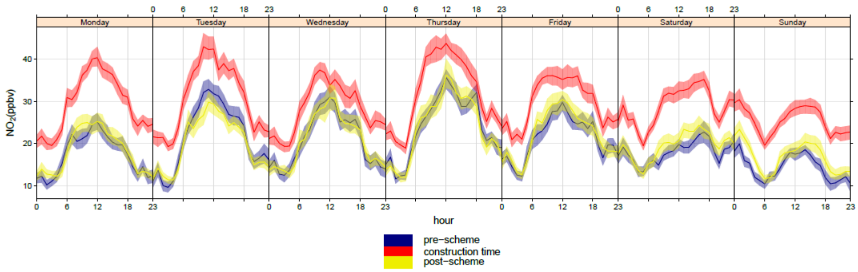




CD3. Construction period: January to December 2009.







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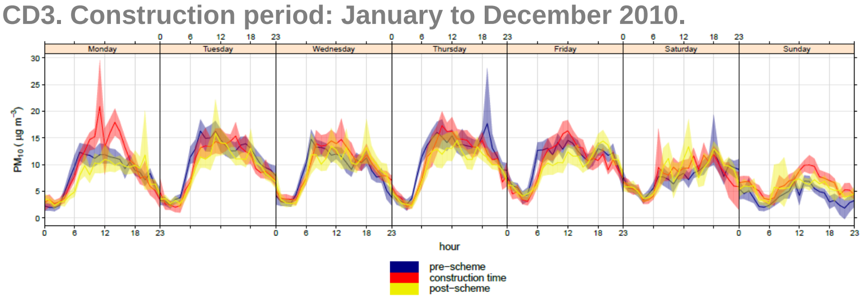

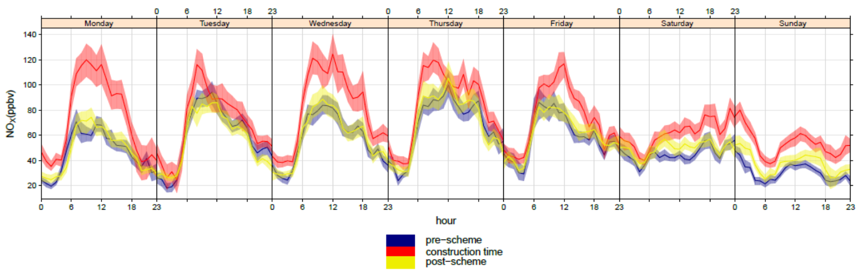

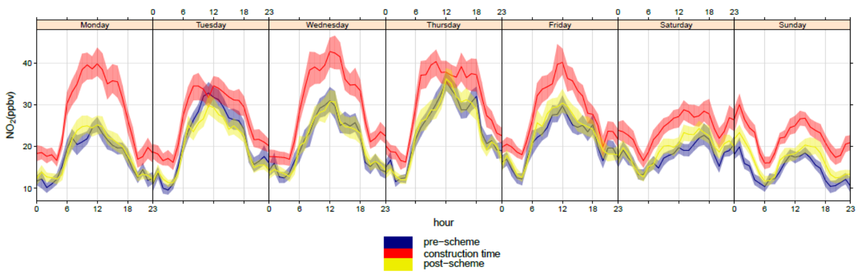

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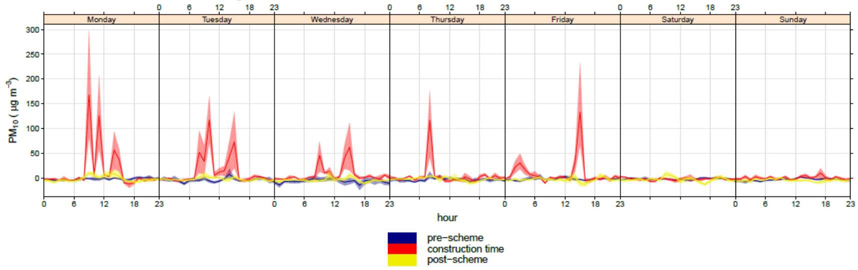

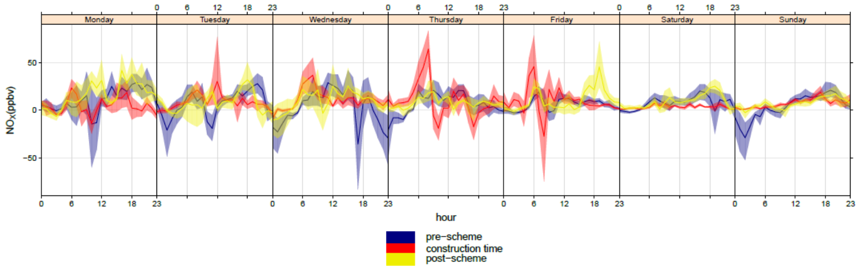

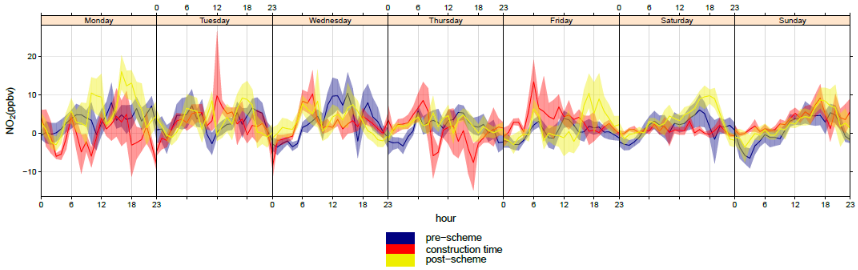

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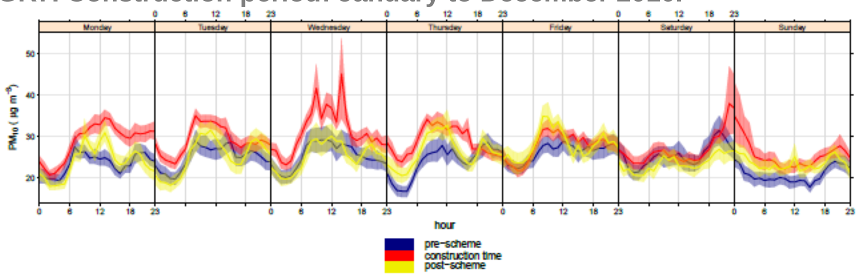

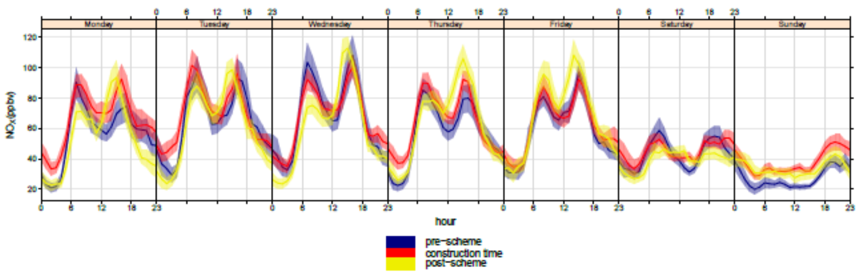

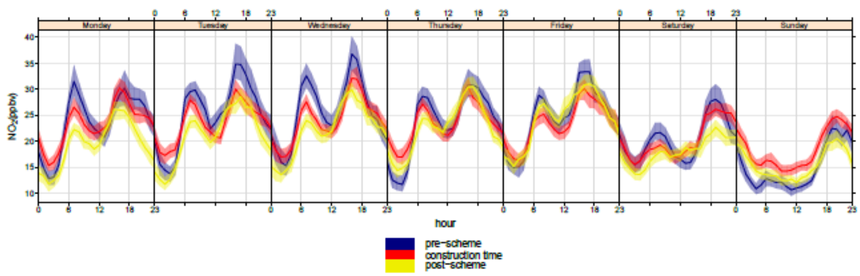

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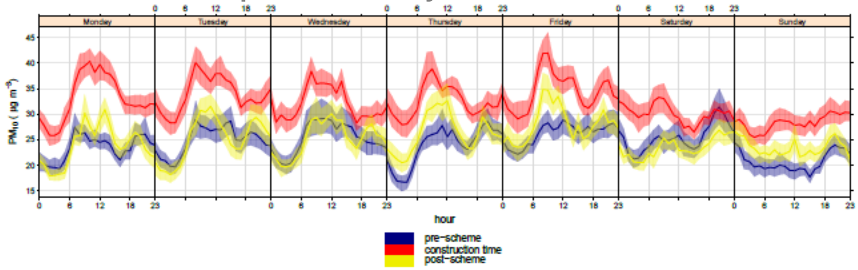

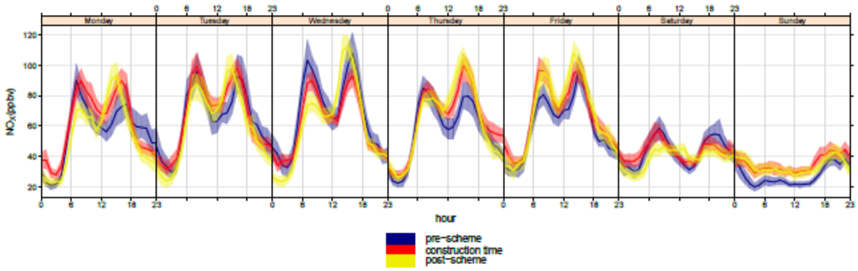

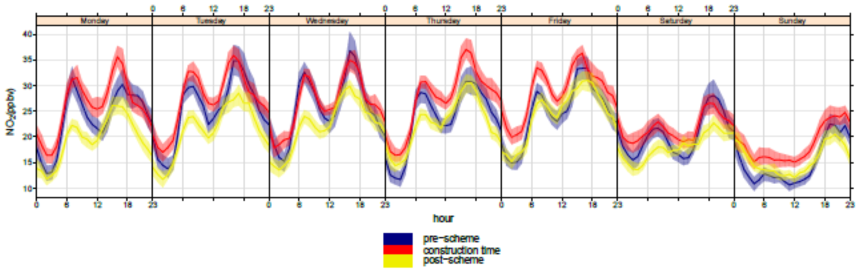

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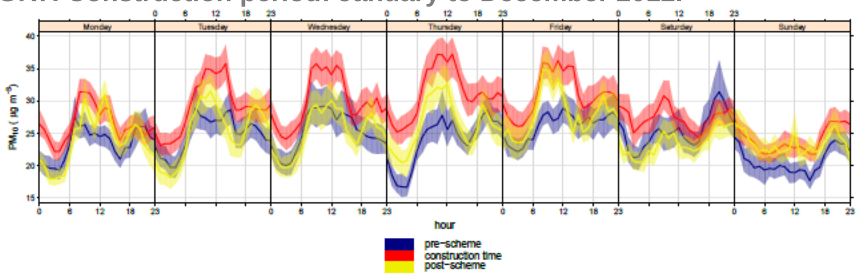

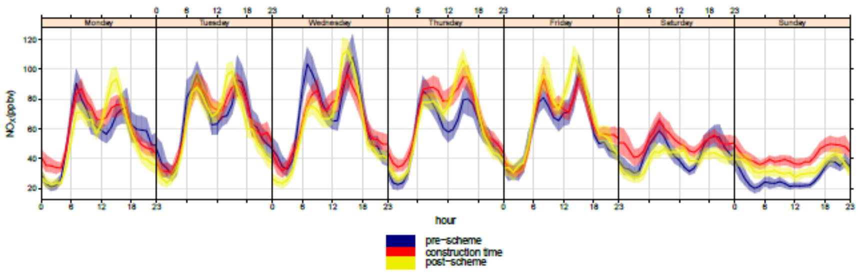

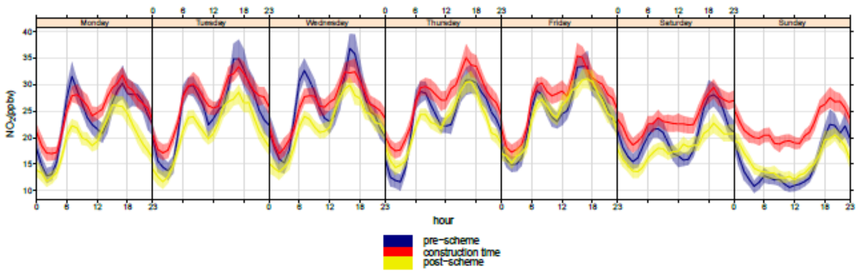

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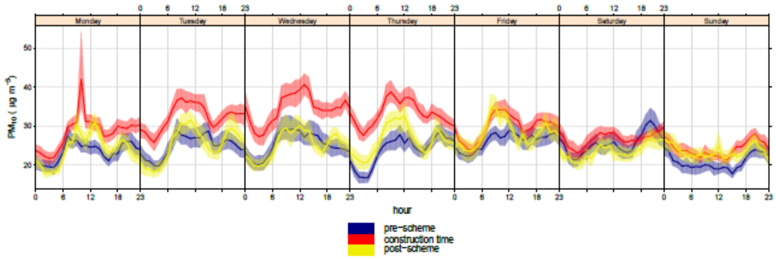

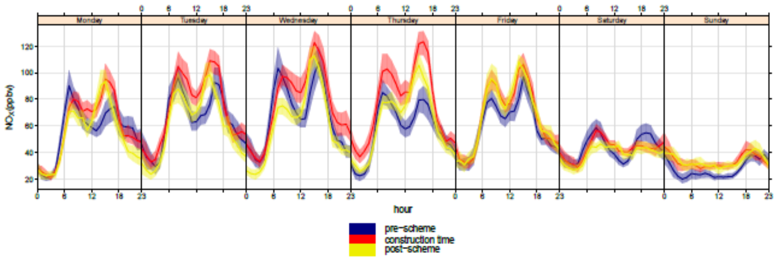

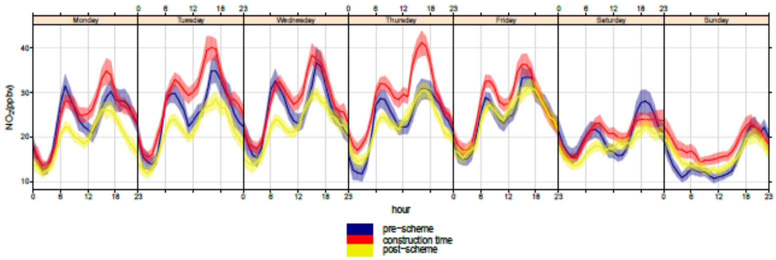

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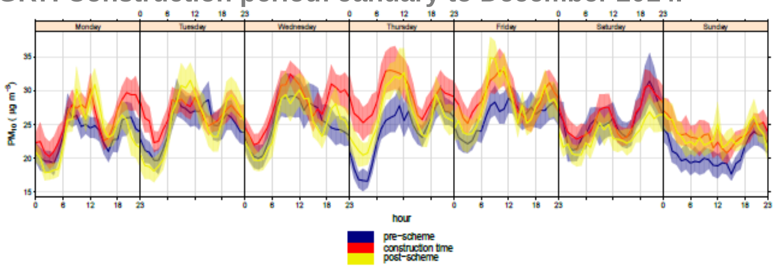

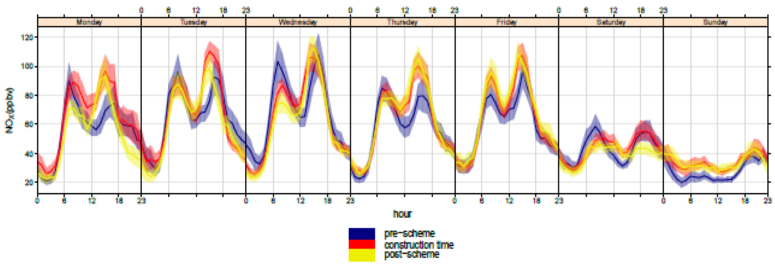

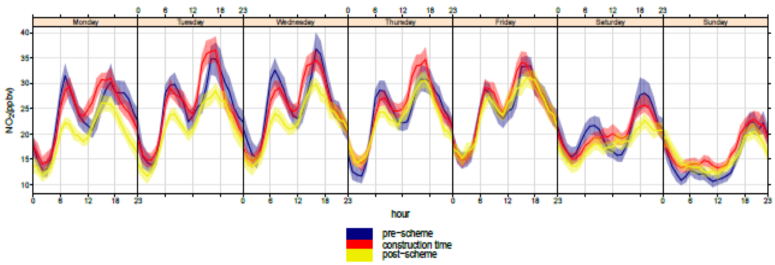

Re-assessment of the 250 µg m^{-3} action limit

Work Package 2

Assessing the performance of light scattering instruments

KING'S College LONDON

August 2016
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Environmental Research Group
King's College London

Title	Assessing the performance of light scattering instruments

Customer	HS2

Customer Ref	C0870 – Construction dust research

File Reference	Z:\AIRQUALI\Construction Dust\Construction Projects\HS2\WP2\Reports

Report Number	WP2

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[1] *Minor typographical changes following HS2 peer review*

Contents

1. Summary

The Greater Local Authority (GLA) code of practice for construction emissions and that by the Institute for Air Quality Management (IAQM) have trigger limits to indicate when PM_{10} from construction activities might be affecting local air quality.

Work package 1 of this project recommended a revised trigger concentration of 190 µg m^{-3} measured as an hourly mean. This was based on measurements made using PM_{10} instruments that have demonstrated equivalence to the European Union reference method. Practical constraints mean that smaller and simpler instruments are generally used for perimeter measurements around construction sites.

Work package 2 therefore considers the performance of two commercially available instruments. In previous short-term test these instruments required correction factors to achieve an acceptable performance envelope. For one instrument, the required correction was very different between tests.

For the first time, long-term (up to 4 ½ year) data sets were examined from locations within, or close to construction sites. Both instruments had difficulties in the measurement of volatile particulate. During pollution episodes, this volatile particulate can dominate the air in urban areas of the UK and Europe. The Osiris tended to measure less than the reference equivalent method by a factor close to 0.5 but there was no single correction factor. The E-sampler tended to measure more than the reference equivalent instrument (up to around two times) when volatile particles were prevalent.

It was difficult to isolate construction dust from the datasets. Based on limited data there was no evidence to support a modification to the trigger concentration of 190 µg m^{-3} when measured with indicative instruments.

In addition to difficulties in the measurement of volatile particles, even with high quality assurance control, Osiris instruments displayed long-term drift, with divergences ranging from factors of 0.5 to 2. The level of drift in instruments operated with a lower quality assurance is likely to be greater. Basic steps to maximise data quality and improve site alert systems and any subsequent data analysis include:

1. Good quality sitting with a free movement of air around the inlet and clear lines of sight to expected sources
2. Correct configuration of instruments; paying particular attention to ensure that the sample system is heated to reduce interference from water and secondary PM.
3. Regular visits to change filters and adjust flows as necessary and to assess site environs to ensure that the monitor and location remain fit for purpose
4. Regular servicing, either on-site or back to base for cleaning and recalibration
5. Regular data download and checking to ensure that equipment remains operational, to assess for consistency over time and make between instrument comparisons to identify outlier performance.

The long-term drift would also introduce large uncertainties if these types of instrument were used to compare PM_{10} during pre-construction with construction periods. This drift might lead to a false impression that a construction site was or was not affecting local air pollution.

The current test methods of PM_{10} monitoring equipment focus on measuring concentrations and particle types that occur in typical urban areas. This is not the same as construction dust. There is a clear need to test indicative PM_{10} monitoring equipment in construction environments. There are three ways to achieve this:

1) Construction activities and emissions could be simulated using existing test platforms.

2) Equipment could be installed at construction sites and construction PM would be measured as they arose during the project.

3) A mobile test platform could be used and taken around construction sites to test a range of site activities.

2. Introduction

The Greater Local Authority (GLA) code of practice for construction emissions and that by the Institute for Air Quality Management (IAQM) have trigger limits to indicate when PM_{10} from construction activities might be affecting local air quality. According to these guidance developers should respond to significant breaches of the trigger threshold by stopping work immediately and ensuring best practice measures are in place before restarting. With breaches of the PM_{10} trigger value local authorities can use their powers to prevent the statutory nuisance (GLA, 2014).

As used in the codes of practice, the 250 µg m^{-3} trigger value (15 minute mean) is designed to protect the local population from construction emissions. Alternative metrics based on hourly increments above a background were implemented at the Olympic Park and lower warning thresholds have been adopted at sites close to sensitive receptors, specifically a 200 µg m^{-3} as 15 minute means or 50 µg m^{-3} as hourly mean increments above the background (GLA, 2014, IAQM, 2012).

Work package 1 of this project recommended a revised trigger concentration of 190 µg m^{-3} measured as an hourly mean. This was based on measurements made using PM_{10} instruments that have demonstrated equivalence to the European Union reference method. Practical constraints mean that these types of instruments are not generally practical for perimeter measurements around construction sites. Instead smaller and simpler instruments are used. These normally employ light scattering as a measurement method.

Work package 2 therefore considers the performance of two commercially available instruments that are used for perimeter measurement. The work package considers how well these instruments measure the background PM_{10} in urban areas and also how well they measure the PM_{10} from construction sources.

The work package aims to

- Compare perimeter measurement devices to EU reference equivalent instruments to provide a conversion factor
- Investigate periods of divergence between the instrument types to provide insight into methodological differences.
- Explore the operational divergence between perimeter measurement devices.
- Provide recommendations for the use of light scattering instruments to assess the proposed trigger concentration; these include recommendations on equipment operation and measurement interpretation.

2.1. Background

Particulate matter (PM) is emitted into the atmosphere form a variety of primary sources; it is also formed from precursor gases via a range of chemical reactions. This results in a PM being a mixture of particles with varying physical (e.g. size and shape) and chemical (e.g. volatility) characteristics.

The measurement of PM for regulatory assessment is defined the mass concentration of a particle size fraction (PM_{10} or $PM_{2.5}$). The reference method, as defined in the Air Quality Directive for reporting to the European Commission (EC) is a 'gravimetric' method relying on the collection of size selected PM onto a pre-weighed filter for 24 hours; this is subsequently re-weighed after exposure and the mass concentration calculated (CEN, 2014).

Although the gravimetric method is widely used, in air quality networks it is often either augmented or replaced with automated methods that are capable of measuring at higher time resolution and disseminating information in real-time. The suitability of automatic instruments is assessed via a set of laboratory and field tests (EC, 2010). A key assessment criteria is the expanded uncertainty when compared to the reference method in field trials. If the expanded uncertainty is within the Air Quality Directive's 25% data quality objective at the limit value they can be declared equivalent for reporting to the EC. Within the UK, this equivalence procedure is overseen by MCERTS, the Environment Agency's Monitoring Certification Scheme. All instruments reported by Defra to the EC, such as the FDMS and BAM, have been shown to be reference equivalent although some do require a slope and intercept correction to be applied.

The MCERTS certification was extended to provide a performance standard for 'Indicative Ambient Particulate Monitors' (EA, 2015) that are used to make measurements of ambient dust on a qualitative or quantitative basis where an indicative result is acceptable. Again suitability is assessed in laboratory and field trials but there are more flexible acceptance criteria; if the expanded uncertainty when compared to the reference method is less than 50% at the limit value they can be declared indicative.

2.2. Reasons for divergence between instrument types

As well as issues relating to instrument uncertainty, there are a number of valid reasons why the higher time resolution instruments differ from the reference method and why one instrument type may differ from another. The key areas are summarised in Table 1. This comparison helps to define the analysis undertaken to draw out the PM source and environmental characteristics which drive differences between the instruments.

Table 1: Summary of key differences in operational parameters for instruments used in this study

	Reference Method	FDMS	$TEOM_{vcm}$	Osiris	E-Sampler
Size selection	Size selection inlet (TSP, PM_{10}, $PM_{2.5}$, PM_1)	Size selection inlet (TSP, PM_{10}, $PM_{2.5}$, PM_1)		No size selection as particle size is used to determine mass as different size fractions	Size selection inlet (TSP, PM_{10}, $PM_{2.5}$, PM_1)
Sample inlet temperature	Ambient temperature	Elevated sample temperature (30^{o}C) to stabilise measurement system	Elevated sample temperature (50^{o}C) to stabilise measurement system	Elevated sample temperature to (50^{o}C) stabilise measurement system and drive off water	Elevated sample temperature to stabilise measurement system and drive off water when RH >50%
Sample Flow	2.3 m^3/h	1 m^3/h (50% through sample/ 50% through purge)	1 m^3/h	0.12 m^3/h	0.036 m^3/h
Detection Methodology	Laboratory mass measurement	Oscillating microbalance		Light scattering	
Calibration	Calibration using traceable mass standards	Calibration using filter transfer standards		Manufacturer sensor calibration	Manufacturer sensor calibration
Treatment of volatile PM	Zero by convention	Corrects for volatile loss using purge measurement	Volatile Correction Model (Green et al., 2009)	Volatile material lost in heated inlet	

Sample inlet temperature and its impact on volatilising PM components has been an important consideration for PM measurement for many years (Patashnick and Ruppecht, 1991, Allen et al., 1997, Smith et al., 1997, Green et al., 2001, Green et al., 2009, Tasić et al., 2012). In the UK, the volatile components which contribute most to the mass concentration are ammonium nitrate and organic compounds and the difference between the instruments will clearly depend on the magnitude of these components in the PM mixture. The concentration of these components depends on their formation mechanisms, including the availability of gaseous precursors and the correct conditions for atmospheric reactions, as well as a suitably low atmospheric temperature to ensure that they remain in the particulate phase and do not partition back into their gaseous precursors. In the UK, the highest concentrations are found in the springtime with the lowest in the summer; this is summarised in Figure 1.

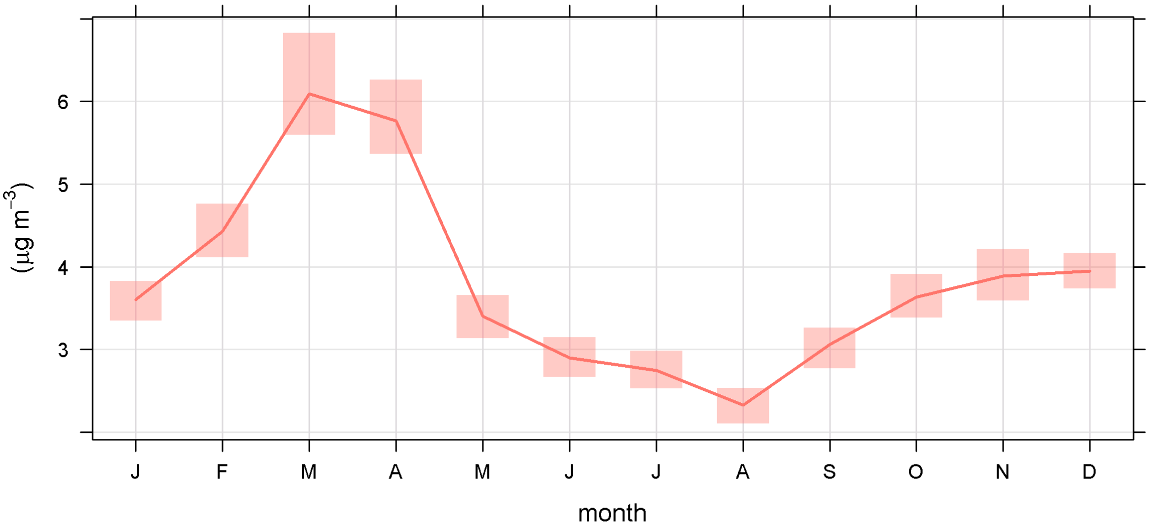

Figure 1: Volatile PM concentrations measured using the FDMS at North Kensington

Size selection is undertaken using specific inlets on the all instruments except the Osiris, which uses the forward light scattering signal to infer particle size. Individual size selective inlets differ in design and flow rate, however they have been tested in wind tunnels and with known particle sizes to ensure accurate size separation (an example is shown in Figure 2). The Osiris relies on the conversion of the light scattering signal into particle size measurements, assuming a uniform refractive index. Uncertainty in these assumptions increase when particles are spherical, their refractive index is close to that of air and particles size is close to wavelength of light source (Hinds, 1999).

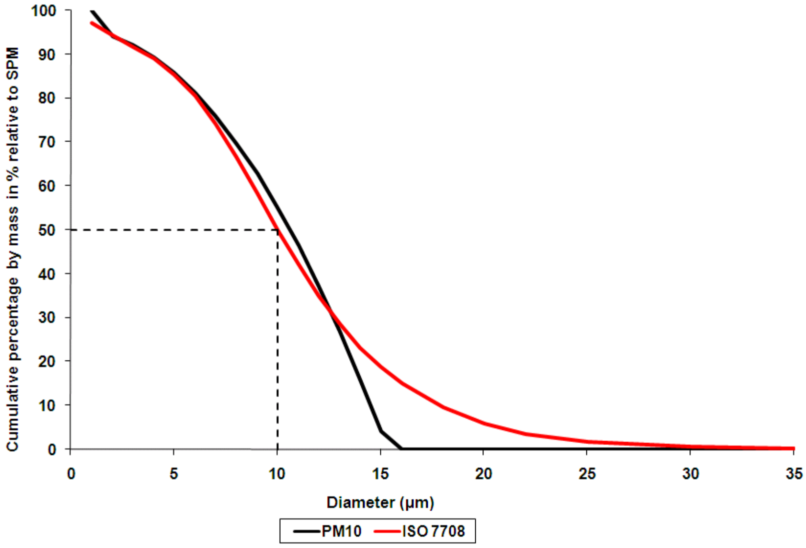

Figure 2: Cumulative percentage by mass of the PM_{10} fraction and the thoracic fraction (ISO 7708) relative to Suspended Particulate Matter (CEN, 1998)

How well the sample taken by the instruments represents the ambient environment can depend on the sample flow and mode of operation. This artefact is particularly pronounced when concentration changes are transient - as they are during construction activity. The FDMS instrument samples particle free air for 50% of the time, switching between phases every 3 mins, this enables an accurate treatment of volatile PM but compromises how representative the sample is. However it can simply miss short-term peaks and can measure a lower concentration than an instrument that is sampling continuously. The overall sample volume may also impact on how representative the sample is, especially when the mass is driven by a small number of large particles or that the particle 'plume' is not well mixed. Both these issues may lead to differences when examining relationships between instruments.

2.3. Existing evidence of divergence between instrument types

In the UK, the Topas instrument was equivalence tested during 2003 and 2007 in Teddington, London (Harrison, 2008). The sensor modules of the Orisis and the Topas were accepted as identical; consequently a certificate could be issued to pass the Osiris as indicative for PM_{10} measurements based on this evidence. The slope and intercepts shown in Table 2 were derived using the standard approaches laid out by CEN (EC, 2010). These were used to correct the Osiris measurements according to the co-located reference measurements; the data quality objective of 50% expanded uncertainty at the limit value for indicative monitors was subsequently achieved. It is worth noting the large disparity in the slopes; 0.782 for the high concentrations (up to 100 µg m^{-3} as a daily mean) experienced in 2003 compared to 30 µg m^{-3} in 2007 and suggests either a concentration or composition dependence. In a latter report covering much of the same data (Harrison, 2012), the author recommends applying a locally derived correction factor and that significant care is taken when deriving such factors due to significant inter-annual variation. The Topas $PM_{2.5}$ measurements were not found to be equivalent using any correction. The E Sampler was tested in two periods in Teddington, London (December 09 – March 10 and April 12- July 12).

Table 2: Results from UK equivalence tests

Instrument	Year	Slope	Intercept µg m-3	Correction Type	Expanded Uncertainty (%) at 50 µg m^{-3}
Topas	**2003**	0.782 (±0.0.62)	2.334 (±2.889)	Slope and Intercept	50.10
Topas	**2007**	1.331 (±0.174)	2.177 (±1.882)	Slope and Intercept	46.20
E-Sampler	**2012**	1.008 (±0.054)	-0.128 (±0.968)	Slope and Intercept	18.04

Further co-location studies are also available. Tasić et al (2012) found that the Osiris appeared to underestimate indoor PM_{10} concentrations measured using the reference sampler by approximately 12%; although the results were strongly correlated (r^2 = 0.87). The Osiris $PM_{2.5}$ measurements were again found to significantly underestimate the reference measurements; in this case by 63%. Green (2003) found that the Osiris measured a higher concentration than the PM_{10} reference sampler in a location east of London during 2002; reporting a slope of 1.31 and an intercept of 6.44 µg m^{-3} . There was significant seasonal variation with the largest divergence in the summer months and a season and site specific correction factor was recommended.

3. Measurement methods

This section describes measurement methods examined in this report, in particular it outlines the indicative instruments used and the reference and reference equivalent measurement methodologies to which the indicative monitors are compared.

3.1. Turnkey Osiris

The Osiris continuously measures the concentration of total suspended particles (TSP), PM_{10} , $PM_{2.5}$ and PM_1 at a range of up to 6000 µg m^{-3} based on an optical method. The instrument samples at 0.6 l min^{-1} through an inlet heated to 50°C to minimise the effects of water droplets and particle bound water. It measures the intensity of the light scattered by individual particles allowing an assessment of aerodynamic diameter. Using known collection efficiencies of physical inlets for different size fractions, it assigns a percentage of the calculated mass to a size fraction, thereby simulating a physical size selective inlet. It detects light scattered by particles through 10 degrees or less, minimising the effects of reflected and refracted light and therefore the particle colour. Particles can be collected on a Whatman GFA 25mm filter for subsequent mass determination and therefore instrument calibration. Mass determination was not undertaken during this study.

The sample tube was heated (35 °C) to avoid condensation. The sample inlet was designed by the manufacturer; no test report for the sample inlet against the reference method was available. No software correction factors were made available by the manufacturer.

3.2. Metone E-Sampler

The E-Sampler provides real-time particulate measurement through near-forward light scattering. Size selection is provided by either a PM_{10} or $PM_{2.5}$ inlet. An internal rotary vane pump draws air at 0.12 m^3h^{-1} via a size selective inlet into the sensing chamber where it passes through visible laser light. The inlet is heated if necessary to keep the sample air humidity below 50% to prevent measurement errors caused by moisture. Aerosols in the air scatter light in proportion to the particulate load in the air. Scattered light is collected by glass optics and focused on a PIN diode. The intensity of the focused light is measured and output a signal to the CPU. The output is linear to concentrations greater than 65,000 ug m^{-3}. Particles can be collected on a 47 mm filter for subsequent mass determination and therefore instrument calibration. Mass determination was not undertaken during the study reported here.

3.3. Thermo Tapered Element Oscillating Microbalance 1400 (TEOM) adjusted using the volatile correction model (TEOMvcm)

The TEOMs sampled air through a Rupprecht & Patashnick Co.(R&P) PM_{10} inlet at 1 m^3 h^1 and diverted 0.18 m^3 h^1 to the microbalance for mass measurement. The microbalance consisted of a hollow glass tapered tube, clamped at one end and free to oscillate at the other; an exchangeable filter was placed on the free end. The frequency of oscillation was measured and recorded by a microprocessor at 2 s intervals and provided a 15 min running mean concentration. The filter and the air stream passing through it were heated to 50 ˚C to maintain the filter above the dew point and at a low relative humidity, therefore reducing water uptake (Rupprecht & Patashnick Co., 1996).

The TEOM was found not to be equivalent to the EU reference method (Harrision, 2006) but later corrective method was devised by Green et al (2009) using measurements of the volatile PM_{10} concentration at a regional scale to correct for particle losses from nearby TEOMs.

3.4. Thermo Scientific Filter Dynamics Measurement System 8500 (FDMS)

The FDMS aims to measure the total mass concentration of airborne particulate matter and quantify the mass changes of the filter due to evaporative and condensation processes that will affect the measured concentrations at ambient conditions. It has been shown to measure the total mass of $PM_{2.5}$, including semi-volatile ammonium nitrate and organic material (Grover et al., 2005) and has demonstrated equivalence to the reference measurement in the UK (Harrison, 2006). As discussed, the reference measurement is prone to both positive and negative artefacts from the adsorption of organic gases onto the filter, absorption and evaporation of semi-volatile components and the incomplete removal of particle bound water. Equivalence to this method should therefore be considered with these uncertainties in mind and an increase in the magnitude of any of these effects could result conditions out the range for which the FDMS has demonstrated equivalence.

The FDMS mass detector and sampling system was based on older TEOM technology. The FDMS sampled air through an R&P PM_{10} inlet at 1 m^3 h^{-1} and 0.18 m^3 h^{-1} was diverted to the microbalance. As variation on the TEOM method, the diverted air passed through a diffusion dryer to remove water from the sample; this allowed the mass to be measured at 30 ˚C rather than 50 ˚C. After the dryer, measurement was alternated between two cycles (base and purge), switching between them every 6 minutes; the change in mass on the filter was measured by the microbalance during both cycles. The FDMS base measurement provided a mass concentration of PM_{10} analogous to that measured by the TEOM; the difference being the dryer and the reduced sampling temperature.

During the purge cycle a filter, chilled to 4 ˚C, removed particulate matter from the sample stream. This purged air was passed through the microbalance filter and the change in mass of filter measured. A total particulate matter concentration measured by the FDMS was calculated as FDMS base minus FDMS purge. To enable a valid comparison between the measurement methods, adjustments were made to the FDMS (where the instrument configuration required) so that measurements were reported at ambient temperature and pressure..

3.5. PM Reference Method

During the equivalence trial in the UK (2004-2006), Leckel Kleinfiltergerat LVS1 samplers were used to collect PM_{10} onto a pre-weighed Emfab filters (Pall Corp., NY, USA; Type: EMFAB TX40HI20-WW; Part No.: 7221) at a flow rate of 2.3 m3 h1. Filters were loaded up to 8 days in advance and removed within 1 h of sample changeover; at 10 am or 11 am each day. Filters were then transported to the laboratory under chilled conditions, re-weighed under standardised conditions in a glove box 20 (±1) ˚C and 45 (±5)% relative humidity after a suitable period of conditioning to determine the mass of particulate collected on the filter. Measurements of sample volume at ambient conditions were used to calculate a mass concentration of PM_{10}. The conditioning and weighing methodology followed the CEN methodology (CEN, 2014) although stricter protocols for handling and weighing were also used as proposed in Brown et al. (2006). These included chilled storage and transport, additional conditioning time pre- and post-exposure, tighter temperature and relative humidity controls and the reweighing of unloaded and loaded filters to ensure repeatability (leading to discarding of filters) (Harrison, 2006).

4. Measurement Locations

4.1. King's Cross Construction Site - Coopers Lane, Camden

The Coopers Lane monitoring site is in a background location to the south west of the Argent's King's Cross construction site and is designed as an upwind reference location. During the long term operation of this site other construction activity, such as the building of the Francis Crick Institute have also impacted on measurements.

Figure 3: Coopers Lane monitoring site

4.2. Lend Lease Construction Site - Heygate Estate, Southwark

The Heygate Estate comprises an area of 90,000 m^2 in Southwark, central London. The old estate buildings were demolished in two phases, starting in April 2011 and completed in November 2014. New domestic buildings, a park, retail spaces and community areas are currently being built as the new Elephant Park. As such, the principal sources of local emissions of PM were the demolition and construction activities in the surroundings.

Two Air Quality Monitoring Sites (AQMS) were located on opposite sides of Deacon Way separated by 10 m, named North (N) and South (S) AQMSs, respectively; both inlets were at a height of 2.5 m. The traffic along Deacon Way was only associated with the construction activity (construction machinery, delivery trucks, etc.). Public traffic flowed along Heygate Street, which runs parallel south to Deacon Way.

A background monitoring site in the perimeter of the demolition site was also equipped with an Osiris instrument.

Figure 4: A Location of the Heygate estate in London; B the made road surface, C the unmade road surfaces,

4.3. Garth Road – Merton

Measurement and sampling equipment was installed at two locations in Merton, south London; the rear garden of a house in Haydon Court and the rear garden of a house in nearby Salcombe Drive. The measurement strategy was designed to focus on PM_{10} sources close to Haydon Court with Salcombe Drive acting as a background site. By placing two monitoring sites less than 500 m apart the measurement analysis was designed to be able to detect sources at the local scale that would affect one site more than the other and separate these from distant sources that would affect both locations equally. The instruments were run on battery and it is unclear whether the heaters were enabled during sampling; the implications of this are discussed in results section of this report.

Figure 5: Map showing the locations of the measurement and sampling locations. Haydon Court is shown in red and Salcombe Drive in yellow

5. Results and discussion

5.1. King's Cross Construction Site - Coopers Lane

An FDMS and Osiris were co-located at the Coopers Lane monitoring site (Figure 3), close to the King's Cross redevelopment. The six-year data set spanning 2009 to 2015 offers a unique opportunity to assess the long-term variability and seasonality when comparing an Osiris with a reference equivalent instrument and provides evidence to place other short equivalence trials in context.

The PM_{10} measurements for both the FDMS and the Osiris are shown in Figure 6; these demonstrate the excellent data capture from both instruments. There was a clear seasonality in the FDMS PM_{10} measurements; peak concentrations occurring during the spring which is not fully reflected in Osiris measurements.

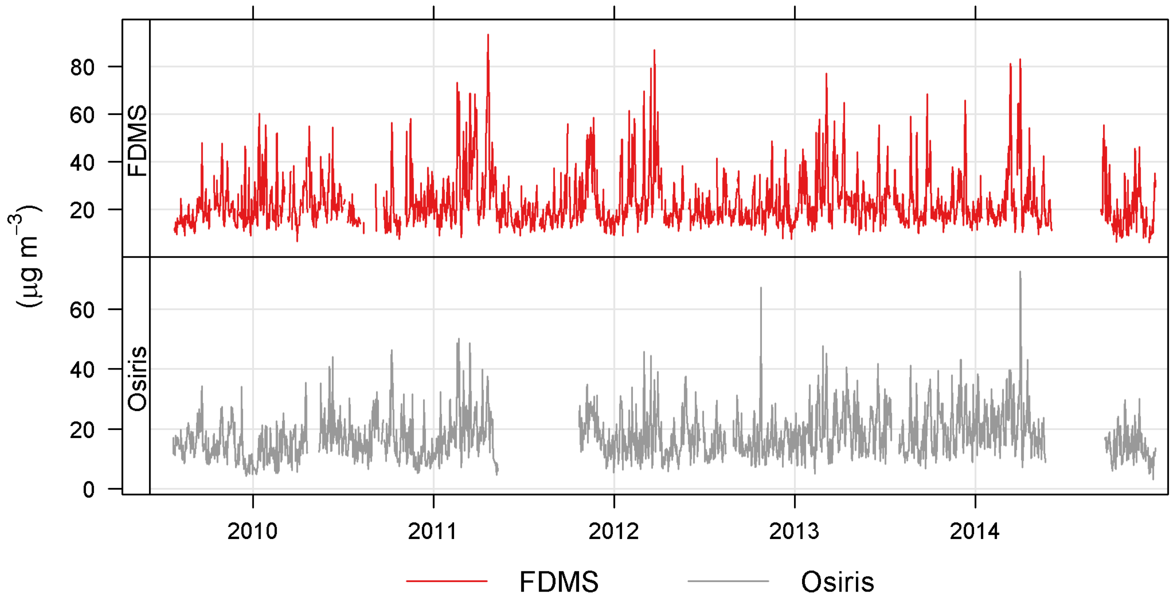

Figure 6: Daily mean PM_{10} from the FDMS and Osiris at Coopers lane

The differences between these two instruments (FDMS-Osiris) have been explored by examining the monthly and hourly means, shown in Figure 7. Figure 7 (top) shows seasonality in the daily differences but also a change, or trend, over time; after 2013 the Osiris measurements were often greater than the FDMS. Figure 7 (left) shows that the difference between the two methods had a clear seasonality; the largest differences occurred during winter, spring and autumn and the measurements were much more equal during the summer months of June, July and August. This mostly likely reflects the different composition of PM_{10} during these periods as a result of the influence of varying sources, meteorological effects along with the difference between the sample conditioning and measurement principles of the two instruments. The diurnal variation of the mean difference between the two instruments was relatively uniform.

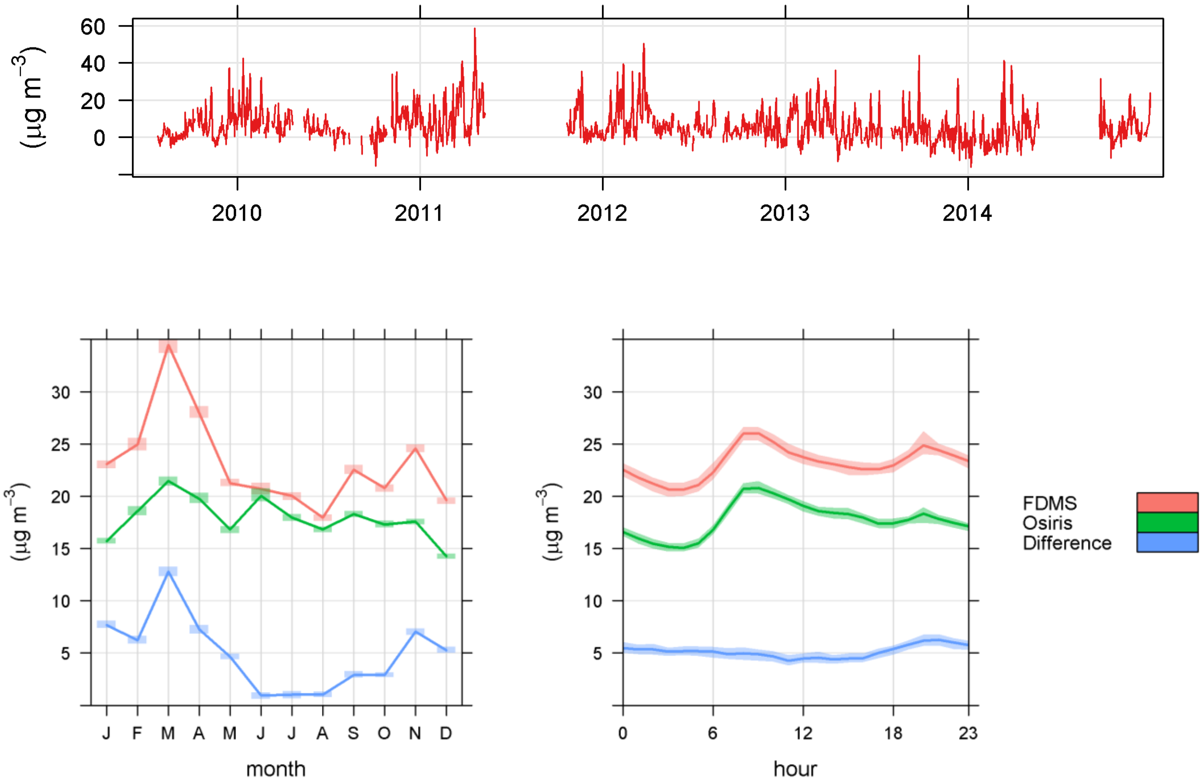

Figure 7: Measurements from the FDMS and Osiris at Coopers lane. The top panel shows the daily mean difference between the instruments. The lower panels show the difference along with the mean measurements from each instrument. This is shown as a monthly mean (left) and as a diurnal mean (right).

The relationship between the daily mean FDMS and Osiris PM_{10} measurements is shown in Figure 8 alongside the slope, intercept and R^2 from orthogonal regression. Overall, this analysis demonstrates a poor agreement between the instruments and results in a lower slope and larger intercept than the previous equivalence trials reported in Table 2. This may be the result of the wide range of atmospheric conditions being examined over the 4 ½ years studied or due to drift and instrument response changes during this period. Nevertheless, given that the location and operating procedures at Coopers Lane were more aligned with those employed at construction measurement sites, it may provide a more realistic estimate of the comparability of the Osiris to reference equivalence measurements than short-term equivalence trails.

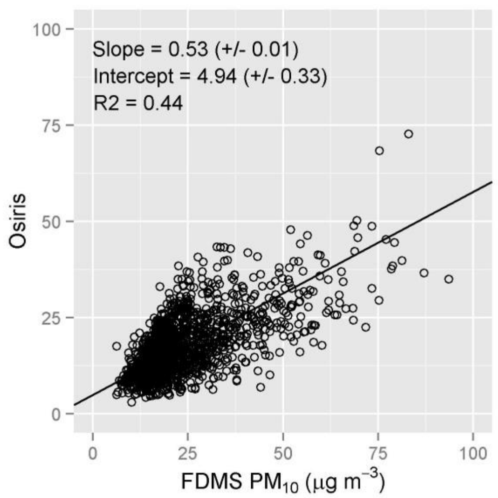

Figure 8: Correlation between daily mean FDMS and Osiris PM_{10} measurements

5.1.1. Monthly and seasonal variation

Data was split into 49 separate 3-month data sets, starting every month, to examine whether there were seasonal or long-term variations in the relationship between the two instruments. Orthogonal regression analysis was undertaken on each dataset to provide a monthly time-series which reflected both longitudinal and seasonal variation. The results of this analysis are summarised in Figure 9.

Regression statistics demonstrated that the relationship between the two instruments fluctuated substantially over time; slope 0.19-1.33 (mean 0.61, median 0.61), the intercept -5.59-9.39 µg m^{-3} (mean 2.94 µg m^{-3}, median 2.84 µg m^{-3}) and R^2 0.19-0.91 (mean 0.46, median 0.45). There was no clear seasonal variation or longitudinal trend, however, the final four sets of regression statistics, that occur after a repair, exhibit lower slopes, higher intercepts and lower R^2 than average which may indicate that these are erroneous. A sensitivity analysis showed that this small number of points did not affect either the overall regression or the summary regression statistics.

Figure 9: Orthogonal regression statistics of 3-monthly rolling datasets from Coopers Lane (error bars represent uncertainty)

To explore whether a seasonal variation in the relationship between the two instruments, driven by changes in PM composition, source or meteorology was present, the regression statistics were grouped by month of year as shown in Figure 10. The median slope varied between 0.49 and 0.78 and was notably higher between April and August (except a dip in May). The median intercept and R^2 were more uniform through the year 0.03-3.8 µg m^{-3} and 0.30-0.54 respectively. The greater slopes during the warmer summer months may have been due to:

1. Lower volatile PM concentrations resulting in less divergence caused by the heated inlet system in the Osiris.
2. Higher concentrations of non-volatile and/or coarse PM due to dry weather and/or increased construction activity.

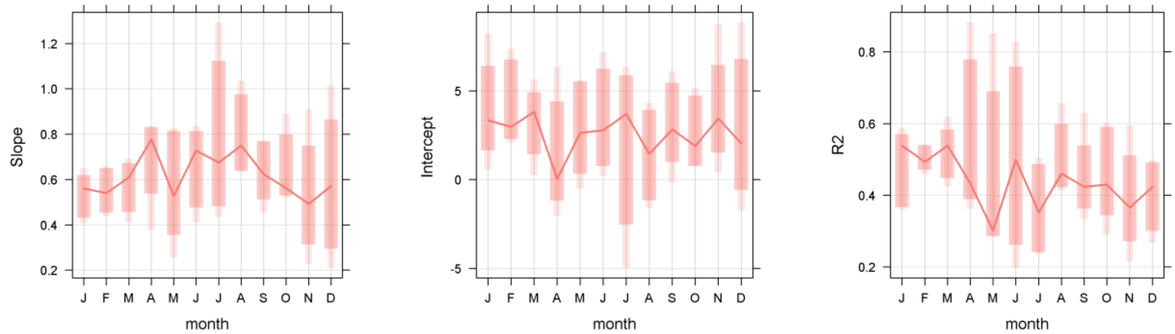

Figure 10: Median orthogonal regression statistics of 3 monthly rolling datasets from Coopers Lane grouped by month (bars represent 75th and 95th percentiles)

5.1.2. Influence of composition

An increase in volatile PM results in an increase in PM mass concentration, however there are many sources of ambient PM that can confound this. It is important to consider the frequency distribution of measurements with respect to both mass and volatile PM, as shown in Figure 11. The FDMS mass measurements were log-normally distributed with a mode at 16 µg m^{-3} while the volatile PM measurements had a mode 3 µg m^{-3}. The number of FDMS measurements at high concentrations was very low, as was the number of volatile measurements at high concentrations.

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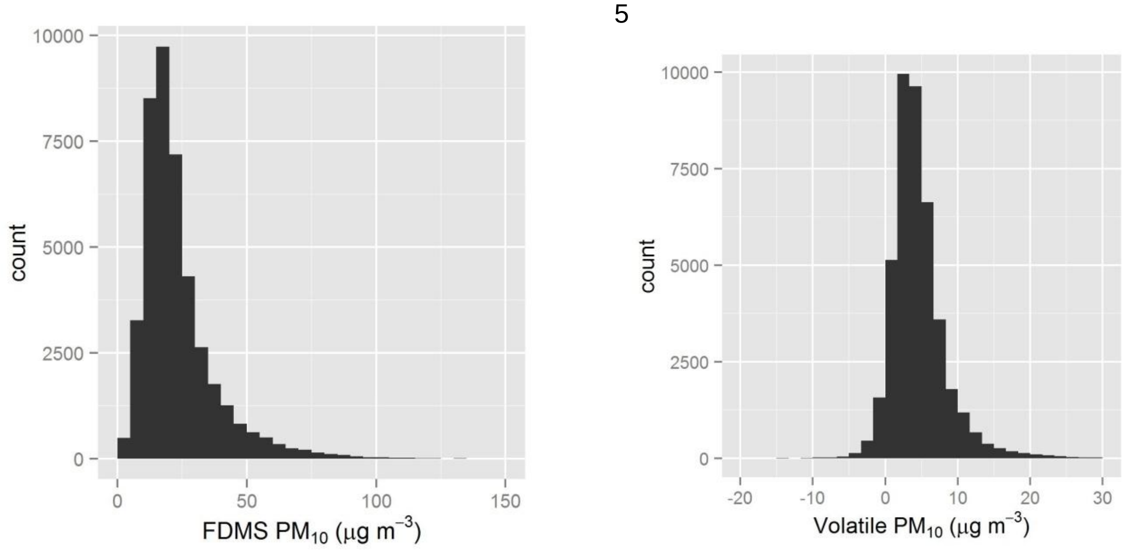


Figure 11: Distribution of measurements from Coopers Lane; FDMS mass (left), volatile PM (right).

The data was reordered so that the range of FDMS mass concentrations is considered alongside the volatile PM concentration; as shown in Figure 12. This demonstrates that the median FDMS concentrations tended to increase with increasing volatile PM concentration but that many of the greatest concentrations occurred when volatile PM concentrations are not elevated. It also shows that the range of FDMS mass concentrations when volatile PM concentrations is either high or low is small; this can affect the robustness of any regression analysis. The width of the box is proportional to n and it can additionally be seen that the majority of FDMS measurements occurred when both the mass and volatile PM concentrations were low.

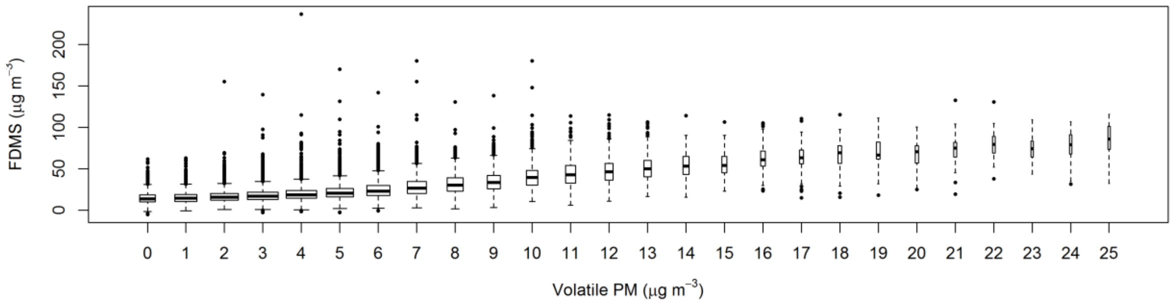


Figure 12: Distribution of mass concentration sorted by volatile PM data from Coopers Lane FDMS, width of box is proportional to n

To investigate whether the relationship between the instruments varied as a function of volatile PM composition, the co-located hourly Coopers Lane data was stratified by 1 µg m^{-3} increments in the co-located measurement of volatile PM measured by the FDMS. Data sets with less than 20 measurements were deemed insufficient to generate a robust regression relationship. Orthogonal regression between the PM_{10} measurements from the two instruments was undertaken on the remaining 29 datasets and the resulting slope, intercept and R^2 is shown in Figure 13.

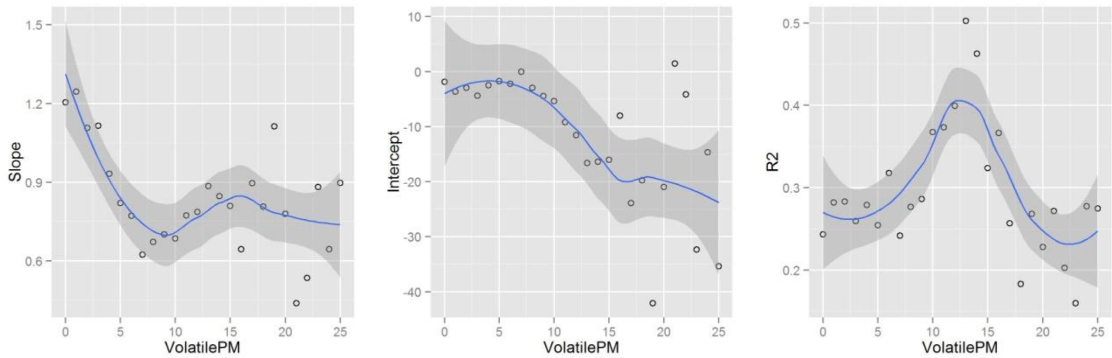


Figure 13: Regression analysis between FDMS volatile PM and Osiris PM_{10}, stratified by 1 µg m^{-3} bins of volatile PM

In general, grouping data into these smaller datasets and using hourly mean concentrations reduced the correlation coefficients compared with those reported in previous sections. As the volatile concentration increased towards 10 µg m^{-3} the slope decreased from 1.3 to 0.7 as the Osiris volatilised an increasing proportion of the PM_{10}. At volatile PM concentration >10 µg m^{-3} the slope stayed relatively constant but the intercept gradually decreased; this indicated that at the higher volatile PM concentrations the relative response stays the same but the intercept simply shifted to the downwards due to the loss of the additional volatile PM with an approximately 1:-1 change in intercept with increasing volatile PM. This demonstrated the complex relationship between the instruments that is dependent on the aerosol composition and the proportion of volatile PM in the ambient PM mixture.

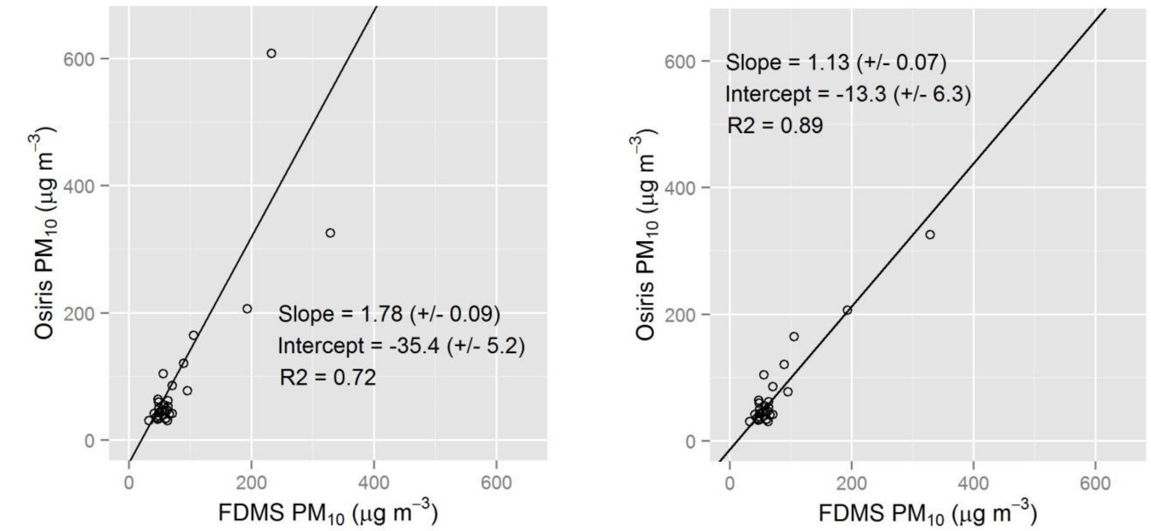
5.1.3. Influence of construction activity

The influence of construction activity on the instrument performance was examined in three ways.

- Using wind direction to compare PM from construction areas with PM from non-construction areas.
- Looking at instrument performance during known periods of very local construction activity.
- Looking at PM_{10} concentrations in excess of the trigger value proposed in work package 1.

5.1.3.1. Wind direction analysis

Long-term construction areas during the analysis period were principally to the east and to the south of Coopers Lane associated with the King's Cross development and the construction of the Crick Institute. The FDMS and Osiris data from Coopers lane was grouped by 10 degree wind sector and



orthogonal regression was undertaken on each dataset. The results are shown in Figure 14. Greater slopes were found during wind direction from the south and R^2 was greatest from the south east and south. However, construction was not the dominant PM source in any wind direction; sources were diverse by wind sector and, with no means to account for seasonal differences, this analysis was therefore inconclusive.

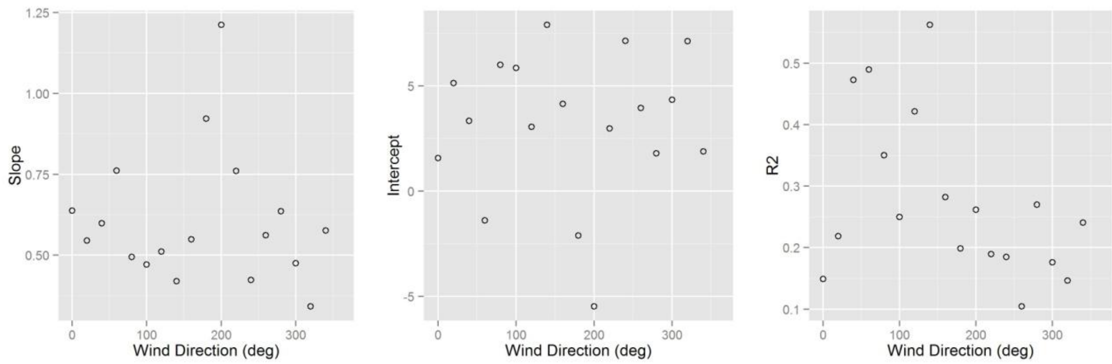


Figure 14: Correlation between the Osiris and FDMS PM_{10} grouped by 10 degree wind sector

5.1.3.2. Local Construction Activity

Paving work took place close to Coppers Lane during 2015. Although this was outside the main ratified data period initial quality assurance checks indicated no issues and this section alone considers the 2015 data in addition to the 2009-2014 data. By examining the time series of data between February and April 2015 and comparing to London mean background concentrations; one day in February (21st) and seven days in March (6th, 7th, 9th, 10th, 11th, 12th & 13th) were identified as being influenced by construction activity. Construction was always undertaken between 8 am and 8 pm was allowing the analysis to be further constrained to these hours. To focus on times when construction dominated PM_{10} and thereby reduce the influence of background PM on the relationship the analysis focused on the higher concentrations only. Using a stepwise approach, a threshold of 30 µg m^{-3} was chosen as this created a sufficiently large dataset (n=31) to enable a robust regression. The results of this regression analysis are shown in Figure 15.

The left-hand figure shows all 31 data points and resulted in a slope of 1.68 with a large negative intercept (-35.4 µg m^{-3}). This large slope and large negative intercept was driven by the single point at around 600 µg m^{-3} measured by the Osiris. Closer examination of the time series showed that this was a period of sustained construction activity at the site and it was surmised that the switching of the FDMS between sample and purge cycles led to it missing some of the peak concentrations and measuring a concentration lower than the Osiris. The regression analysis was therefore repeated, removing this outlier and is shown in the right hand figure; here the slope is closer to one and the intercept somewhat closer to zero.

Figure 15: regression analysis between FDMS and Osiris mass during period of local construction, all data (left) and excluding one outlier (right).

5.1.3.3. PM_{10} above the µg m^{-3} trigger

It is not possible to stratify the dataset by PM_{10} concentration and still maintain sufficient data range to enable a robust regression as there were insufficient data points at high concentrations. Instead the ratio of FDMS to Osiris hourly mass concentrations was calculated for each 10 µg m^{-3} FDMS mass bin as a proxy for a regression slope calculation. The results of this analysis are shown in Figure 16 and the median values are summarised alongside in

Table 3. At PM_{10} concentrations <10 µg m^{-3} the Osiris tended to measure lower than the FDMS but at higher concentrations the mean ratio was approximately 0.5 (very similar to the 0.53 shown in Figure 8 for the regression of all data). At PM_{10} close to and greater than the proposed 190 µg m^{-3} trigger from work package 1, this ratio was difficult to interpret due to the low number of measurements and there was no consistent evidence on which to base a correction slope for the Osiris.

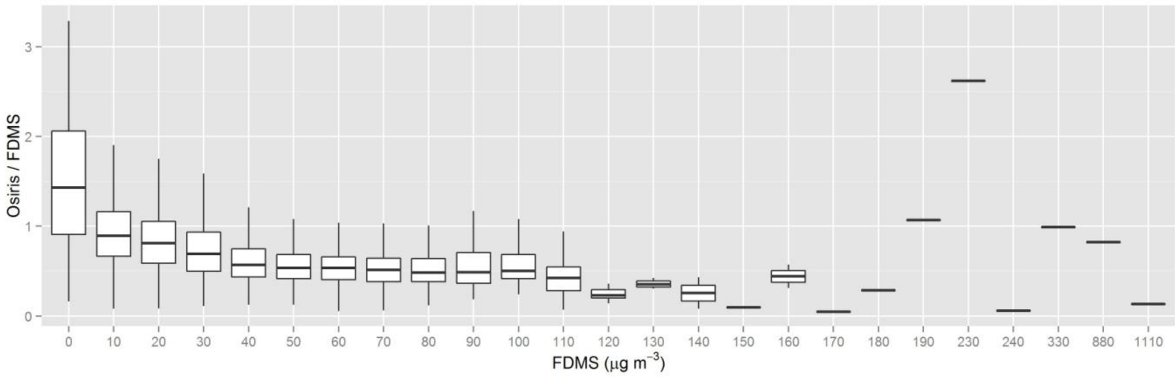


Figure 16: Mass Osiris / FDMS stratified by 10 µg m^{-3} FDMS mass concentration bins

Table 3: Median Osiris / FDMS mass and number of hourly measurements (n).

FDMS	Median Osiris / FDMS	n
0	1.81	769
10	0.89	12987
20	0.81	16889
30	0.69	6961
40	0.57	3084
50	0.53	1481
60	0.53	869
70	0.51	475
80	0.48	249
90	0.485	144
100	0.5	64
110	0.42	36
120	0.23	17
130	0.355	4
140	0.255	2
150	0.1	1
160	0.44	2
170	0.05	1
180	0.28	1
190	1.07	1
230	2.62	1
240	0.06	1
330	0.99	1
880	0.82	1
1110	0.13	1

In summary the only strong evidence for a correction slope for the Osiris at concentrations relevant to the 190 µg m^{-3} threshold was provided by the analysis of the very local construction source. This gave a slope of 1.13 (+/- 0.07) with an intercept of 13.3 (+/- 6.4). The limited data used for this slope and the large negative intercept preclude using this as a correction slope going forward. However, the slope was not substantially different from 1 and the other evidence from examining the relationship between the instruments by wind direction and by concentration does not yield any evidence for an alternative slope.

The analysis of ratio between the Osiris and FDMS mass at different concentrations demonstrated that the relationship between the two is not uniform across the concentration range. This is consistent with the analysis of the relationship at different concentrations of volatile PM in section 5.1.2 and confirms that supposition that the instruments respond differently to different PM compositions.

5.2. Garth Road, Merton - E-Sampler measurements

Data for the E-Sampler is available from a study in Garth Road, Merton (

Figure 5) where two E-samplers were located on either side of a park. Compared with Coppers Lane this dataset has some limitations principally the short duration (6 weeks) and lack of a co-located reference equivalent instrument. Nevertheless, examination of this dataset should add to the very limited available data on this instrument. The close location of a pair of E-samplers provide an opportunity to compare the performance of two E-samplers and PM_{10} concentrations were also compared with the local PM_{10} measurements made with a nearby background TEOMvcm at Barnes Wetlands, Richmond, and with the London-wide mean measurements of volatile PM measured using FDMS. The hourly mean time series of these measurements are shown in Figure 17.

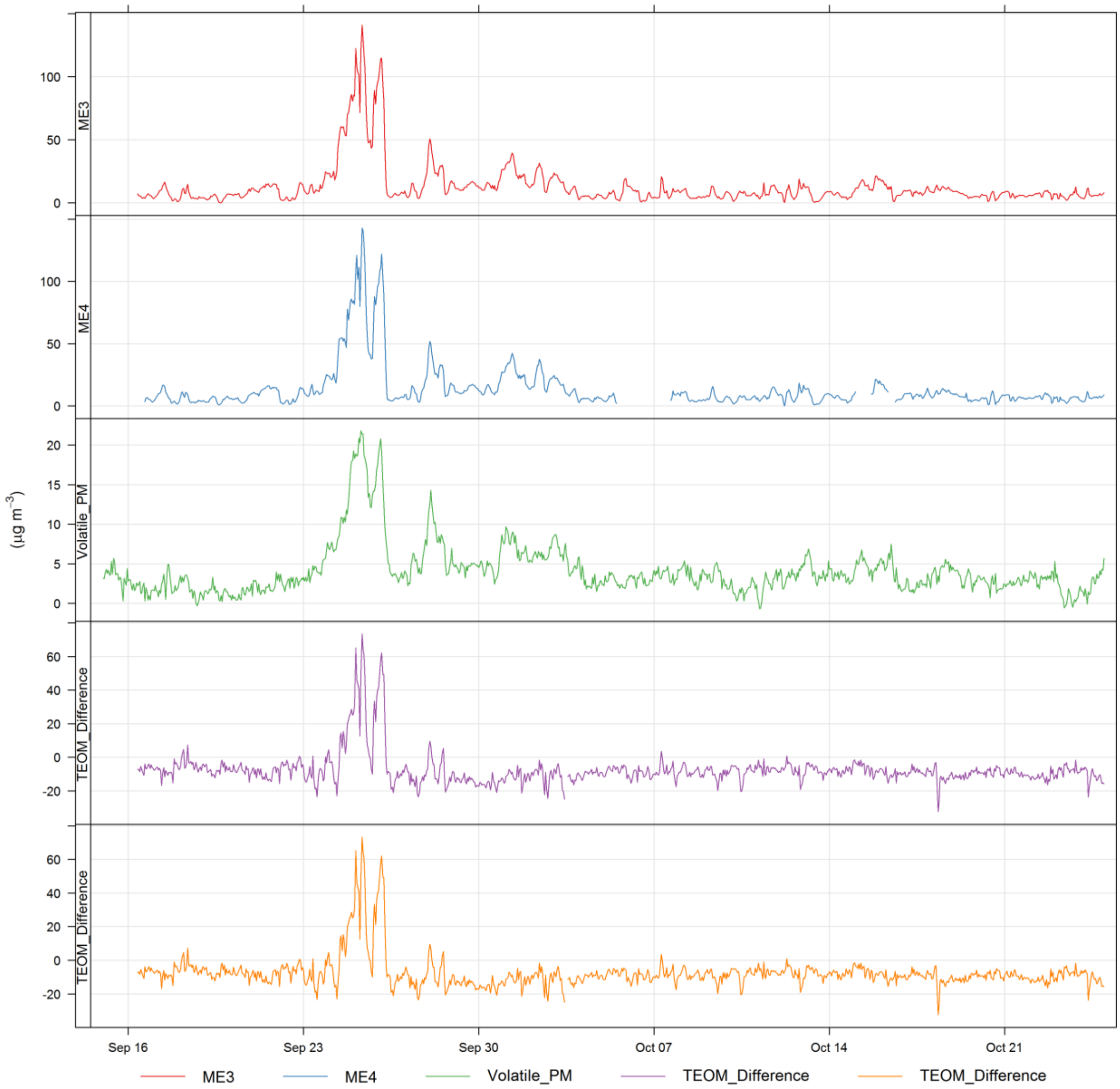


Figure 17: Time series of hourly E-Sampler measurements compared with each other and with the London mean volatile PM and the Richmond Barnes TEOMvcm

Although not co-located the measurement locations were very close (less than 500 m apart) and in similar background locations (residential gardens). The level of agreement between the two E-Samplers was generally good (within ±2 µg m^{-3}) except for a period between 24^{th} and 26^{th} September. A closer examination of the time series shows a 15-30 min time shift between the instruments during this period which caused substantial inter-sampler variability. It is unclear whether this was due operator error or software error as the measurements agreed again within 24 hours.

As shown in Figure 17 (bottom) and Figure 18 the agreement between the (mean of) the E Samplers and the VCM corrected TEOM at the Richmond Barnes Wetlands site was not always good. Although the measurements at lower concentrations (<50 µg m^{-3}) were relatively consistent, at higher concentrations they deviated by a factor of 2. This deviation was coincidental with an increase in the volatile PM concentration measured in London and demonstrated that the E-Sampler is overly sensitive to aerosols mixture when volatile PM is elevated. This was likely to be a consequence of the heater not being turned on or not working correctly.

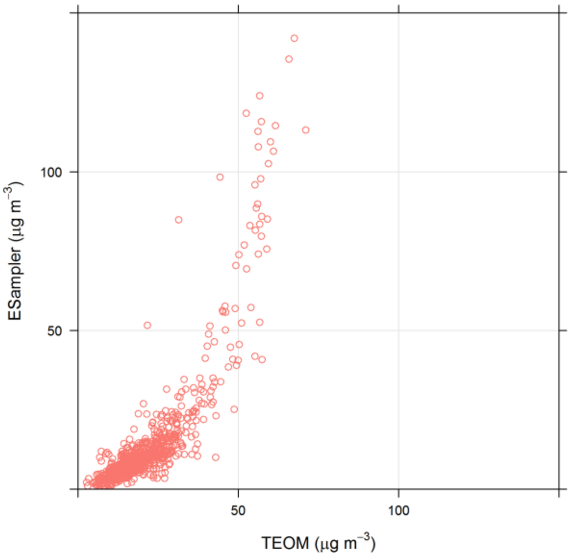


Figure 18: Scatterplot showing relationship between the TEOMvcm at Richmond Barnes and the mean of the two ESamplers at Garth Road, Merton

Volatile PM has been shown to be highly correlated with ammonium nitrate concentration in London (Green et al., 2009) and elsewhere (Grover et al., 2006). Ammonium nitrate exists in equilibrium in atmosphere between its gaseous and aerosol phase, it is hygroscopic and ammonium nitrate particles increase in size and mass as they take up water. As a consequence many instruments, including the E-Sampler, heat or dry the sample to reduce the impact of water on the measurement. This is an especially important consideration for instruments which use the particle size to infer the mass.

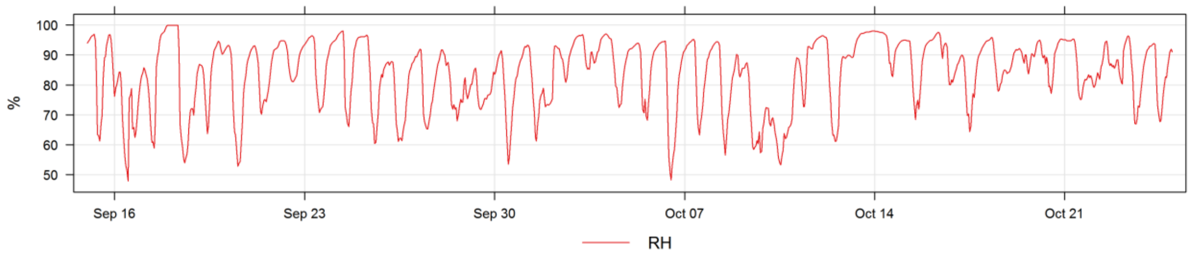


Figure 19: London mean relative humidity measurements during the E-sampler deployment.

As a default E-sampler heaters would be switched on when relative humidity was greater than 50% and thus should have operated during all of the measurement period (Figure 19). The heater can, however, be disabled to conserve power when operating on batteries. Given the apparent sensitivity of both E-samplers to volatile PM it appears that the sample heating system was not switched on, or was not functioning. This would be consistent with the lack of mains power hook-up during the Garth Road project.

5.3. Long-term stability of OSIRIS measurements

The measurements at the Heygate construction site allowed an opportunity to examine the long-term stability of the Osiris.

Instruments were subject to a high-level of quality assurance; including two-weekly changes of inlet filters, flow calibration using a transfer rotameter along with six-monthly service and manufacture's factory calibration.

To assess the long term stability of two instruments separated by 10 m (AQMS-N and AQMS-S), very local influences of the construction site were first eliminated by considering only hourly data from Sundays when no construction activity took place. Orthogonal regression was performed on the paired measurements shown in Figure 20. Several changes can be seen between the instruments. An increase in the slope was seen in the first half of the dataset before a step change in the middle of the time series when the slope returned to approximately 1:1 after service. This step change can also be seen in Figure 21 (left) where two populations are clear; some of these suggest a slope of around 2 while others would be well represented by a slope of around 0.5. A scaling correction was therefore applied to the dataset with the resulting final dataset shown in the right-hand figure showing a significant improvement.

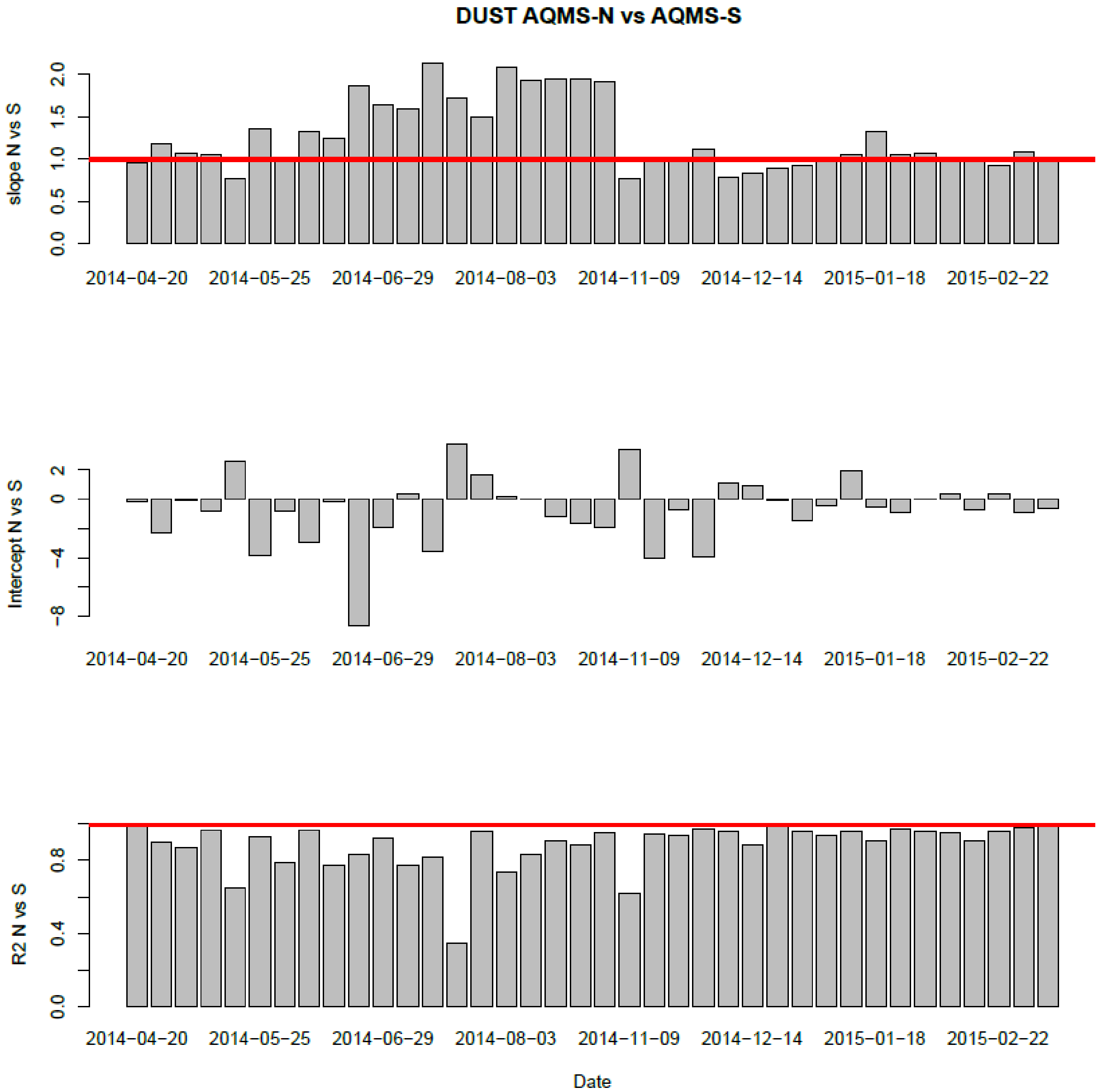


Figure 20: Time series of the slope, offset and determination coefficient for the hourly comparison of dust concentrations measured by two Osiris at Heygate on Sundays.

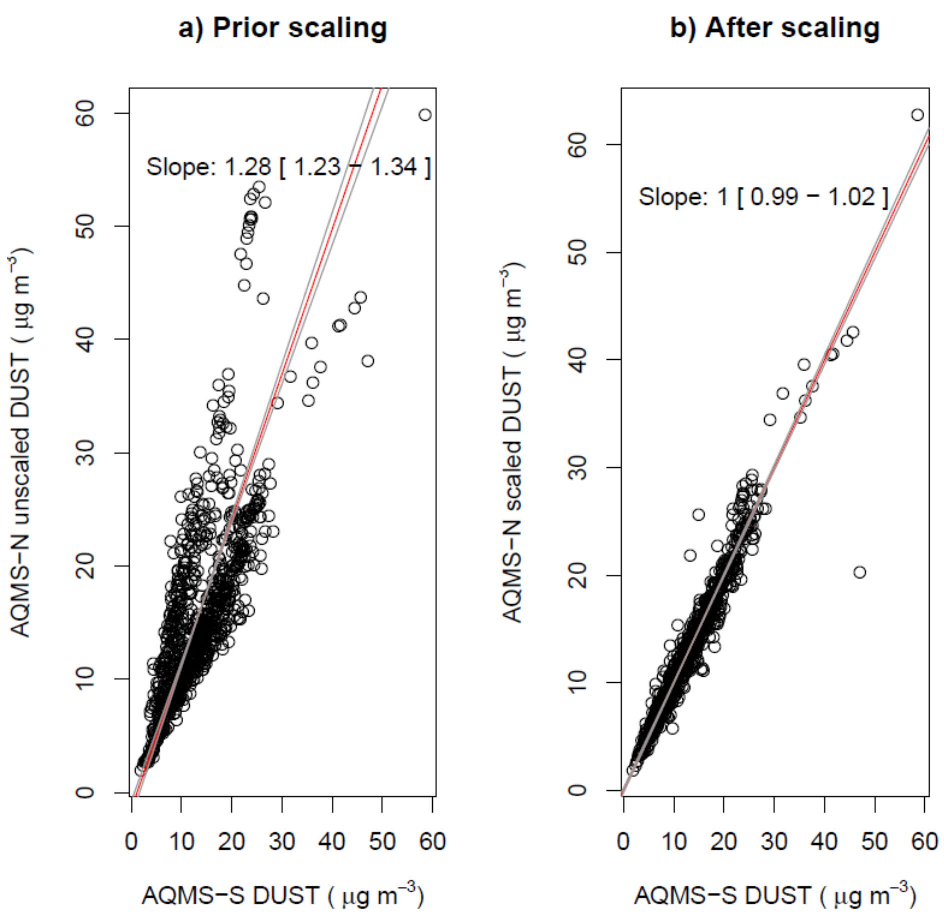


Figure 21: Scatterplot showing relationship between two Osiris instruments at Heygate construction site between April 2014 and April 2015 as measured (left) and after correction with the calculated regression slopes and intercepts (right)

This analysis was extended to an instrument at the perimeter of the construction site approximately 100m to test whether this approach could be adopted more widely to normalise instruments across a site; the results of this analysis are shown in Figure 22. Prior to scaling there were different populations within the relationship, varying between 1:2 and 1:½ that would clearly have a significant impact on the alert threshold. However, the slope between instruments was much improved (from 1.28 to 0.99) by the scaling process and the scatter is also substantially reduced.

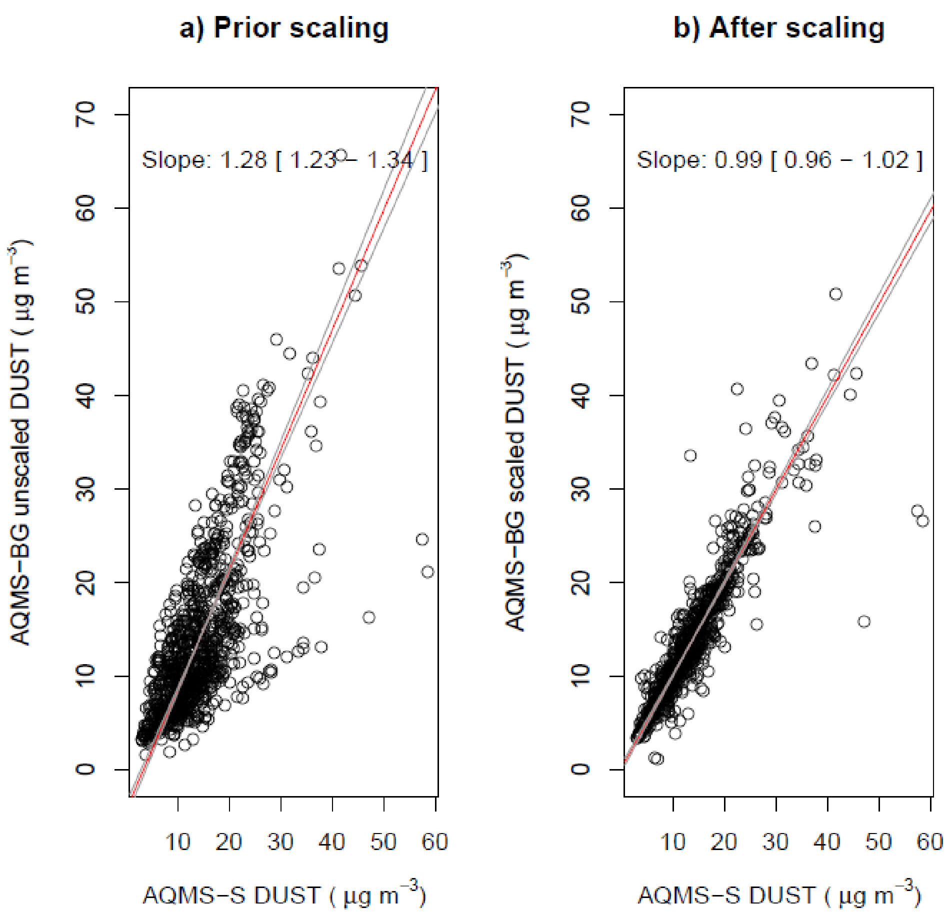


Figure 22: Hourly comparison of the dust concentrations measured in AQMS-BG vs AQMS-S on Sundays a) before b) after the data was corrected for drift.

This evidence raises concerns regarding the long term stability of the Osiris under standard operating conditions. The ability to detect these changes in response is often difficult due to changes in local sources that are inherent at construction sites. However, the application of this correction method suggests that it may be possible to apply this approach to account for sensor drift *post hoc* if periods when sources are relatively uniform (such as Sundays) can be identified. This would be challenging to undertake in real-time to provide improved measurements for an active notification system, consequently the issues of sensor drift are of genuine concern for site notification alerts. However, it could realistically be employed to highlight outliers and to correct data for investigative studies.

6. Discussion and conclusions

This report compared instruments that are typically used for construction site monitoring with EU reference methods. It sought to inform the interpretation of the data from these instruments when used in construction environments and also to inform the measurement of alert trigger levels as part of dust management. Data was available from pre-existing equivalence trials and co-location data from a number of studies in London.

Previous MCERTs equivalence trials consisted of short-term (a few months) comparisons against the EU reference method. However, the trials were undertaken at an urban background location that was not influenced by construction activity. The trials therefore did not adequately reflect the particle mixture found around construction sites or the concentration range that incorporated the trigger level. Indeed, the indicative monitors are only MCERTS certified in the 0-150 µg m^{-3} range (E Sampler) and 0-100 µg m^{-3} range (Osiris). Furthermore, the short-term nature of the trials meant that they did not encompass long-term drift and stability.

In the previous MCERTs equivalence trails, the E-sampler had a low measurement uncertainty (18%) while the Osiris was reported as either 46 or 50 % depending on which set of tests were chosen. Both the E-sampler and the Osiris were tested during a range of conditions; however the 2003 testing period for the Osiris was characterised by very high concentrations of volatile PM and this was reflected in the smaller slope. In MCERTS test the E Sampler agreed relatively well with the reference instrument. The ability of these instruments to cope with volatile PM is a consistent factor in interpreting their data. The conclusions from the MCERTs reports from both instruments recommended site specific correction factors where possible to reduce the expanded uncertainty of these measurements.

To investigate whether a more construction-specific correction factor could be derived, the 4 ½ years of co-located Osiris and FDMS measurements from the King's Cross boundary site in Coopers Lane were analysed in detail. The influence of local construction activity on the relationship between the instruments was investigated by examining by both seasonal and wind direction specific datasets; however no consistent patterns could be defined. The influence of volatile PM on the relationship between Osiris and FDMS was also examined and it was found that the instruments diverged with increasing volatile PM concentration. This divergence was complex; depending on both the absolute concentration of volatile PM and the proportion of volatile particulate in the ambient mixture. This demonstrated the importance of the volatile PM when interpreting the relationship between the light scattering instruments and the EU reference (and reference equivalent) instruments. The only strong evidence for a correction slope for the Osiris at concentrations relevant to the alert threshold was provided by the analysis of data during a period of local resurfacing work. This gave a slope of 1.13 (+/- 0.07) with an intercept of 13.3 (+/- 6.4). This slope was not substantially different from 1 and the limited data available along with the large negative intercept preclude using this as a correction going forward. Therefore in the absence of an alternative construction-specific correction factor, a correction factor of 1 is recommended and there is no reason to suggest that a 190 µg m^{-3} would not represent a valid construction trigger level for the indicative monitors..

A 2 ½ month period of E-sampler data from Merton was also examined. Two E Samplers were compared to a near-by TEOM (corrected using the VCM). This analysis again demonstrated the strong confounding influence of volatile PM on light scattering instruments. At concentrations less than 50 µg m^{-3} the relationship between the E-sampler and TEOMvcm was close to unity. However, when the PM mixture contained high concentrations of volatile PM the E-sampler measured concentrations 2-3 times that of the TEOMvcm. This contrasts with the E-Sampler performance during the equivalence tests. The correct operation of the heater during the Garth Road trial is therefore questionable. This highlights the need to ensure that the indicative samplers are operated in identical conditions and configuration to which they were tested. The sensitivity of the E-Sampler during the Garth Road trail is in contrast to the Osiris instrument, which measured concentrations below that of the co-located FDMS by volatilising, and therefore not measuring, the volatile PM.

It was clear that, as with all measurements of PM, the treatment of the sample is a key factor in making a reliable measurement. For indicative monitors, which use light scattering, controlling or normalising the water content of the aerosol by heating is especially important as it influences particle size and therefore the assumed mass especially when the PM mixture contains a high concentration of secondary PM. Also, as construction sites use aerosolised water, from hoses or mist cannons to reduce PM emissions, the concentration of water in the local atmosphere can therefore be especially high. Both these aspects may have implications for the trigger level detection. High concentrations of PM away from constructions sources tend to occur when there are high concentrations of secondary PM. If this fraction of PM causes an overestimation of PM concentrations then this will lead to false triggers; the correct operation of sample conditioning systems is therefore very important. It is possible to measure the sample temperature in the field and this should be considered as an additional regular quality assurance check. Nevertheless, these instruments will still measure large peaks in construction activity analysed in Work Package 1.

Given that breaches of the proposed trigger value are likely to be dominated by construction emissions the evidence from construction emission here suggests that no correction factor should be applied to these measurements. This is in contrast to the recommendations from equivalence test that imply the need for correction factors for the two instrument types investigated here based on the measurements of more typical ambient conditions. However, during times of high volatile PM measurements of PM_{10} close to the trigger concentration are likely to have additional uncertainty. Samplers with heated inlet systems are likely to underestimate at these times and those without heaters are likely to overestimate. However, peaks of construction PM_{10} that are well above the trigger concentration will be identified with less uncertainty from the confounding effects of volatile PM.

The issues with longer–term drift of the Osiris measurements might also apply to other light scattering instruments since all instruments of these types might be vulnerable to progressive dirtying of optics and clogging of sample flow controls. Good quality assurance is essential. Even for well-run instruments with regular servicing these drifts can lead to factors of between 0.5 and 2 times between pairs of instruments. Instrument comparisons can indentify outliers and drifting equipment. These instruments could be taken out of service for maintenance or corrected mathematically. Comparisons could be done based on times where no construction or utilise wind direction to comparing all sites that are upwind and away from sources.

The long term stability of indicative monitors is a cause of concern. Evidence from the measurements at Heygate Estate, which had new instruments and high-levels of site quality assurance (2 weekly visits for filter changes and flow adjustment as well as routine back-to-base servicing) but still experienced substantial sensor drift with divergences ranging from factors of 0.5 to 2. The level of drift in instruments operated with a lower quality assurance is likely to be higher.

While a method of *post hoc* data correction was found to be effective in correcting for this drift it would be difficult to apply in real-time without substantial data processing after collection. It could however be used to identify instruments which drift apart or to correct data to a background or upwind site where further analysis requires a higher level of quality assurance; especially when comparing concentrations during different periods of construction or pre and post construction periods.

It should be remembered that indicative monitors are lower cost analysers than EU reference and reference equivalence instruments (about ¼ of the cost) and would not be expected to report data of the same quality or consistency. They are operated in rapidly changing and challenging environments that are characterised by high levels of dust and often with nearby mist cannons or water sprays as dust mitigation. Equipment operation is often undertaken by relatively untrained staff. Nevertheless, some basic steps can be taken to maximise data quality:

1. Good quality sitting with a free movement of air around the inlet and clear lines of sight to expected sources
2. Correct configuration of instruments; paying particular attention to ensure that the sample system is heated to reduce interference from water and secondary PM.
3. Regular visits to change filters and adjust flows as necessary and to assess site environs to ensure that the monitor and location remain fit for purpose
4. Regular servicing, either on site or back-to-base for cleaning and re-calibration
5. Regular download and checking of data to ensure the equipment remains operational, to assess for consistency over time and make between instrument comparisons to identify outlier performance.

If these simple steps are followed then both the site alert system and any subsequent data analysis will be more successful.

The long-term drift would also introduce significant uncertainties if these types of instrument were used to compare PM_{10} during pre-construction with construction periods. This drift might lead to a false impression that a construction site was or was not affecting local air pollution. We believe that a better use of indicative monitors is as part of near-real time management of construction dust such as that in the GLA code of practice rather than in pre-construction monitoring to compare with construction periods.

The current test methods of PM_{10} monitoring equipment focus on measuring concentrations and particle types that occur in typical urban areas. This is not the same as construction dust. There is a clear need to test perimeter PM_{10} monitoring equipment in construction environments. There are three ways to achieve this:

1) Construction activities and emissions could be simulated and existing test platforms such as the one at the National Physical Laboratory could be used.
2) Paired reference equivalent and indicative monitoring equipment could be installed at construction sites and construction PM would be measured as they arose during the project.
3) A mobile test platform could be used and taken around construction sites to test a range of site activities.

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Re-assessment of the 250 µg m^{-3} action value

Work Package 3

Implications for construction site monitoring strategies

August 2016

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Environmental Research Group
King's College London

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Customer	HS2 Ltd.

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Report Number	WP3 – Implications for construction site monitoring strategies

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Contents

Summary

This project set out to reassess the trigger values given in the Greater London Authority (GLA) guidance for construction emissions and by the Institute for Air Quality Management (IAQM). These trigger values are used to indicate when PM_{10} from construction activities might be affecting local air quality; providing important near-real time feedback to operators and enabling them to take rapid and responsive measures to control emissions. The triggers are not health-based standards.

In urban areas PM_{10} comes from many sources including traffic and wood burning. Particles also come from natural sources such as sea salt and windblown dust. Smaller particles tend to be formed by combustion or chemical reactions between gaseous air pollutants and can remain in the air for a week or more meaning that very distance sources can affect our air. Some particles are easily volatile making them hard to measure. Construction sites can add to local PM_{10} concentrations. This can come from exhaust from construction machinery and also dust from many demolition and construction activities.

The trigger values were examined using measurements from nine construction sites covering a range of construction activities and locations. Measurements were made with modern EU reference equivalent instruments. This dataset comprised 1.8 million measurements and is the largest analysis of construction PM_{10} to our knowledge.

The majority of construction sites caused an increase in the number of days when the daily mean PM_{10} EU limit value concentration was exceeded. There was no consistency in the type of construction that gave rise to high peak concentrations suggesting the need to manage PM_{10} in all types of construction. The greatest PM_{10} was measured very close to construction activity consistent with what is understood about atmospheric dispersion. The distance between source and receptor is important, with concentrations falling with distance. There was a considerable difference between the worst and best sites indicating the scope for good site management practices to control construction dust. Additional local PM_{10} during the construction periods can also arise on haulage routes, most likely from the resuspension of tracked out material.

Measurements before or after construction were compared with those during construction period. Based on this analysis an hourly mean trigger value of 190 µg m^{-3} (PM_{10}) is recommended for the identification of construction dust. This trigger value is applicable in urban areas in main land UK. Compared with the trigger values given in the Greater London Authority (GLA) guidance for construction emissions and by the Institute for Air Quality Management (IAQM), the new trigger provides an important lowering of the false alarm rate giving site managers and the public greater surity that measured triggers will be due to construction activity.

Pre-scheme measurements are recommended where significant local sources could produce short-term PM_{10} peaks. Such sources include waste facilities and agriculture in rural areas. Based on data assembled for this project, baseline or pre-scheme measurements would not be necessary in most urban settings.

Many practical issues restrict the use of EU reference equivalent instruments around construction site. Smaller indicative light scattering instruments are therefore used in practice. These indicative instruments allow measurements in locations that would otherwise not be possible with EU reference equivalent methods. They open up the opportunity for more comprehensive measurement programmes close to sensitive populations or close to construction sources.

The use of indicative instruments introduces additional uncertainties but there was no evidence to support a modification to the trigger concentration of 190 µg m^{-3} when measured with indicative instruments.

The performance of indicative instruments from two manufactures was assessed through a review of previous studies and new datasets. For indicative monitors, especially those that use light scattering, controlling or normalising the water content of the aerosol by heating is especially important. The instruments performed badly as volatile particle concentration increased. Instruments can experience sensitivity drifts resulting in PM_{10} differences that can be as large as a factor of between 0.5 or 2.

Indicative monitors are lower cost analysers than EU reference instruments (about ¼ of the cost) and would not be expected to report data of the same quality or consistency. They are operated in rapidly changing and challenging environments that are characterised by high levels of dust and often with nearby mist cannons or water sprays as dust mitigation. Equipment operation is often undertaken by relatively untrained staff. Nevertheless, some basic steps can maximise data quality:

- Good quality siting with a free movement of air around the inlet and clear lines of sight to expected sources.
- Correct configuration of instruments; paying particular attention to ensure that the sample system is heated to reduce interference from water and secondary PM.
- Regular visits to change filters and adjust flows as necessary and to assess site environs to ensure that the monitor and location remain fit for purpose
- Regular servicing, either on site or back-to-base for cleaning and re-calibration
- Regular download and checking of data to ensure the equipment remains operational.
- Routine between-instrument comparisons to assess for consistency over time and to identify outlier performance. This could be achieved through non-working day comparisons.

Indicative instruments are not suitable for approaches that compare mean or median PM_{10} in pre-construction and construction periods due to instrumental drift. However, with state of the art quality assurance, indicative instruments can be deployed effectively in near real-time trigger and alerting systems, providing feedback to site managers and also protecting the public from exposures to high concentrations of construction dust. Concentrations of PM_{10} above the trigger values are dominated by coarse particles and contain a relatively low proportion of volatile PM, which plays to the strengths of these indicative instruments.

Research recommendations

Real-time construction dust measurement strategies are limited by the capabilities of current measurement devices. Research into measurement methods and their application is needed.

New standard methods need to be developed for the operational quality assurance and quality control for indicative PM_{10} instruments. Improved cross–comparisons between local networked instruments are likely to be fruitful. The long-term performance of indicative instruments also needs to be characterised through co-locations.

EU test methods (e.g. MCERTS in the UK) for PM_{10} monitoring equipment focus on measuring concentrations and particle types that occur in typical urban areas. This is not the same as construction dust. There is a clear need to test indicative PM_{10} monitoring equipment in construction environments.

1.0 Introduction

1.1 Background

The Greater Local Authority (GLA) guidance for construction emissions and that by the Institute for Air Quality Management (IAQM) have action levels or triggers values to indicate when PM_{10} from construction activities might be affecting local air quality. Developers should respond to significant breaches of the trigger threshold by stopping work immediately and ensuring best practice measures are in place before restarting. With breaches of the PM_{10} trigger value, the guidance suggests that local authorities can use their powers to prevent the statutory nuisance (GLA, 2014).

As used in the codes of practice, the 250 µg m^{-3} trigger value (15 minute mean) is designed to protect the local population from construction emissions. Construction site managers have expressed concern that breaches of the trigger concentration can happen without an obvious cause. False alarms may cause undue concern to people living around the construction site and can be disruptive to construction activities. It is also possible that the 250 µg m^{-3} trigger value is missing some emissions sources from construction that could be controlled by better working practices.

The 250 µg m^{-3} value was based on analysis of a single construction site in 1999. Urban air pollution and measurement techniques have changed since this time. This project was designed to reassess the 250 µg m^{-3} PM_{10} trigger level for construction emissions based on new data sets and more modern measurement techniques.

1.2 Aims

The project was divided into three work packages.

Work package 1 aimed to:

- Test the efficacy of the 250 µg m^{-3} trigger to discriminate between construction and non-construction PM_{10} events using data from different types of construction projects using new EU reference equivalent PM measurements. The project also aimed to profile the concentration ranges that can be expected in rural, urban and roadside environments in and around London in the absence of construction through a dataset assembled from around ten construction sites.

- Test the efficacy of alternative PM_{10} metrics based on longer averaging times and also those based on incremental concentrations above the urban background. Assessment of the pros and cons of pre-scheme measurements were also included in the scope.

- Seek evidence for the impacts of construction on local concentrations of NO_X, NO_2 and $PM_{2.5}$ where these data were available.

Work package 2 aimed to:

- Compare typically used construction site perimeter measurement devices to EU reference equivalent instruments to provide a conversion factor.

- Investigate periods of divergence between the instrument types to provide insight into methodological differences.

- Explore the operational divergence between perimeter measurement devices.

- Provide recommendations for the use of light scattering instruments to assess the proposed trigger concentration; these include recommendations on equipment operation and measurement interpretation.

Work package 3 aims to:

Assimilate findings and recommendations from work packages 1 & 2 on new trigger values to detect construction dust emissions and how these can be measured.

2 Results from work package 1: assessing the trigger values using reference equivalent measurements

Pollution measurements from nine construction sites were analysed using modern EU reference instruments. This dataset comprised 1.8 million measurements from London and south east England. It covered a wide range of different types of construction projects as shown in Table 1 and was the largest analysis of construction PM_{10} to our knowledge. For each site, measurements during construction activity were compared to periods before or after. Construction sites were found to be a clear source of local PM_{10} concentrations and many contributed to local breaches of the EU limit value.

Following extensive data analysis a revised trigger concentration of **190 µg m^{-3}** was recommended. This should be measured as an **hourly mean**. This trigger limit can be used to indicate when PM_{10} from construction activities might be affecting local air quality. The trigger was selected based on a predicted false alarm rate of not more than 0.1%. In practice around half of the construction sites measured no false alarms in the pre and post construction periods and the greatest false alarm rate was 1.4% of days

From the nine construction sites examined, the worst case showed the trigger being exceeded on around one day in three. Three construction sites showed triggers being exceeded on more than one day in 12. By contrast, some sites showed no more than the expected false alarm rate. This shows that there is considerable scope for good site management practices to control construction dust. Even by controlling peak concentrations, to ensure that the trigger is not exceeded, local PM from construction might still increase by 4-5 µg m^{-3} as a median over the construction project.

Local PM_{10} from construction can also arise from dust resuspension from the road surface along haulage routes away from construction sites.

Table 1. List of construction sites close to an Air Quality Monitoring Site (AQMS). Description of construction activity and air pollutants measured.

Construction activity	Construction site	Dates construction projects	Air quality monitoring site (AQMS) and code	Distance to construction (m)	Air pollutants measured
Refurbishment & external works to building	University of Westminster (London)	Jun - Dec 1999	Marylebone Road (MY1)	~5	PM_{10} (TEOM), NO_X, NO_2
Trunk road widening	A206, Thames Road (London)	Jan 2006 - Aug 2007	Bexley 6, Bexley 7, Bexley 8 (BX6, BX7, BX8)	~10	PM_{10} (TEOM, FDMS), $PM_{2.5}$ (TEOM), NO_X, NO_2
Landscaping, earthworks over 3.2 ha	Shepherds Bush Green (London)	Nov 2011 - May 2013	Hammersmith & Fulham 4 (HF4)	~10	PM_{10} (TEOM), NO_X, NO_2
Demolition of ten storey office building	Upper Thames Street (London)	6 Sept 2014 - 31 Mar 2015	City of London 8 (CT8)	~10	PM_{10} (TEOM)
Construction of electrical sub-station	Devonshire Place (Eastbourne)	3 Feb 2014 - 20 Feb 2014	Eastbourne 1 (EB1)	<5	PM_{10} (TEOM), NO_X, NO_2
New road junction layout and public area	Streatham Green (London)	28 Jan – 14 Feb 2014	Lambeth 6 (LB6)	0, within site area	PM_{10} (BAM)
Demolition & construction of 15 floor office (66Km^2), retail and residential	Central St Giles (London)	2007 to May 2010	Camden 3 (CD3)	~30	PM_{10} (TEOM), NO_X, NO_2
Demolition of house, excavation and construction of flats	Merton Road (London)	June 2011 – Dec 2013	Merton 2 (ME2)	~70-120	PM_{10} (BAM)
Phased demolition of blocks of flats and construction of new.	Blackheath Hill (London)	2010 to 2014	Greenwich 7 (GR7)	>10	PM_{10} (TEOM), NO_X, NO_2

3 Results from work package 2: assessing the performance of perimeter measurement equipment

Work package 1 (WP1) of this project recommended a revised trigger concentration of 190 µg m^{-3} measured as an hourly mean. This was based on measurements made using PM_{10} instruments that have demonstrated equivalence to the European Union reference method. Practical constraints mean that smaller and simpler instruments are generally used for perimeter measurements around construction sites.

Work package 2 (WP2) therefore considered the real-world performance of two commercially available instruments; the Osiris (Turnkey Instruments) and the E-Sampler (MetOne). In previous short-term tests, these instruments required correction factors to achieve an acceptable performance envelope for indicative instruments. The Osiris (Topas) has been subject to greater testing than the E-Sampler. These test results range from under reads of around 40% to over reads of around 30% with evidence of seasonal effects. Testing programmes have therefore recommended that local correction factors are established for PM_{10} measurement. The Osiris (Topas) was not able to meet the required 50% uncertainty envelope for measurements of smaller particles in the $PM_{2.5}$ size range.

For the first time, long-term (up to 4 ½ year) data sets were examined from locations within or close to construction sites. Both perimeter instruments had difficulties in the measurement of volatile particulate. During pollution episodes, this volatile particulate can dominate the air in urban areas of the UK and Europe. The Osiris tended to measure less than the reference equivalent method by a factor close to 0.5 but there was no single correction factor. The E-sampler tended to measure more than the reference equivalent instrument when volatile particles were prevalent. At times the E-sampler measured up to twice the reference equivalent instrument.

It was difficult to isolate periods with only construction dust from the datasets. Although based on limited data, there was no evidence that these instruments have a bias when measuring the relatively large and non-volatile particles from construction. There was therefore no evidence to support a modification to the trigger concentration of 190 µg m^{-3} when measured with indicative instruments.

In addition to difficulties in the measurement of volatile particles, even with high quality assurance control, Osiris instruments displayed long-term drift, with divergences ranging from factors of 0.5 to 2. The level of drift in instruments operated with a lower quality assurance is likely to be greater. The issues with longer–term drift found in WP2 are likely apply to other light scattering instruments since these instruments might be vulnerable to progressive soiling of optics and clogging of sample flow controls. A long-term dataset for the E-Sampler was not available and therefore no comment can be made.

It should be remembered that indicative monitors are lower cost analysers than EU reference equivalent instruments (about ¼ of the cost) and would not be expected to report data of the same quality or consistency. They are operated in rapidly changing and challenging environments that are characterised by high levels of dust and often with nearby mist cannons or water sprays as dust mitigation. Equipment operation is often undertaken by relatively untrained staff. Nevertheless, some basic steps can maximise data quality, as highlighted in WP2:

1. Good quality siting with a free movement of air around the inlet and clear lines of sight to expected sources
2. Correct configuration of instruments; paying particular attention to ensure that the sample system is heated to reduce interference from water and secondary PM.
3. Regular visits to change filters and adjust flows as necessary and to assess site environs to ensure that the monitor and location remain fit for purpose
4. Regular servicing, either on site or back-to-base for cleaning and re-calibration
5. Regular download and checking of data to ensure the equipment remains operational, to assess for consistency over time and make between instrument comparisons to identify outlier performance.

4 Additional Analysis

4.1 Testing the trigger value outside London and the south east.

WP1 used measurements from London and southeast England. To test the applicability of the trigger values elsewhere in the mainland UK, additional measurements from four other cities were considered.

Method

Urban background PM_{10} measurements for a five year period, between 2010 and 2014, were extracted from a copy of the UK Automatic Urban and Rural Network database held at King's. Cities were selected to cover the UK from north to south: Birmingham, Leeds, Newcastle and Edinburgh. For each location, the number of hours exceeding the 190 µg m^{-3} threshold value was calculated.

Results

The greatest number of hourly mean concentrations above the recommended 190 µg m^{-3} trigger value were measured at Birmingham Tyburn (Figure 1). This measured 10 hours in the five year period suggesting a false alarm rate of around 0.02%. Of these ten hours, six were on Guy Fawkes Night. Eight hours above 190 µg m^{-3} were measured at Leeds Centre and one at Newcastle. The Edinburgh monitoring site did not measure any hours with PM_{10} greater than 190 µg m^{-3}.

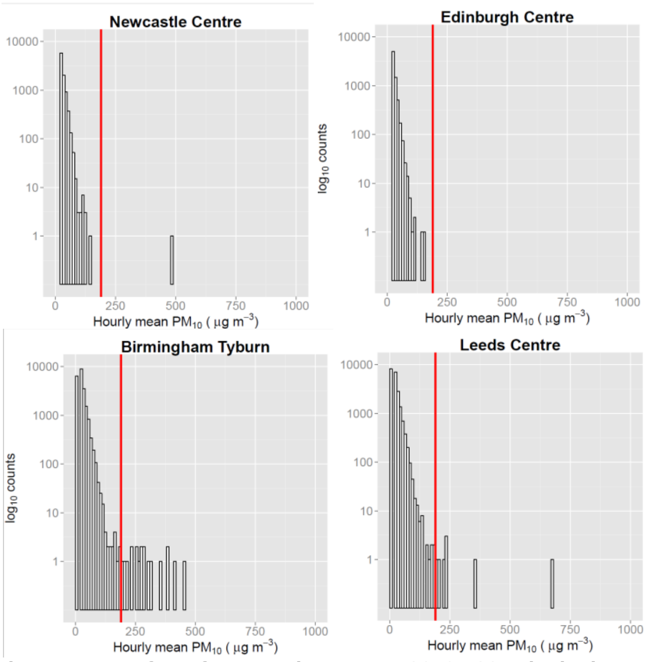

Figure 1 Histograms of hourly mean PM_{10} from four UK city centres 2010 - 2014 inclusive. 190 µg m^{-3} trigger is shown as a red vertical line.

Conclusion

Background PM_{10} concentrations in major UK cities outside London and the southeast would not lead to a significant false alarm rate. The recommended trigger can be used with confidence to identify construction impacts in other parts of main land UK. Background PM concentrations have a decreasing gradient with increasing distance from the continent (AQEG, 2012). Studies in Scotland, Wales or western and northern parts of England could yield more precise trigger values for these areas, however, we are not aware of suitable datasets for this purpose.

4.2 Assessing the likely impact of particle composition on perimeter PM_{10} measurement

WP2 highlighted the confounding influence of volatile particulates on the measurement of PM_{10} made by both the Osiris and E-Samplers tested. Although WP2 was able to draw upon a unique 4 ½ long data set of co-located Osiris and reference equivalent instrumentation, this dataset contained only a small number of data points which had been affected by construction emissions. To investigate further the likely impacts of volatile particulates on perimeter measurements, volatile PM measurements were added to the larger set of construction measurements created for WP1 as detailed in Table 1.

As described in WP2, the perimeter measurement devices using light scattering also have trouble with the measurement of smaller particle sizes (< 2.5 µm in diameter). The likely effect of this on construction dust measurements was also evaluated.

Method

Measurements of volatile PM were extracted from the London Air Quality Network database for each of the construction sites and periods indentified in WP1. Volatile PM_{10} measurements were the London-wide mean of those measured by TEOM-FDMS (Green et al 2009) and used in UK local air quality management (DEFRA, 2009, 2016). Particle size information, in terms of coarse particle (PM_{10} – $PM_{2.5}$) concentrations was available for the A206 widening project (see Table 1) and was also added to the WP1 dataset.

Results

Figure 2 shows hourly mean concentration of PM_{10} (log scale) during the WP1 construction periods and the London-wide volatile mean PM concentration. Maximum concentrations of volatile PM_{10} reached 36 µg m^{-3}. It is clear that while volatile PM can contributes a mean 12% of PM_{10} concentrations below the trigger of 190 µg m^{-3}, the volatile PM is not the main driver for concentrations above the trigger, with a mean contribution of 2%.

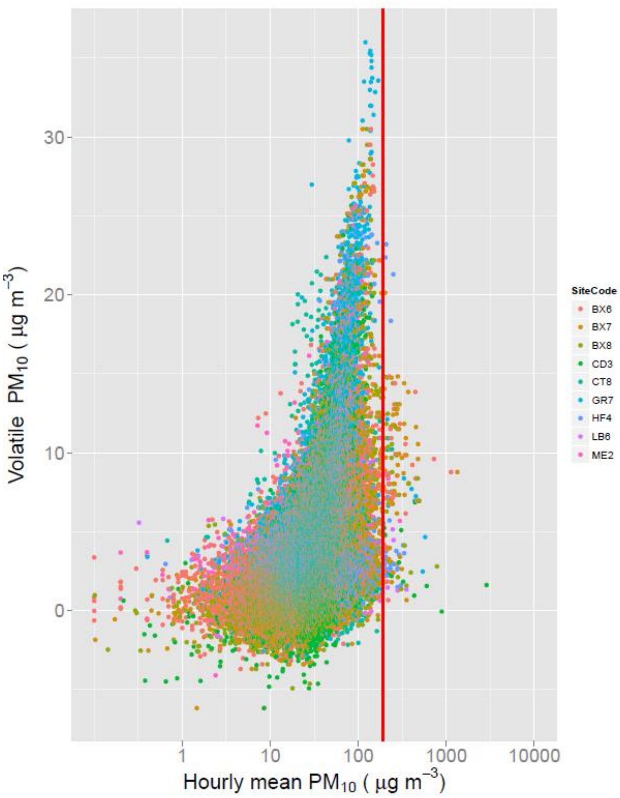

Figure 2 Hourly mean volatile PM and PM_{10} concentrations for all construction periods. See table 1 for site codes. Red vertical line indicates the 190 µg m^{-3}trigger value.

Further insight into the sources that determines PM_{10} concentrations above the trigger concentration are shown in Figure 3. This shows coarse PM in addition to volatile and PM_{10} concentrations as measured during the A206 widening. In order to minimise the spread of PM_{10} and volatile PM_{10} measurements, the median of these was calculated for each 1 µg m^{-3} bin. It is clear that PM_{10} concentrations above the trigger are, in general, dominated coarse PM consistent with the findings of Fuller and Green (2004). Coarse PM comprised an average of 44% of the PM_{10} when concentrations were less than the 190 µg m^{-3}; and 72% when PM_{10} was greater than the trigger.

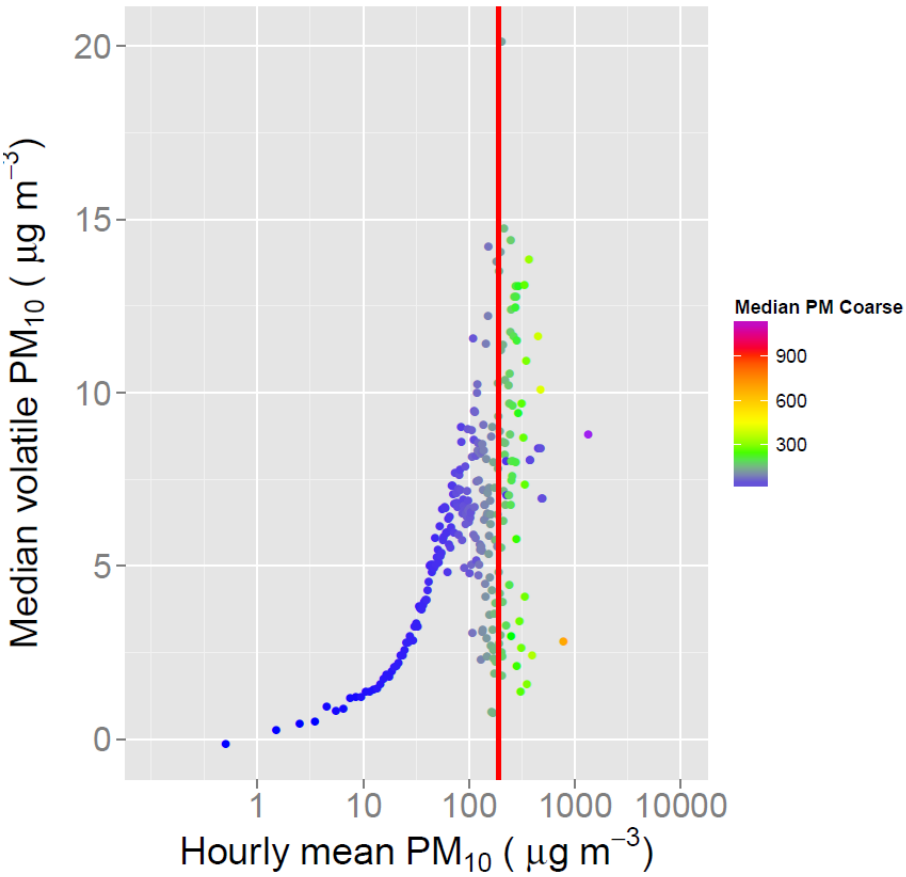

Figure 3 Median volatile PM_{10} binned by hourly mean PM_{10} from the A206 road widening. Data points are coloured by the median coarse PM concentration.

5 Implications for construction site measurement strategies

5.1 Purpose of construction air quality measurement

The IAQM 2012 guidance on air quality monitoring around construction and demolition sites (IAQM, 2012) highlights the importance of identifying the purpose of the monitoring programme before devising a strategy. The IAQM provides five measurement objectives:

- "To ensure that the construction activities do not give rise to any exceedences of the air quality objectives/limit values for PM_{10} and/or $PM_{2.5}$, or any exceedences of recognised threshold criteria for dust deposition/soiling;
- To ensure that the agreed mitigation measures to control dust emissions are being applied and are effective;

- To provide an "alert" system with regard to increased emissions of dust, and a trigger for cessation of site works or application of additional abatement controls;

- To provide a body of evidence to support the likely contribution of the site works in the event of complaints and

- To help to attribute any high levels of dust to specific activities on site in order that appropriate action may be taken."

The findings of WP1, 2 & 3 of this project have implications for construction site air quality management strategies as discussed below.

5.2 GLA and IAQM recommended methods – measurement of action / trigger levels as part of a responsive dust management programme

Aim

The GLA and IAQM recommended methods require measurements of PM_{10} around a construction site and also close to any sensitive receptors. If an action or trigger level is breached then the site manager should take appropriate action to remedy the cause. An action or trigger level of 250 µg m^{-3} is recommended as a 15 minute mean, but alternatives are given.

Methods

Recommendations are given on the location of measurement equipment. For optimal feedback measurements need to be scrutinised in near-real time and alerts provided rapidly to the site manager. It is recommended that indicative light-scattering instruments such as the Osiris and the E-Sampler are used but no specific recommendations were given on quality assurance and quality control.

Implications from WP1, 2 and 3

From analysis of the extensive measurement database in WP1 we recommend a revised trigger or action value of 190 µg m^{-3} measured as an hourly mean. When reference equivalent measurements are used a low false alarm rate of less than 0.1% of days was expected. When individual data sets were assessed for non-construction periods, false alarm rates were found to be zero in around half of locations and were a maximum of 1.4% of days.

WP2 highlighted that Osiris and E-Samplers had difficulty in the measurement of small particles in the $PM_{2.5}$ fraction and also with volatile PM. A single adjustment factor would not correct these. However, there was no evidence of bias in the measurement of high concentrations of PM_{10} from construction dust. Analysis in WP3 highlighted that peaks of PM_{10} from construction were dominated by relatively large particles that light scattering instruments would be expected to measure well. A measurement strategy focusing on the detection of high concentrations of PM from construction therefore plays to the strengths of the indicative measurement technologies.

However, the long-term drift in indicative measurements of between 50 and 100% could seriously confound near-real time feedback to site managers and information to local communities. Such drifts could result in large numbers of false alarms or the non-identification of periods when construction dust was affecting the neighbouring area. Quality assurance needs be at or beyond the current best practice with the cross – instrument comparisons playing an important role in indentifying divergent equipment for calibration. This would require construction sites to use an expanded pool of instruments to enable co-locations and to allow failing instruments to be swapped out of service for calibration and repair without degrading the monitoring programme.

WP2 found different performance from the two instrument types considered. All equipment should therefore be of the same type and design.

5.3 Detecting construction dust impacts using long-term measurements.

Aim

Detecting a change in before and after situation is a core method for determining any effects of an environmental source or intervention.

Methods

Although it seems straightforward to look for differences between a mean or median concentration great care is need avoid false conclusions from confounding effects such as differences between meteorology between the two periods, seasonality and also the effects of air quality management policies at national, city or local levels. Several strategies are outlined below:

The Lenschow method

This was first applied in Berlin by Lenschow et al (2001) and has seen been applied in London (Bohnenstengel et al 2014) and Paris (Bressi et al 2014).The method attempts to isolate pollution sources by location and spatial-scale. It assumes a uniform regional background concentration from distant sources, overlaid by a city-wide background and finally a locally acting source such as a road and shown in Figure 4.

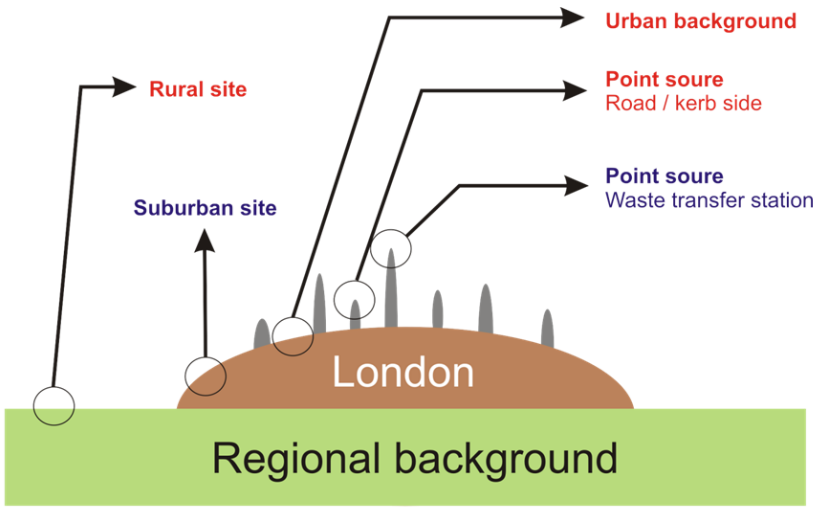

Figure 4 Urban air pollution as envisaged by Lenschow et al (2001).

By making simultaneous measurements in rural areas (preferably up and down wind of the city), in the urban area away from the study site and then close to the source, the concentrations from the local source can be isolated by subtraction. By tracking concentration increments over time, changes in regional or city-wide sources can be controlled for allowing differences from the local source to be detected. Long-term data sets are required since the method does not fully account for seasonal effects and local meteorology. This approach was used to estimate the changes in median PM_{10} concentrations around construction sites in WP1.

Up and downwind

Changes in concentrations from a local source can be determined by analysis of up and downwind concentrations. Monitoring sites need to be located around the source along with wind speed and direction sensors. Concentration differences between up and downwind measurement sites can be used to estimate changes in the local sources. Recent examples of this approach include Font et al (2014) where measurements were made on opposite sides of a road widening scheme and Azarmi et al (2016) for construction sites in London. Again long datasets are required during the pre-construction period also in the construction period before changes can be detected.

Meteorological normalisation and change point detection

Empirical models have been used to remove the effects of meteorology on pollution concentrations allowing the change from a source to be detected. In addition to measuring close to the source, or at the receptor, meteorological and other measurements are required, depending on the method.

Ethane concentrations have been used to create empirical models to account for background dispersion of air pollution from urban sources. Ethane leaks from the natural gas grid at a constant rate and ethane concentrations therefore show an inversion relationship with urban dispersion. Ethane has been used to account for the effects of dispersion in an assessment of the air pollution impacts of London's Congestion Charging (Kelly et al 2012) and also to determine weekly patterns in PM_{10} from wood burning (Fuller et al 2014).

Statistical approaches to remove the effects of meteorology differ in their complexity. Barratt and Fuller (2014) used a regression-based approach to allow for the effects of rainfall and relative humidity. Carslaw et al (2012) used a more complex statistical modelling method to determine improvements in air pollution concentrations from the closure of Heathrow airport during the Eyjafjallajökull eruption and more recently to assess the impacts of retrofitting exhaust abatement to buses (Barratt and Carslaw 2014).

Even removing the effects of meteorology from a time series does not directly determine if a source or concentration change has taken place. This requires a second stage of analysis. Techniques such as cumulative sum (CUSUM) (Barratt et al 2007, Barratt and Fuller, 2014) can then be applied.

Comparative trend analysis

Impacts of change in a local source can be estimated wrongly if they occur against a background of rising or falling air pollution concentrations. Conversely, a comparatively more rapid or slower rate of change can also be used to determine the additional effects of a local intervention or source. Recent examples include Malina and Scheffler (2015) who quantified the effects of Low Emissions Zones across all of Germany and Font and Fuller (2016) who explored the varying response to air pollution management policies in London.

Implications from WP1, 2 & 3

WP1 revealed a complex picture of changes in median PM_{10} concentrations from construction sites when compared to pre and post construction period. At some locations, changes of up to 5 µg m^{-3} were evident but at many locations there was no clear change. We can therefore expect a change of 20% or less of the median concentration due to construction emissions.

Common in all of the approaches listed above is the use of long-term datasets to detect a change. This requires measurements to be consistent over the whole time period. WP2 highlighted long-term drift of between -50% and +100% in instrument performance over periods of a few months making it difficult to detect a change of 20% or less in median concentrations with indicative monitoring equipment.

WP2 also highlighted difficulties in the measurement of volatile PM experienced by both of perimeter measurement devices tested. As shown in WP2 and WP3, volatile PM makes its greatest contribution to ambient PM at concentrations below the trigger value which would confound long term assessment of changes in mean or median concentrations.

5.4 Pre-scheme or baseline assessment of trigger or action levels

Aim

IAQM (2012) outlines the benefits of pre-scheme or baseline measurement to support trigger or action levels. These benefits include setting local trigger values or mapping local sources to aid the analysis of PM during the construction period.

Methods

The positioning of measurements will be very site dependent and will depend on the location of likely sources and sensitive populations.

Implications from WP1, 2 & 3

IAQM (2012) suggest that such baseline measurements are not always required in urban areas where there is a large body of existing monitoring data. Measurements from WP1 and WP3 along with the recommended trigger values add much to the evidence of typical urban air pollution, further reducing the need for baseline or pre-scheme measurements. However, measurements from the two long-term rural measurement sites in southern England show that agricultural activities and local fires can give rise to occasional breaches of trigger values in the absence of construction activities. These events would cause false triggers. If local investigations indicate a risk then rural baseline measurements would be prudent. Waste processing facilities can also cause high concentrations of PM_{10} (Barratt and Fuller, 2014). If such facilities are close to construction sites then baseline measurements may help to characterise these sources to avoid false alarms during the construction period.

WP2 found different performance from the two instrument types considered. It is therefore important that the same instrument type is used for the pre-scheme and construction period.

6 Conclusions

This project set out to reassess the trigger values given in the Greater London Authority (GLA) guidance for construction emissions and that by the Institute for Air Quality Management (IAQM). These are used as trigger limits to indicate when PM_{10} from construction activities might be affecting local air quality providing important near-real time feedback to operators enabling them to take rapid and responsive measures to control emissions. However the current 250 µg m^{-3} trigger value (15 minute mean) was based on a single study at Marylebone Road in 1999 (Fuller and Green 2004) with a non-reference equivalent instrument (TEOM*1.3). Alternative metrics based on hourly increments above a background have been implemented (GLA, 2014, IAQM, 2012) but we are not aware that these have been tested.

The trigger values were examined using measurements from nine construction sites covering a range of construction activities and locations, mainly within London. Measurements were made with modern EU reference equivalent instruments. This dataset comprised 1.8 million measurements and is the largest analysis of construction PM_{10} to our knowledge.

Peak concentrations proved a good indicator of PM_{10} from construction. The majority of construction sites caused an increase in the number of days when the daily mean PM_{10} EU limit Value concentration was exceeded. There was no consistency in the type of construction that gave rise to high peak concentrations suggesting the need to manage PM_{10} in all types of construction. The greatest PM_{10} was measured very close to construction activity consistent with what is understood about atmospheric dispersion; that the distance between source and receptor is important and concentrations fall with distance from source. From our nine construction sites the worst case showed the trigger being exceeded on around one day in three. By contrast, other sites showed no more than the expected false alarm rate. This shows that there is considerable scope for good site management practices to control construction dust.

Based on non-construction periods, an hourly mean trigger value of 190 µg m^{-3} was recommended. This would generate false alarms (indicating construction dust when none is present) on an average of 0.4 % of days. Analysis of background concentrations outside London and south east England confirm that the recommended trigger can be used with confidence to indentify construction impacts in other parts of main land UK.

Even by controlling peak concentrations, to ensure that the trigger is not exceeded, local PM from construction might still increase by 4-5 µg m^{-3} as a median over the construction project.

There is evidence that additional local PM_{10} during the construction periods can also arise from the roadway in addition to that from within the construction site boundary. This was mostly likely caused by resuspension of material tracked from the construction site. Haulage therefore also needs to be considered in any site management plan.

The analysis of PM_{10} around construction sites was undertaken by EU reference equivalent methods. Many practical reasons restrict the use of these types of instruments around construction sites. These include the physical size of the measurement systems, their high electrical power demands and, in some cases, their sensitivity to vibration. The size of reference equivalent equipment often means that planning permission is required before installation. Smaller indicative measurement systems therefore are used in practice to measure construction PM_{10}. These indicative instruments allow measurements in locations that would simply not be possible with EU reference equivalent methods. They therefore open up the opportunity for more comprehensive measurement programmes close to sensitive populations or close to construction sources. However, the use of indicative instruments introduces additional uncertainties.

There was no evidence to support a modification to the trigger concentration of 190 µg m^{-3} when measured with indicative instruments.

It was clear that, as with all measurements of PM, the treatment of the sample is a key factor in making a reliable measurement. For indicative monitors, that use light scattering, controlling or normalising the water content of the aerosol by heating is especially important as it influences particle size and therefore the assumed mass especially when the PM mixture contains a high concentration of secondary PM. The correct operation of sample conditioning systems is therefore very important but these difficulties mean that these instruments are not suitable for resolving the changes in the mean or median PM_{10} concentrations between pre-construction and construction periods that were found in WP1.

There are likely to be issues with the longer–term drift of light scattering instruments since all instruments of this type might be vulnerable to progressive dirtying of optics and clogging of sample flow controls. Good quality assurance is therefore essential. Even for well-run instruments with regular servicing these drifts can lead to factors of between 0.5 and 2 times between pairs of instruments. Instrument comparisons can indentify outliers and drifting equipment. These instruments could be taken out of service for maintenance or corrected mathematically. Comparisons could be done based on times when there was no construction or utilise wind direction to compare sites that are upwind and away from sources. Even with excellent quality assurance indicative instruments are unlikely to be able to accurately measure the changes in the mean or median PM_{10} concentrations between pre-construction and construction periods that were found in WP1.

We believe that it is better to use indicative monitors as part of near-real time management of construction dust such as that in the GLA guidance rather than in approaches that compare pre-construction with construction periods. Concentrations of PM_{10} above the trigger values are dominated by coarse particles and contain a relatively low proportion of volatile PM, which plays to the strengths of these indicative instruments. With state of the art quality assurance, indicative instruments could be deployed effectively in near real-time trigger and alerting systems, providing feedback to site managers and also protecting the public and workforce from exposures to high concentrations of construction dust.

In addition to requiring high quality long-term datasets, measurement strategies based on comparing baseline or pre-scheme concentrations to concentrations during the construction period do not provide rapid feedback. These approaches require extensive data processing to reliably detect a source change free from confounders and require a sustained period before a change can be determined. They are not suitable for near real-time alerting. We believe that the opportunities to take rapid action to control construction dust would lead to a better outcome for the exposed population.

7 Recommendations for further research

Real-time construction dust measurement strategies are limited by the capabilities of current measurement devices. Research into measurement methods and their application would improve construction dust management.

New standard methods need to be developed for the operational quality assurance and quality control for indicative PM_{10} instruments. Improved cross–comparisons between local networked instruments are likely to be fruitful. The long-term performance of indicative instruments also needs to be characterised through co-locations.

The current test methods of PM_{10} monitoring equipment focus on measuring concentrations and particle types that occur in typical urban areas. This is not the same as construction dust. There is a clear need to test indicative PM_{10} monitoring equipment in construction environments. There are three ways to achieve this:

- Construction activities and emissions could be simulated at existing equivalence testing platforms such as the one at the National Physical Laboratory.
- Paired reference equivalent and indicative monitoring equipment could be installed at construction sites and construction PM would be measured as they arose during the project.
- A mobile test platform could be used and taken around construction sites to test a range of site activities.

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Appendix

This section compares the percentage of days when a trigger exceedance was recorded based on the old and the new PM_{10} construction trigger threshold (250 µg m^{-3} as 15-minute means and 190 µg m^{-3} as hourly means, respectively) (Supplementary Table 1) for the sites utilised in WP1.

A reduction of the false alarm rates were recorded with the new threshold with fewer triggers in both pre and post scheme times. The reductions were 53-65% when all time was considered and up to 96% when construction hours only were considered.

Using the new PM_{10} threshold there was a decrease in the number of exceedences recorded during the construction periods. With the old threshold trigger exceedences were observed on 3.4% (all hours) and 2.9% (only construction hours considered) of the days. The exceedences decreased to 2% and 1.8% (all hours and construction times, respectively) with the new threshold.

The new trigger provides an important lowering of the false alarm rate giving site managers and the public greater surity that measured triggers will be due to construction activity.

Supplementary Table 1. Number of times (15-min or hours) and number of days when the old and the new PM_{10} construction trigger was exceeded in the different AQMS during different phases.

				OLD THRESHOLD (15 MINUTE MEANS > 250 µg m^{-3})						NEW THRESHOLD (HOURLY MEANS > 190 µg m^{-3})					
Site	**Start date**	**End date**	**Case**	***N* 15-min**	***N* days**	**% days**	***N* 15-min**	***N* days**	**% days**	***N* hours**	***N* days**	**% days**	***N* hours**	***N* days**	**% days**
				All Times			**Construction times**			**All Times**			**Construction times**		
MY1	01-Jun-1997	31-Dec-1997	Pre scheme	0	0	0.0	0	0	0.0	2	1	0.5	0	0	0.0
MY1	01-Jun-1998	31-Dec-1998	Pre scheme	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
BX7	02-Jan-2004	31-Aug-2005	Pre scheme	20	6	1.0	5	4	0.7	4	1	0.2	0	0	0.0
BX8	02-Jan-2004	31-Aug-2005	Pre scheme	17	2	0.3	2	1	0.2	6	2	0.3	1	1	0.2
HF4	11-Sep-2011	21-Mar-2012	Pre scheme	1	1	0.5	1	1	0.5	0	0	0.0	0	0	0.0
CT8	06-Sep-2013	31-Mar-2014	Pre scheme	4	3	1.4	3	2	1.0	0	0	0.0	0	0	0.0
EB1	24-May-2006	31-Aug-2006	Pre scheme	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
CD3	01-Jan-2006	31-Dec-2006	Pre scheme	2	2	0.5	0	0	0.0	2	2	0.5	0	0	0.0
GR7	01-Jan-2009	31-Dec-2009	Pre scheme	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
			Mean			**0.4**			**0.3**			**0.2**			**0.0**
Percentage change Old vs New Threshold												**-61%**			**-96%**
MY1	01-Jun-1999	31-Dec-1999	Construction	159	21	9.8	157	21	9.8	56	18	8.4	55	18	8.4
BX7	02-Jan-2006	31-Aug-2007	Construction	66	26	4.3	44	22	3.6	29	15	2.5	21	11	1.8
BX8	02-Jan-2006	31-Aug-2007	Construction	24	9	1.5	10	7	1.2	6	2	0.3	1	1	0.2
HF4	22-Mar-2012	30-Sep-2012	Construction	55	24	12.4	52	22	11.4	33	19	9.8	31	18	9.3
CT8	06-Sep-2014	31-Mar-2015	Construction	9	5	2.4	7	3	1.4	4	2	1.0	4	2	1.0
EB1	24-May-2007	31-Aug-2007	Construction	21	9	9.0	18	7	7.0	6	5	5.0	5	4	4.0
CD3	01-Jan-2007	31-Dec-2007	Construction	23	14	3.8	12	10	2.7	5	3	0.8	2	2	0.5
CD3	01-Jan-2008	31-Dec-2008	Construction	19	13	3.6	15	12	3.3	3	1	0.3	1	1	0.3
CD3	01-Jan-2009	31-Dec-2009	Construction	12	10	2.7	9	7	1.9	3	3	0.8	3	3	0.8
CD3	01-Jan-2010	31-Dec-2010	Construction	3	3	0.8	1	1	0.3	1	1	0.3	1	1	0.3
GR7	01-Jan-2010	31-Dec-2010	Construction	20	3	0.8	4	1	0.3	8	4	1.1	3	2	0.5
GR7	01-Jan-2011	31-Dec-2011	Construction	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
GR7	01-Jan-2012	31-Dec-2012	Construction	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
GR7	01-Jan-2013	31-Dec-2013	Construction	4	1	0.3	4	1	0.3	1	1	0.3	1	1	0.3
GR7	01-Jan-2014	31-Dec-2014	Construction	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
			Mean			**3.4**			**2.9**			**2.0**			**1.8**
Percentage change Old vs New Threshold												**-41%**			**-47%**
MY1	01-Jun-2000	31-Dec-2000	Post scheme	15	4	1.9	11	3	1.4	6	3	1.4	5	2	0.9
BX7	02-Jan-2008	31-Aug-2009	Post scheme	7	5	0.8	7	5	0.8	2	2	0.3	2	2	0.3
BX8	02-Jan-2008	31-Aug-2009	Post scheme	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
HF4	01-Oct-2012	11-Apr-2013	Post scheme	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
EB1	24-May-2008	31-Aug-2008	Post scheme	5	1	1.0	0	0	0.0	2	1	1.0	2	1	1.0
CD3	01-Jan-2011	31-Dec-2011	Post scheme	13	10	2.7	3	3	0.8	1	1	0.3	0	0	0.0
GR7	01-Jan-2015	31-Dec-2015	Post scheme	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
			Mean			**0.9**			**0.4**			**0.4**			**0.3**
Percentage change Old vs New Threshold												**-53%**			**-65%**

The new threshold was based on a far larger, and better quality evidence base compared, with the old 250 µg m^{-3} trigger. The 250 µg m^{-3} trigger was calculated using data from only one construction site using pre EU reference equalvalent measurement methods. Eleven monitoring sites close to a construction project comprising 1.8 milion data points were used to determine the new recommended trigger. These used EU reference measurement methods. Also, the new dataset comprises a diversity of construction activties and range of distances from the measurement site to the construction site (from 0 to > 100 m) enlarging the applicability of the trigger value to a variety of construction projects.

Another aspect to be considered is that the old threshold was based on 15-minute mean concentrations. The newest EU reference equivalent PM_{10} instruments deployed in air quality networks across the United Kingdom (TEOM-FDMS, BAMs) only provide hourly ambient concentrations therefore the old threshold could not be tested on those instruments.

Re-assessment of the 250 µg m^{-3} action value

Work Package 5

Recommendations for operational quality standards

KING'S College LONDON

June 2017
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Environmental Research Group
King's College London

Title	Recommendations for operational quality standards

Customer	HS2 Ltd.

Customer Ref	C0870 – Construction dust research

File Reference	Z:\AIRQUALI\Construction Dust\Construction Projects\HS2\Reports

Report Number	WP5 – Recommendations for operational quality standards

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Recommendations

At the **start of a sampling** campaign instruments should be:

1) Set up in the same manner as in the MCERTS field tests. This point applies especially to sample heaters / systems and flow.

2) Either
    a. Co-located at the construction site or similar location for at least one week. Reduced (or standardised) major axis regression should be used and bias between instrument pairs should be less than 10% before deployment.

   or

    b. Calibrated by the manufacturer or a test house with traceability to national standards.

The following actions should be carried out **monthly** by the **field operator**:

3) Sample flow should be checked and adjusted with a traceable flow meter with an uncertainty of 5% or better. The field flow meter should be checked annually to ensure continued traceability of measurements.

4) The operation of the heater needs to be verified by continuous measurement of sample temperature or by manual verification of heater operation. A hand-held pyrometer was found to be practical for instrument type I.

5) HEPA filters should be fitted to the sample system and the measured concentration should quickly fall to within the signal noise or limit of detection for the equipment. Failure may indicate a fault which needs to be remedied.

In-service quality checks should be undertaken **monthly**:

6) PM_{10} concentrations should be compared during periods of low concentrations of local sources such as hours 1 to 3 each night or Sundays between pairs of instruments. Reduced (or standardised) major axis regression should be used.
    a. In the event of a bias (gradient) change of ± 20%* (single month or cumulative change in bias between instruments):
        i. Equipment should be investigated for faults. If faults are found these should be remedied.
        ii. If a local overnight or Sunday PM_{10} source is found that would have interfered with the comparison, then no further action need be taken. A local source would be indicated by outliers in the regression or poor correlation.
        iii. The instrument should be placed in a collocation exercise on the construction site. If a bias of greater than 10% is found then the instrument should be subject to manufacturer or test house calibration.

Additionally:

7) Instruments must be serviced in accordance with manufactures recommendations. Servicing needs to include sampling systems.

8) Good record keeping is essential to track the performance of instruments over time. This should include records of field checks, pre and post service calibrations and the results from in-service cross checks.

The proposed quality checks imply that spare equipment needs to be available to enable a full sampling programme to continue if equipment is withdrawn for repair or collocation checks.

Different instrument types will differ in their sensitivity to the various components of the PM mixture. In-service cross checks and collocations need to be conducted with instruments of the same make and model.

(*) for well characterised sites this should be tightened progressively to 15% and then 10%.

Contents

Summary

The Greater London Authority (GLA) guidance for construction emissions and that by the Institute for Air Quality Management (IAQM) have action levels or triggers values to indicate when PM_{10} from construction activities might be affecting local air quality. Developers should respond to significant breaches of the trigger threshold by stopping work immediately to identify the source and to ensure best practice measures are in place before restarting. With breaches of the PM_{10} trigger value, the guidance suggests that local authorities can use their powers to prevent the statutory nuisance (GLA, 2014).

Earlier work packages in this project have recommended a revision of the trigger levels and also examined the real-world performance of the indicative instruments that are used to measure PM_{10} around construction sites.

Work package 5 aimed to make practical recommendations to improve the routine measurement of PM_{10} in construction settings.

When assimilating this evidence we need to remember that these are not reference quality instruments but, in the MCERTS terminology they are indicative. These indicative instruments allow measurements in locations that would simply not be possible with EU reference equivalent methods. However, the use of indicative instruments introduces additional uncertainties.

An over read in perimeter PM_{10} measurements would lead to an increase in false alarms, disrupting construction work. For over reads greater than 20% the rate of false alarms exceeded the real events for trigger definitions. An under read would lead to dust events not being detected. For under reads of 30% and more over half the trigger events would be missed. For indicative instruments to provide useful information for reactive dust management they need to be operated with uncertainties that are ideally less than 10% but certainly not more than 20%.

Analysis of existing datasets found that indicative instruments are susceptible to:

- Changes in sample flow between calibrations. A mean change of -6% was found but changes of more than -10% were seen.
- Incorrect heater operation or heater failure which, in the case of one instrument type led to an over read of 100% during episodes of high volatile PM.
- Changes in performance over time which can result in measurements that are two times or half the actual PM_{10} concentration.
- Sudden jumps or step changes in measurements.

We therefore recommend the following minimum operational requirements:

At the **start of a sampling** campaign instruments should be:

1) Set up in the same manner as in the MCERTS field tests. This point applies especially to sample heaters / systems and flow.

2) Either
    a. Co-located at the construction site or similar location for at least one week. Reduced (or standardised) major axis regression should be used and bias between instrument pairs should be less than 10% before deployment.

   or

    b. Calibrated by the manufacturer or a test house with traceability to national standards.

The following actions should be carried out **monthly** by the **field operator**:

3) Sample flow should be checked and adjusted with a traceable flow meter with an uncertainty of 5% or better. The field flow meter should be checked annually to ensure continued traceability of measurements.

4) The operation of the heater needs to be verified by continuous measurement of sample temperature or by manual verification of heater operation. A hand-held pyrometer was found to be practical for instrument type I.

5) HEPA filters should be fitted to the sample system and the measured concentration should quickly fall to within the signal noise or limit of detection for the equipment. Failure may indicate a fault which needs to be remedied.

In-service quality checks should be undertaken **monthly**:

6) PM_{10} concentrations should be compared during periods of low concentrations of local sources such as hours 1 to 3 each night or Sundays between pairs of instrument. Reduced (or standardised) major axis regression should be used.
    a. In the event of a bias (gradient) change of ± 20%* (single month or cumulative change in bias between instruments:
        i. Equipment should be investigated for faults. If faults are found these should be remedied.
        ii. If a local overnight or Sunday PM_{10} source is found that would have interfered with the comparison, then no further action need be taken. A local source would be indicated by outliers in the regression or poor correlation.
        iii. The instrument should be placed in a collocation exercise on the construction site. If a bias of greater than 10% is found then the instrument should be subject to manufacturer or test house calibration.

Additionally:

7) Instruments must be serviced in accordance with manufactures recommendations. Servicing needs include sampling systems.

8) Good record keeping is essential to track the performance of instruments over time. This should include records of field checks, pre and post service calibrations and the results from in-service cross checks.

The proposed quality checks imply that spare equipment needs to be available to enable a full sampling programme to continue if equipment is withdrawn for repair or collocation checks.

Different instrument types will differ in their sensitivity to the various components of the PM mixture. In-service cross checks and co-locations need to be conducted with instruments of the same make and model.

The expected uncertainty for instruments operated in this way should constrain the uncertainty to between 10% and 20%. The above calculation does not include the uncertainty from the manufacture calibration and also those induced by the variable sensitivity of equipment to different components of the PM mix.

It is clear that even with operational improvements beyond the current state of the art, considerable uncertainty will remain in the measurement of PM around construction sites. With well characterised construction sites operators should tighten the in-service regression approach to take action with changes to 10% or 15%. This would reduce the potential for false alarms and also the number of missed dust events.

Research recommendations

Real-time construction dust measurement strategies are limited by the capabilities of current measurement devices. Research into measurement methods and their application is needed.

EU test methods (e.g. MCERTS in the UK) for PM_{10} monitoring equipment focus on measuring concentrations and particle types that occur in typical urban areas. This is not the same as construction dust. There is a clear need for certification testing of indicative PM_{10} monitoring equipment in construction environments.

1 Introduction

Background

The Greater London Authority (GLA) guidance for construction emissions and that by the Institute for Air Quality Management (IAQM) have action levels or triggers values to indicate when PM_{10} from construction activities might be affecting local air quality. Developers should respond to significant breaches of the trigger threshold by stopping work immediately and ensuring best practice measures are in place before restarting. With breaches of the PM_{10} trigger value, the guidance suggests that local authorities can use their powers to prevent the statutory nuisance (GLA, 2014).

As used in the codes of practice, the 250 µg m^{-3} trigger value (15 minute mean) is designed to protect the local population from construction emissions. Construction site managers have expressed concern that breaches of the trigger concentration can happen without an obvious cause. False alarms may cause undue concern to people living around the construction site and can be disruptive to construction activities. It is also possible that the 250 µg m^{-3} trigger value is missing some emissions sources from construction that could be controlled by better working practices.

This project was designed to improve upon current practices. It considered both the PM_{10} concentrations around construction sites and also the way in which these are routinely measured.

Aims

The project was divided into five work packages.

Work package 1:

- Tested the efficacy of the 250 µg m^{-3} trigger to discriminate between construction and non-construction PM_{10} events using data from different types of construction projects using new EU reference equivalent PM measurements. The project also aimed to profile the concentration ranges that can be expected in rural, urban and roadside environments in and around London in the absence of construction through a dataset assembled from nine construction sites.

- Recommended a new trigger value of 190 µg m^{-3}, to be measured as an hourly mean. This will improve the number of false alarms experienced with the current trigger.

Work package 2:

- Compared typically used construction site perimeter measurement devices to EU reference equivalent instruments to provide a conversion factor.

- Found periods of divergence between the instrument types and when compared with reference instruments.

Work package 3:

- Assimilated findings and recommendations from work packages 1 & 2. It concluded that measurement of the trigger concentration, as part of a real-time dust management programme, played to the strengths of indicative light scattering instruments.

- Showed that the new recommended trigger was appropriate to cities outside London.

Work package 4 aimed to disseminate the findings of work packages 1 to 3 to a wide range of stakeholders. Work is on-going.

- Presentations have been made to:
  - HS2 engineering and environment teams.
  - London boroughs, major construction projects and other stakeholders through the London Low Emission Construction Partnership.
  - Scientists at the European Aerosol Conference.
  - Policy makers and scientists at the Royal Society of Chemistry AAMG annual air quality event.
  - Local authorities along the proposed HS2 route.
  - Environmental professionals, mainly those in the consultancy sector via the Institute of Air Quality Management.

Work package 5 was commissioned following the findings of work packages 1 to 3 and feedback from the dissemination exercises in work package 4. Work package 5 aims to make practical recommendations to improve the routine measurement of PM_{10} in construction settings. The work package was divided into two streams:

Stream 1: Investigated the consequences of uncertainty in PM_{10} measurements around construction sites in terms of increased false alarms and also missed trigger events.

Stream 2: Drew on extensive data from real world applications to investigate the main causes of uncertainty in the PM_{10} measurements when used in construction environments and how these can be minimised. This included:

- Sample flow.
- Sample heater operation.
- Medium term drifts in sensitivity.
- Calibration by the manufacturer.
- Discussion with instrument manufacturers through meetings, teleconferences, email along with scrutiny of manuals and standard operating procedures.

2 Structure of this report

The evidence presented in this report is divided into two sections. The first covers stream 1 looking at the consequences of measurement uncertainty in the context of construction site PM_{10} measurement. The second covers stream 2 which was mainly experimental. Each investigation is presented separately in terms of introduction, method and results.

The report ends with conclusions and recommendations.

3 Stream 1: Consequences of uncertainty in PM_{10} measurements around construction sites

Introduction

Ideally all measurements would be true representations of the parameter being measured. However measurement is never a perfect representation of reality. The Guide to the Expression of Uncertainty in Measurement (GUM) (JCGM, 2008) produced by the International Standards Institute, the Bureau International des Poids et Mesures and several other international standardisation bodies describe this difference between measured and true values in terms of uncertainty, which is a combination of the previous concepts of accuracy (systemic or bias errors) and precision (random errors). It recognises that, "…when all of the known or suspected components of error have been evaluated and the appropriate corrections have been applied, there still remains an uncertainty about the correctness of the stated result, that is, a doubt about how well the result of the measurement represents the value of the quantity being measured."

Although we would wish that all measurements were perfect representations of the true value of a quantity the level of uncertainty depends on practical issues. These include the capabilities of the equipment being used, the calibration standards used on the equipment and the quality assurance and quality control processes that are applied. An important first step in setting up a measurement programme is therefore to consider what level of uncertainty is required for the task. Stream 1 therefore looks at the consequences of uncertainty in PM_{10} measurement for the assessment of the trigger value around construction sites. The consequences of uncertainty in PM_{10} measurements was explored in terms of false alarms and missed trigger events.

Method

The dataset of 1.8 million measurements of construction PM assembled for WP1 was used. This data set was measured with reference instruments around nine construction sites in London and south east England. Although this will have uncertainty it was assumed that the dataset did not have a systematic bias.

The number of breaches of the current trigger value (250 µg m^{-3}, as a 15 minute mean) and the new trigger value recommended in WP1 (190 µg m^{-3}, as an hourly mean) were assessed and bias introduced in steps of 10% to represent uncertainty in the measured PM_{10}.

Results

Simulations of measurement bias are shown in Figure 1.

A positive bias in the PM_{10} measurements or over read increased the reported frequency of trigger events with both the old and new trigger thresholds. These were false alarms. An over read of 10% resulted in an increase of 33% (mean), 26% (median) in the number of triggers with the new definition. The old trigger definition was less sensitive with an increase of 23% (mean), 12% (median). At 20% over read, the old trigger was affected to a greater degree than the new one. A 20% over read caused an increase of 78% (mean), 40% (median) for the new threshold and 114% (mean) and 100% (median) for the old threshold. For over reads greater than 20% the rate of false alarms exceeded the real events for both trigger definitions.

A negative bias or under read in the PM_{10} measurement caused a decrease in the frequency of reported triggers with both old and new definitions. These are missed events. As expected from the skewed normal distribution of PM_{10} measurements the change in trigger frequency was less sensitive to negative bias. An under read of 10% resulted in a decrease in the frequency of triggers of 23% (mean), 20% (median) for the new definition and a decrease of 25% (mean and median) for the old definition. A 20% under read produced a decreased trigger frequency of 38% (mean), 33% (median) for the new definition and 39% (mean), 38% median for the old definition. For under reads of 30% and more, over half the trigger events would be missed.

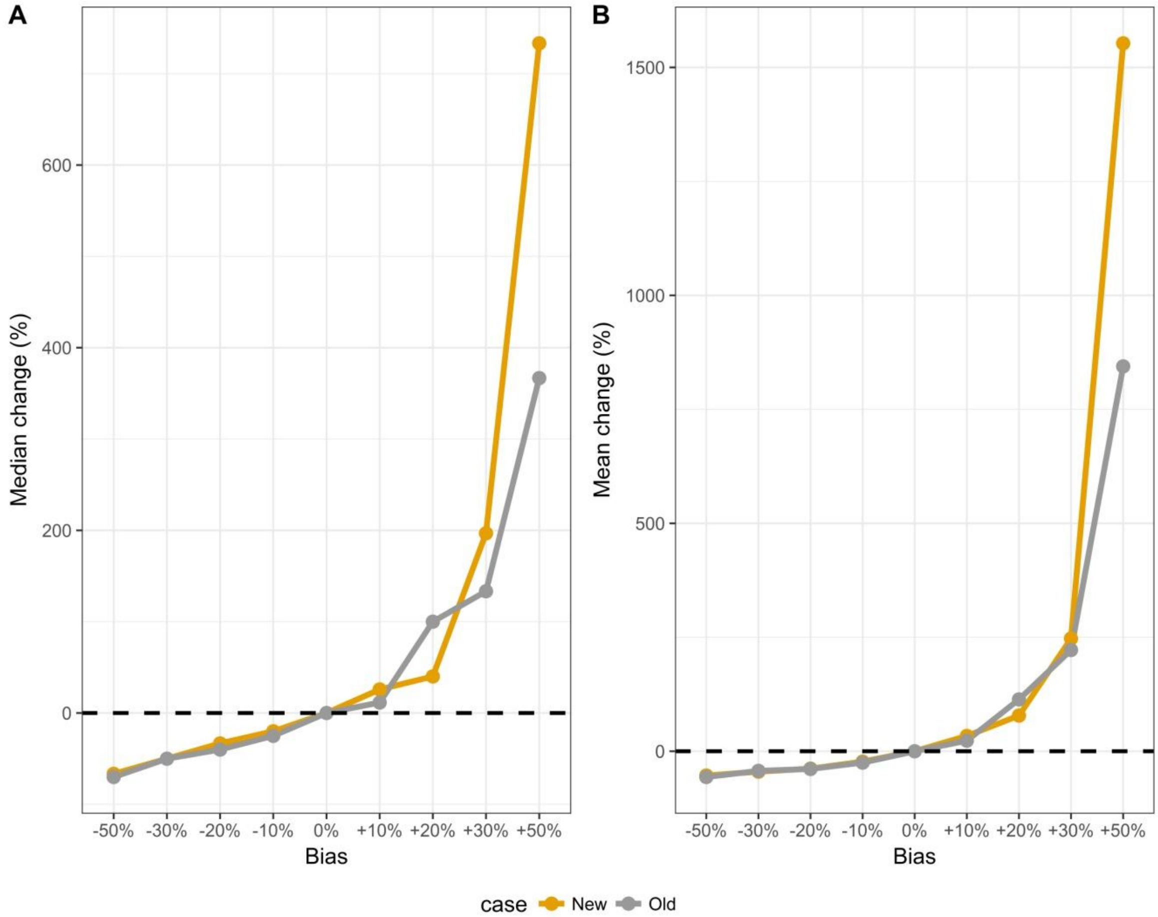

Figure 1 Mean and median change in the number of breaches of the trigger concentration with measurement bias. Orange "new" line represents the proposed trigger based on 190 µg m^{-3} hourly mean and the grey line shows the "old" trigger at 250 µg m^{-3} as a 15 minute mean. The assessment was based on nine construction sites.

Looking at individual construction sites it is possible to consider the absolute change in the number of breaches of the trigger concentration with instrument bias. Figure 2 shows the breaches of the trigger values close to the construction of flats in Merton, south London, part of the WP1 dataset. In this case an over read of 20% caused a substantial increase in the number of false alarms. An under read of 20% caused half of the trigger events to be missed.

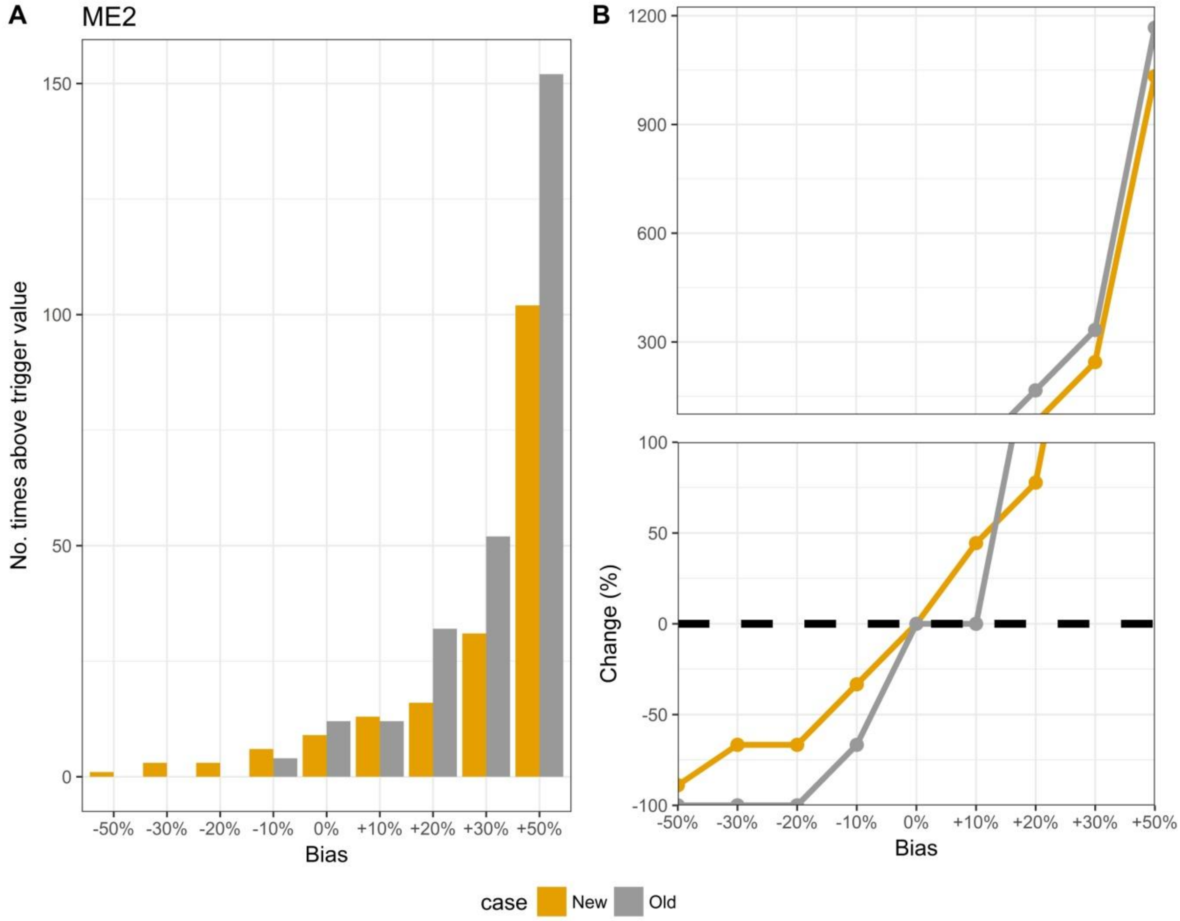

Figure 2 Change in the number (left) and percentage (right) of breaches of the trigger concentration with measurement bias close to the construction of flats in Merton. Orange "new" line represents the proposed trigger based on 190 µg m^{-3} hourly mean and the grey line shows the "old" trigger at 250 µg m^{-3} as a 15 minute mean.

Figure 3 shows breaches of the trigger value concentrations at the Greenwich Blackheath in 2011. In this case the monitoring site did not measure any breaches of the trigger. However an over read of 10% would have caused false triggers to be measured which increased rapidly at a bias of 20% and more.

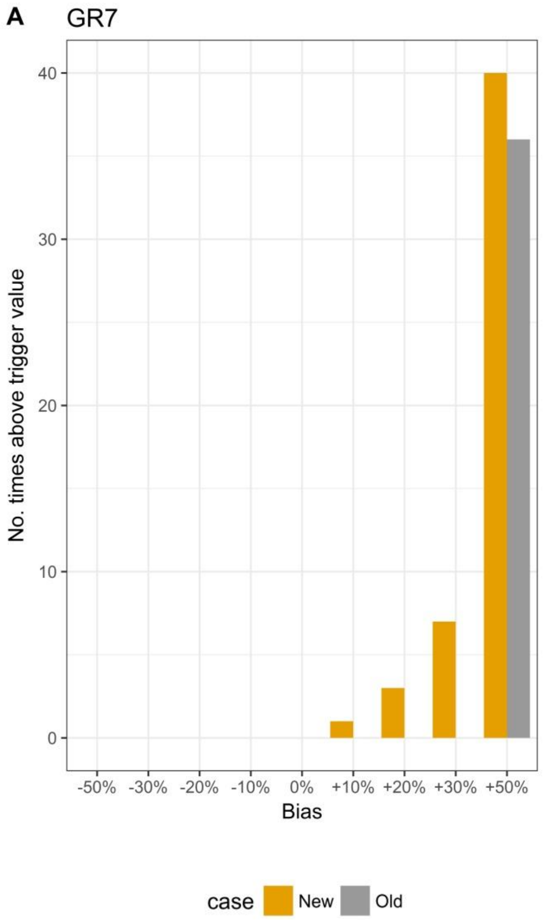

Figure 3 Change in the number of breaches of the trigger concentration with measurement bias close to the construction of flats in Blackheath, Greenwich. Orange "new" line represents the proposed trigger based on 190 µg m^{-3} hourly mean and the grey line shows the "old" trigger at 250 µg m^{-3} as a 15 minute mean.

4 Stream 2 causes of uncertainty in PM_{10} measurements around construction sites

Instruments

The investigations in work stream 2 considered operational evidence from three types of PM_{10} measurement device used in construction settings. All instruments have MCERTS approval for indicative measurement and used laser light-scattering as a detection method.

Instrument type I

Instrument type I is a commonly used device for UK construction sites and also waste management operations. It operates with an externally heated sample tube. The performance of a type I instrument was compared to a reference equivalent PM_{10} instrument in work package 2. Further datasets were examined for this work package. A visit was made to the manufacturer during May 2017 followed by several email exchanges.

Instrument type II

Two examples of instrument type II were compared to a reference equivalent measurement system in work package 2. The work package 2 dataset was reanalysed in this work package. It operates with a smart heating system. Telephone discussions and email exchanges with the UK agent took place in April 2017.

Instrument III

Instrument type III obtained MCERTS certification as an indicative PM instrument in spring 2017 and was therefore not considered in the earlier work packages. Similar instruments from the same manufacture have been widely used to make micro-environmental measurements in health studies and we obtained and studied the results from extensive trials carried out in Spain. Email exchanges with the manufacture took place through April and May 2017.

Flow

Introduction

Incorrect flow can lead to uncertainty in the PM measurement from air pollution measurement equipment. With light scattering instruments, without a size selective head, a mismatch between the actual flow and the flow assumed in the calculation of mass concentration can lead to an error which is proportional to the flow mismatch. For this reason flow should be checked periodically.

Method

Field rotameters were used to measure flow for four examples of instrument type I. A total of 32 flow measurements were made, in the 16 months up to May 2017. The rotameter was periodically checked with a laboratory-based flow measurement device with traceability to national metrological standards.

To assess the change of flow with filter loading, only cases where the flow was not adjusted could be used. A reset of the flow would render the experiment invalid, even if the filter was not changed. For the assessment of change of flow with pump age any two consecutive flow measurements could be used in the dataset.

Estimated filter mass loadings were obtained from the integration of the mass concentrations measured by the instrument.

Results

Figure 4 shows flow checks plotted against the mass of particulate deposited on the internal filter. A systemic reduction in flow was found. This was apparent at all filter loadings but, with the exception of one case with excessive internal filter loading of over 10 mg, there was no clear relationship between change in flow and filter mass. We therefore suggest that filters should continue to be changed as per the manufacturer's recommendations.

Overall checks at typical intervals of between one and three months showed a mean change in flow of -6 ± 5%. This was not random but appeared to induce a bias in measurements; the loss of flow leading to a corresponding mean instrument under-read of -6 ± 5 %. Changes of around -10% were common place.

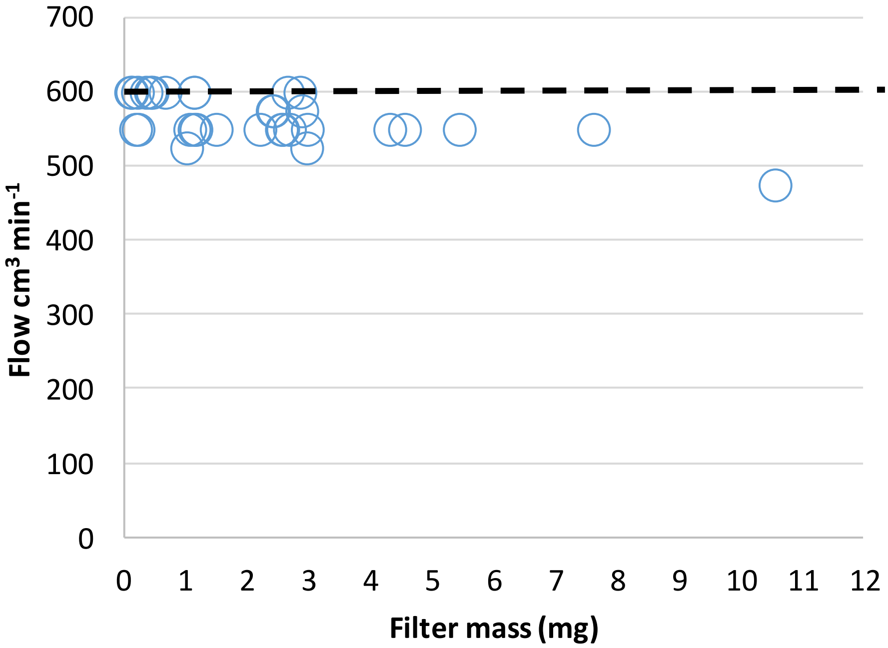

Figure 4 Flow measurements and filter mass for four examples of instrument type I. Flow was measured without intervention from the filter change. The dotted line represents the target flow of 600 cm^3 min^{-1}

The larger set of flow measurements between any two flow checks was used to consider the rate of change of flow with pump age, as shown in Figure 5. There was no obvious indication ($r^2 = 0$) of an increased change in flow with pump aging. Few data points were available for periods where the duration between flow checks was more than one year but these also showed no sign of deterioration in the rate of change of flow. The maximum rate of change approached -0.002 cm^{-3} min^{-1}; around 20 cm^{-3} per week or 3% of the set flow of the type I instrument.

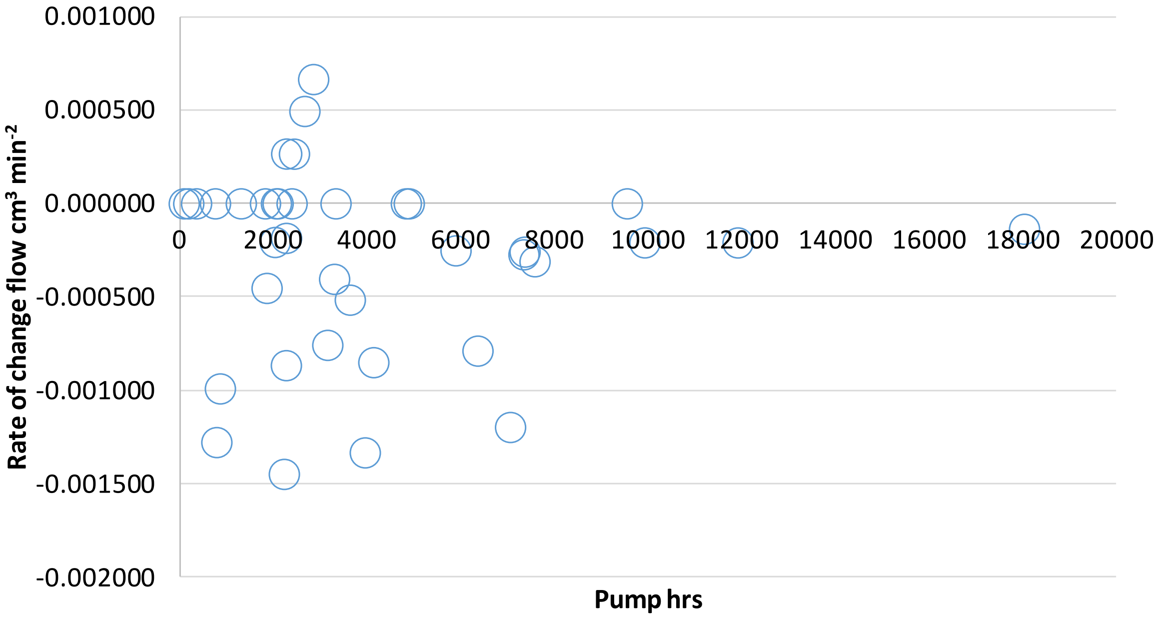

Figure 5 Flow measurement and pump hours for four examples of instrument type I.

Sample heater

Introduction

Water droplets can interfere with measurements of PM mass concentration using light scattering techniques. High amounts of particle bound water can also interfere with the measurement process. For this reason most PM measurement instruments incorporate either dryers or heaters or both in their sample system. However excessive heating of the sample can lead to the loss of particle matter and affect measurements.

In work package 2 an instrument of type I was found to under measure PM_{10} concentrations when compared to a reference equivalent instrument during periods of high volatile particulate that often affect the UK during spring. An instrument of type II was found to over read a reference equivalent instrument during a period of high volatile particulate when the instrument was operated without a heater. This caused the type II instrument to over read the reference by almost a factor of two.

Instruments of type I operate with an external heated inlet and no measurement of sample temperature or heater temperature. Two experiments were therefore carried out to examine the effectiveness of the heaters on different instruments in both field and laboratory conditions.

Method

In the first experiment, three instruments of type I were operated continuously on mains power in a laboratory environment. Sample tube temperature was measured at the inlet at intervals over 16 days using a Hanna - HA9040 temperature probe. Room temperature was controlled by building air conditioning and was measured at between 19.5 and 19.9 ^{o}C during the experiment.

In the second experiment a hand held pyrometer (Benetech GM550) was used to measure the surface temperature of different parts of the heated inlet for five instruments of type I being operated in the field around several construction sites in London. Temperature was measured at seven points during the tests as shown in Figure 6.. Point 1 was a measurement of the ambient temperature and point 2 measured the temperature of the instrument case. Points 3 to 5 were on the inlet tube and points 6 and 7 were on the heater surfaces.

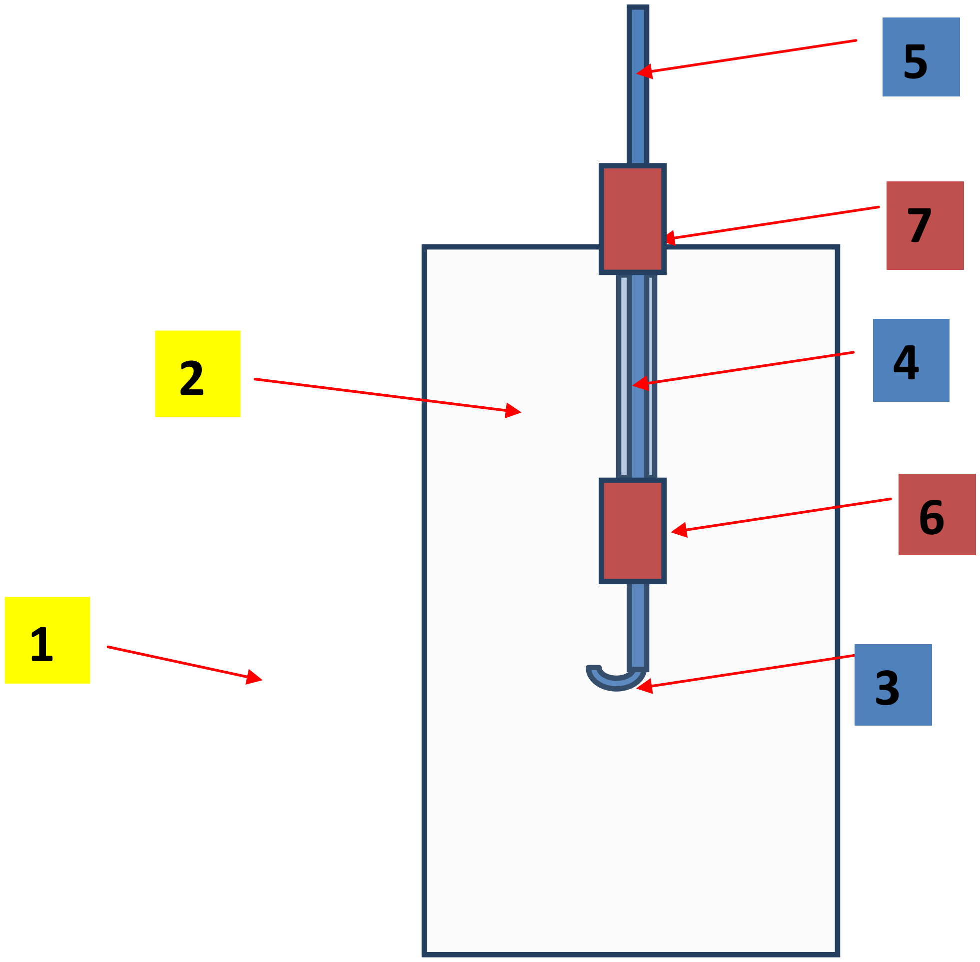

Figure 6 Temperature measurement points for field tests for instrument type I.

Results

Results from experiment 1 are shown in Table 1. Good inlet temperature stability was maintained for each instrument throughout the test period, with standard deviations of around 2% or less. A large variation was found between the different inlet temperatures, from a mean of 87.1 °C to 116.5 °C.

Results from experiment 2 are shown in Table 2. A large variation was found in heater temperatures between the instruments tested; a maximum of 106.7 °C and a minimum temperature of 60.0 °C. The lower heater temperature at J was measured twice during the tests and showed a difference of 11.7 °C. The small diameter and shiny metal surface of the sample tube prevented reliable measurements of the sample tube temperature at points 3, 4 and 5.

Table 1 Laboratory based inlet temperature tests on three instruments of type I.

Day & Time	Instrument number and temperature °C		
	1	2	3
Day 1 15:30	-	98.9	90.1
Day 3 09:10	116.8	101.8	87.3
Day 3 13:00	116.9	100.1	86.8
Day 3 15:00	116.9	100.2	83.9
Day 3 16:00	118.1	102.4	85.6
Day 3 17:00	117.6	104.9	86.7
Day 8 10:00	113.7	101.2	85.3
Day 8 11:30	115.2	99.8	87.6
Day 9 12:00	117.9	100.8	86
Day 15 15:15	117.9	102.8	90.1
Day 16 12:00	113.8	101.7	88.6
Mean	116.5	101.3	87.1
Standard Dev	1.7	1.7	1.9

Table 2 Heater temperatures during field tests. See figure 6 for measurement points 1,2,6 & 7. Site codes are described in the section below.

SITE	DATE/TIME	Ambient (1)	Instrument case (2)	Heater lower (6)	Heater higher (7)
				°C	
J	28/04/2017 15:00	16.7	23.0	95.0	-
G	04/05/2017 10:00	13.9	15.4	64.2	60.0
L	04/05/2017 13:00	14.0	19.0	76.0	62.3
F	10/05/2017 11:12	13.0	22.7	100.8	91.3
J	10/05/2017 13:37	19.7	30.3	106.7	102.6
K	10/05/2017 13:48	18.5	25.3	86.0	82.6

In-service sensitivity changes

Introduction

Work package 2 provided an example of sensitivity drift of two instruments of type I located less than 5 metres apart. Flow and other checks carried out by the operator did not identify any faults however a comparison between the two instruments on successive Sundays found a factor of two difference between the two instruments that developed over around two months. A larger set of instruments (described below) was therefore examined to determine if the response changes found in work package 2 were found in other locations and also to create a set of guidelines for the instrument operators to enable robust in-service checks for changes in instrument sensitivity.

Additionally, data from two closely located instruments of type II were considered using the dataset discussed in work package 2.

Method

PM_{10} measurements were taken from four different sites / projects. All data was from instruments of type I.

- Instruments A and B were deployed to assess an intervention to reduce PM_{10} exposure close to a major road in London. The instruments were placed less than 2 m apart with instrument A closer to the road. On three occasions the instruments were collocated. The dataset covered 14 months.

- Instruments C, D and E were deployed to look at PM_{10} from a haulage route. Instrument C was located in a background location and instruments D and E were located along the haulage road. Instruments C and D were separated by around 200 m and D and E were around 150 m apart. The dataset covered 18 months.

- Instruments F and G were located on opposite sides of a large construction site in London. They were installed close to sensitive receptors beyond the site boundaries and were approximately 200 m apart. The dataset covered 16 months.

- Instruments H and I were located either side of a haulage route on a construction site. They were separated by a distance of 10 m. The dataset used in work package 2 was re-analysed here. The dataset coved 12 months.

Following the methods used in work package 2, data was extracted for each instrument for periods when local PM_{10} sources had least impact on the concentrations. To select these times diurnal and day of week mean data for each of the site groups was compared. An example is shown in Figure 7 for sites C,D and E, which is reflective of the other datasets.

For each site group, the period 1 h – 3 h each night was selected as providing least variation between instruments. For instruments H and I additional comparison was made on Sundays when the construction site was not active. To ensure sufficient data points, regressions were carried out on data gathered on a month by month basis.

Regressions were carried out retrospectively and not for on-going quality control. Co-locations were carried out for instruments A and B only.

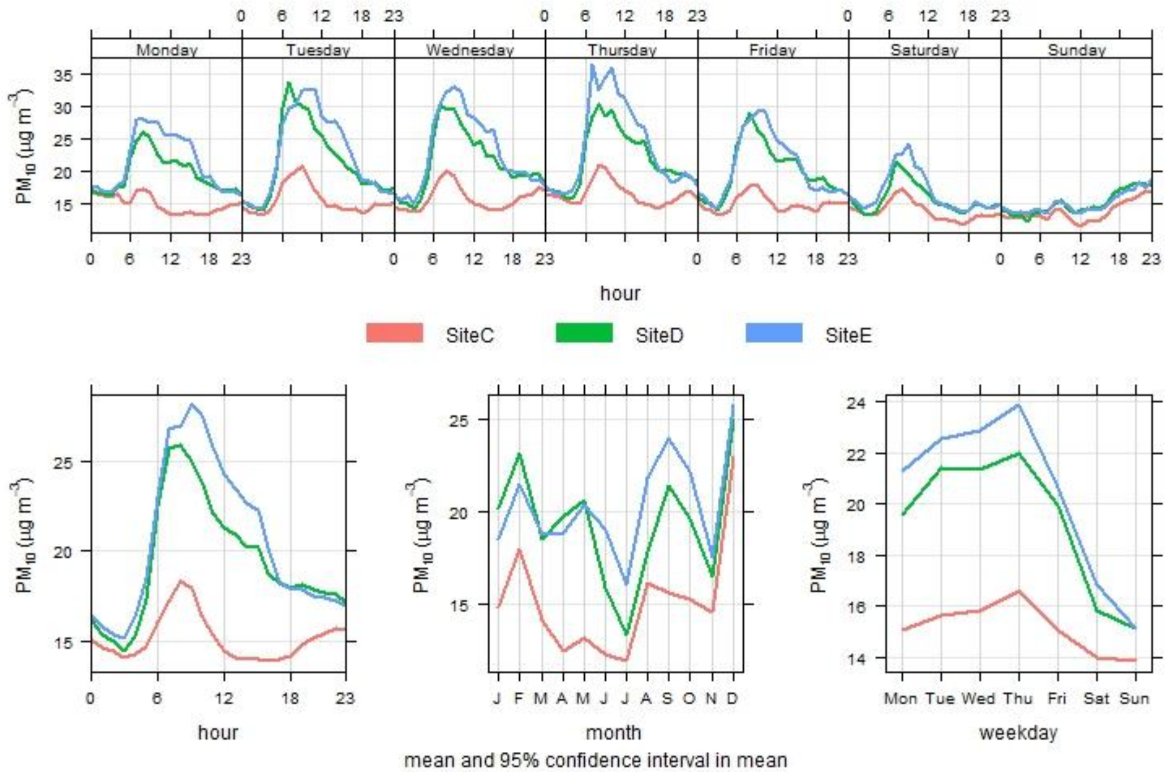

Figure 7 Comparison of mean concentration averaged by time for instruments C, D and E.

It is not expected that all instruments would measure the same concentration, even at times with little activity. Rather than look for differences, mean concentrations from the site pairs were plotted and a regression line fitted. It must be remembered that uncertainty will be present in both x and y qualities in any such regression. Ordinary least squares would be prone to underestimate regression gradients in this situation. Following the recommendations of Ayres (2001) and Warton et al (2006) reduced (standardised) major axis regression was used. The RMA regression was expressed in terms of the gradient of the line (beta) and an intercept. For a perfect match between the instruments, the gradients would be 1 and the intercept would be zero. A gradient different to 1 would indicate a bias and a non-zero intercept would indicate an offset for one of the instruments. The correlation coefficient R indicates the strength of the relationship between the measurements made by the two instruments. A value less than 1 would be expected due to instrument signal noise and also due to differences in PM_{10} sources very close to each instrument.

In addition to the extensive analysis of instruments of type I, regression of two closely located instruments of type II was also undertaken. This used the whole data set, rather than Sunday or overnight sub-sets, or two instruments operated for approximately six weeks in Merton, south London, as discussed in work package 2.

Results

Instruments A and B (type I)

In-service regression gradient and correlation values (R) from instruments A and B are shown in Figure 8. Good R values of greater than 0.9 were obtained for the whole 15 month period. Variation was seen in the gradient (beta) values indicating a bias between the instruments. This was mainly less than 20% with the exception of March 2016 and February and March 2017. As indicated a flow check only was carried out on April 2016 and filter changes (along with flow checks) at intervals.

Although not shown in Figure 8, three collocation exercises were also carried out as detailed in Table 3. The results from collocations in 2016 supported the overnight regressions shown in Figure 8. The collocation in January 2017 indicated a large bias. Despite filter change and flow adjustment at the end of the collocation a bias was detected in the in-service regressions during February 2017 and this increased between the instruments during March 2017 to reach 60%. At this time instruments were three months beyond their recommended service interval.

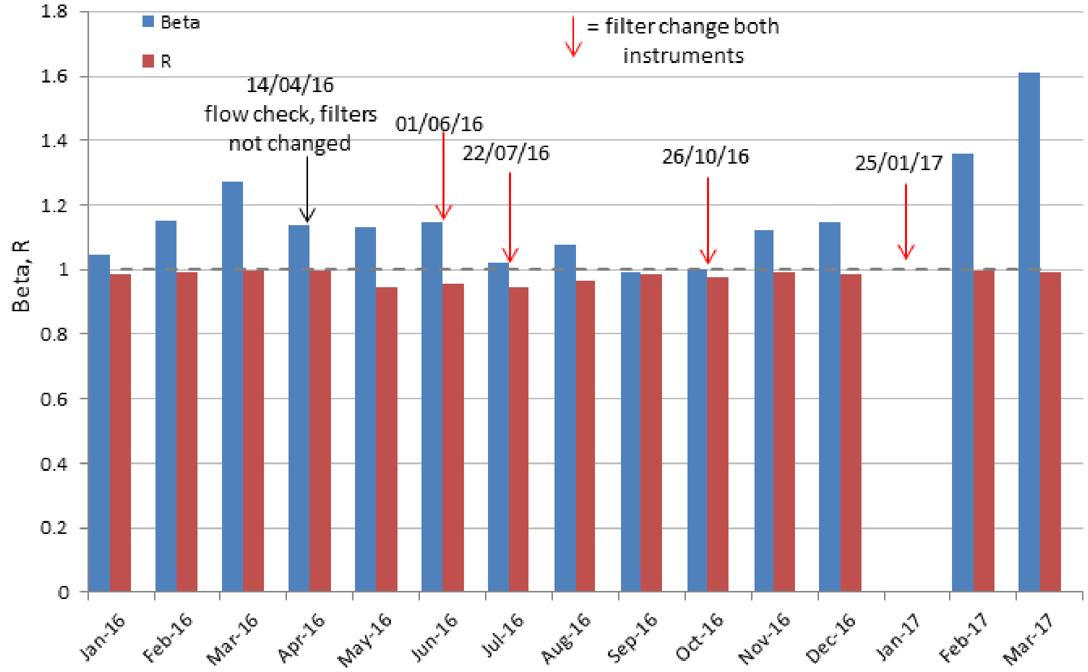

Figure 8 Monthly RMA regressions for instruments A and B showing filter changes and flow checks. Regression gradient beta and correlation R are shown.

Table 3 Regression gradients (beta) and R for co-location exercises for instruments A and B.

Start	End	Beta	R
21/04/16	05/05/16	1.129	0.946
22/07/16	11/08/16	0.995	0.985
11/01/17	25/01/17	1.501	0.94

Instruments C and D (type I)

In-service regression gradient and R values from instruments C and D are shown in Figure 9. Good R values of greater than 0.9 were obtained for the 18 month period. Variation was seen in the gradient (beta) values indicating a bias between the instruments. This was mainly less than ± 0.2 (20%) but larger values were seen during April and May 2016 that appear to have self-rectified. Again all filter changes were accompanied by flow checks.

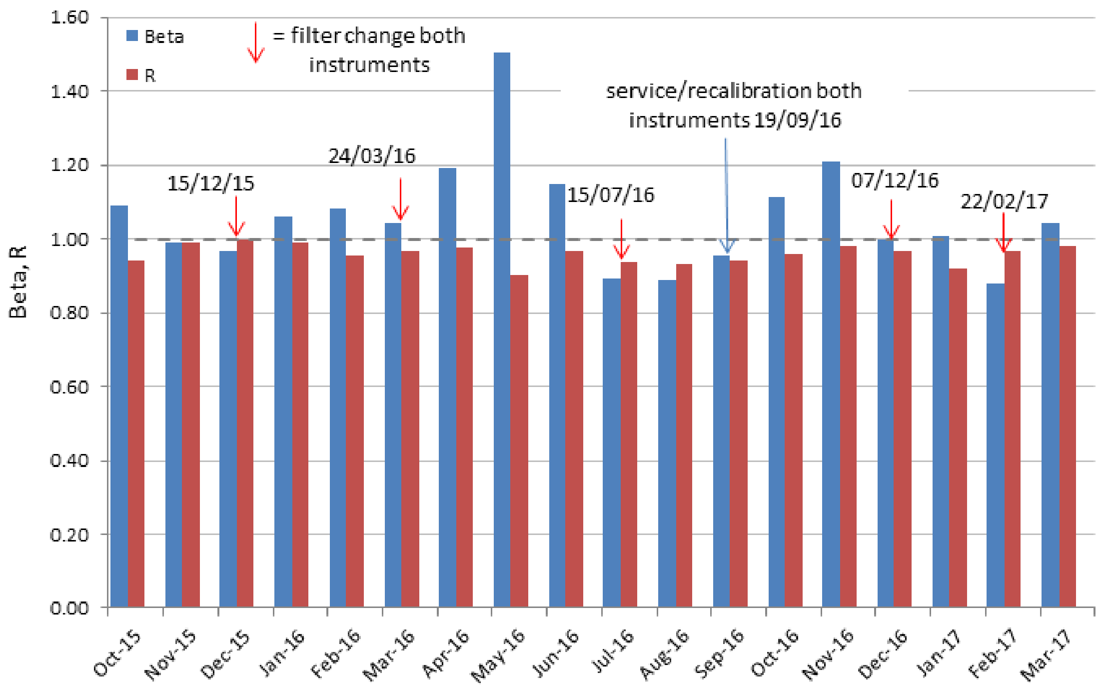

Figure 9 Monthly RMA regressions for instruments C and D showing filter changes and flow checks. Regression gradient beta and correlation R are shown

Instruments C and E (type I)

Figure 10 shows in-service regression gradient and R values from instruments C and E. R values were more variable than between instruments A and B and C and D. Although most values were greater than 0.9, R dropped to 0.8 during summer 2016. Variation was seen in the gradient (beta) values indicating a bias between the instruments. This was mainly less than ± 0.2 (20%) but larger values were seen during May and June 2016. Again all filter changes were accompanied by flow checks.

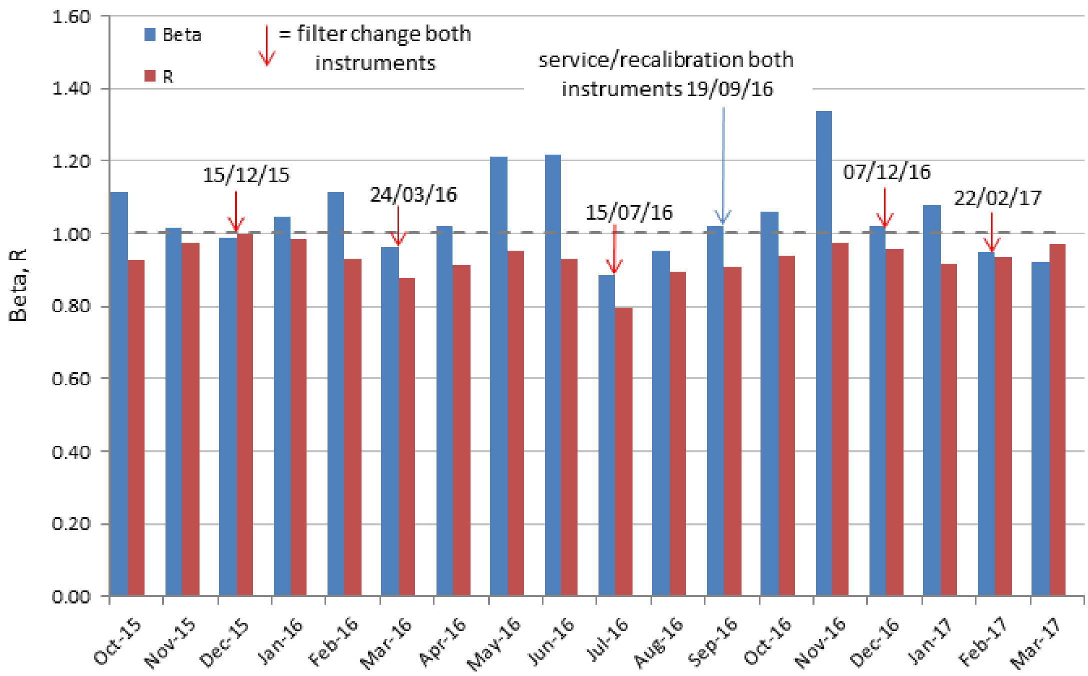

Figure 10 Monthly RMA regressions for instruments C and E showing filter changes and flow checks. Regression gradient beta and correlation R are shown.

Instruments D and E (type I)

Figure 11 shows in-service regression gradient and R values from in instruments D and E. R values were more variable than between instruments C & D and C & E, perhaps due to the greater distances between this site pair. Although most values were greater than 0.9, R dropped below 0.8 during summer 2016. Less variation was seen in the gradient (beta) values than between C and D and between C and E. This was mainly less than ± 0.1 (10%) but lower values were seen during summer 2016. Again all filter changes were accompanied by flow checks.

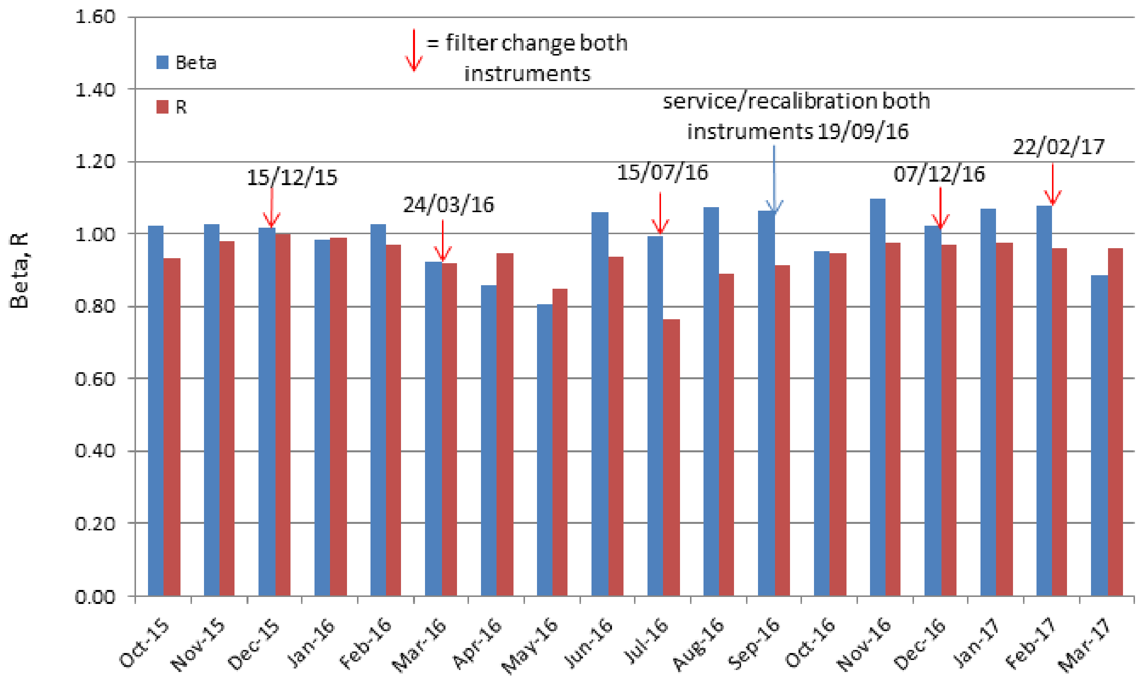

Figure 11 Monthly RMA regressions for instruments C and E showing filter changes and flow checks. Regression gradient beta and correlation R are shown

Instruments F and G (type I)

Figure 12 shows in-service regression gradient and R values from instruments F and G. Given the large number of instrument interventions, these are listed separately in Table 4. R values and gradients remained good throughout but large gradients indicating bias were seen. The peak positive bias was greater than 2.2 (220%) and the peak negative bias was less than 0.4 (-40%). The large positive bias during the latter part of 2015 was not remedied by filter changes, flow adjustments or service of instrument F. The gradient did fall to close to 1 after service and a subsequent repair of instrument G. Similarly filter changes and flow checks by the operator did not resolve the negative bias and poor R values during summer and autumn 2016. This was finally resolved by service of instrument G in December 2016.

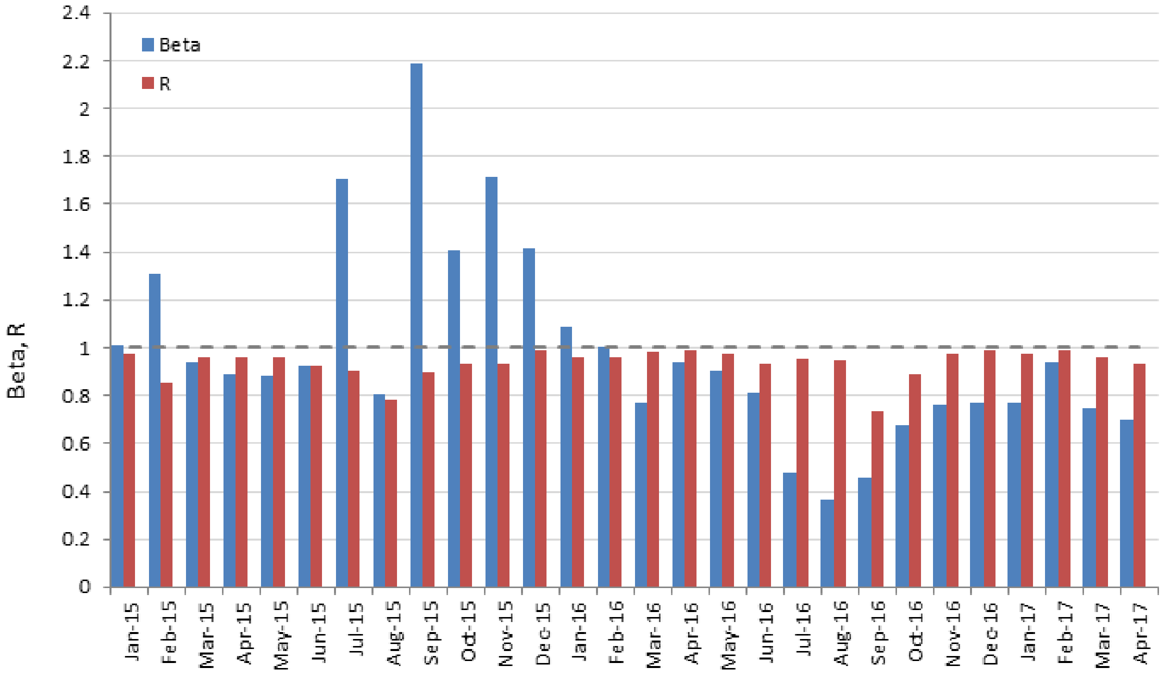

Figure 12 Monthly RMA regressions for instruments F and G. Regression gradient beta and correlation R are shown. Instrument interventions are listed in Table 4.

Table 4 Instrument interventions for instruments F and G.

Instrument F		Instrument G	
Filter change	27/02/15	Filter change	24/05/15
Filter change	22/06/15	Filter change	28/07/15
Service	09/10/15	Service	25/11/15
Repair	02/11/15	Filter change	05/01/16
Filter change	02/03/16	Repair	21/01/16
Repair	09/03/16	Filter change	19/04/16
Filter change	26/05/16	Filter change	19/07/16
Filter change (noisy data)	03/06/16	Filter change	19/09/16
Filter change	19/07/16	Service	08/12/16
Service	21/10/16	Filter change	23/02/17
Service	08/12/16	Filter change	26/04/17

Instruments H and I (type I)

Figure 13 and Figure 14 shows in-service regression gradient and R values from in instruments H and I. Flow checks were undertaken approximately each two weeks and are not shown. Results shown in Figure 13 were from data measured during hours 1 to 3 each evening and Figure 14 presents regressions from Sundays. Both sets of analysis show a substantial change in gradient (beta) from June 2014. This gradient was only rectified by instrument service.

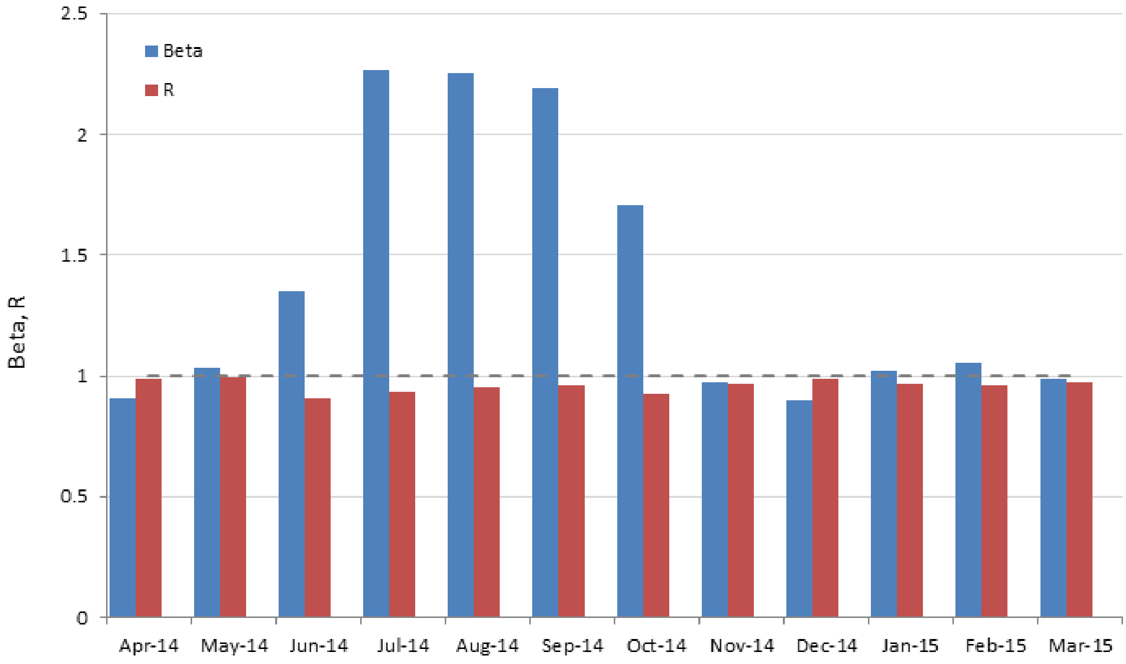

Figure 13 Monthly RMA regressions for instruments H and I. Regression gradient beta and correlation R are shown. Regressions were undertaken for hours 1-3 each night.

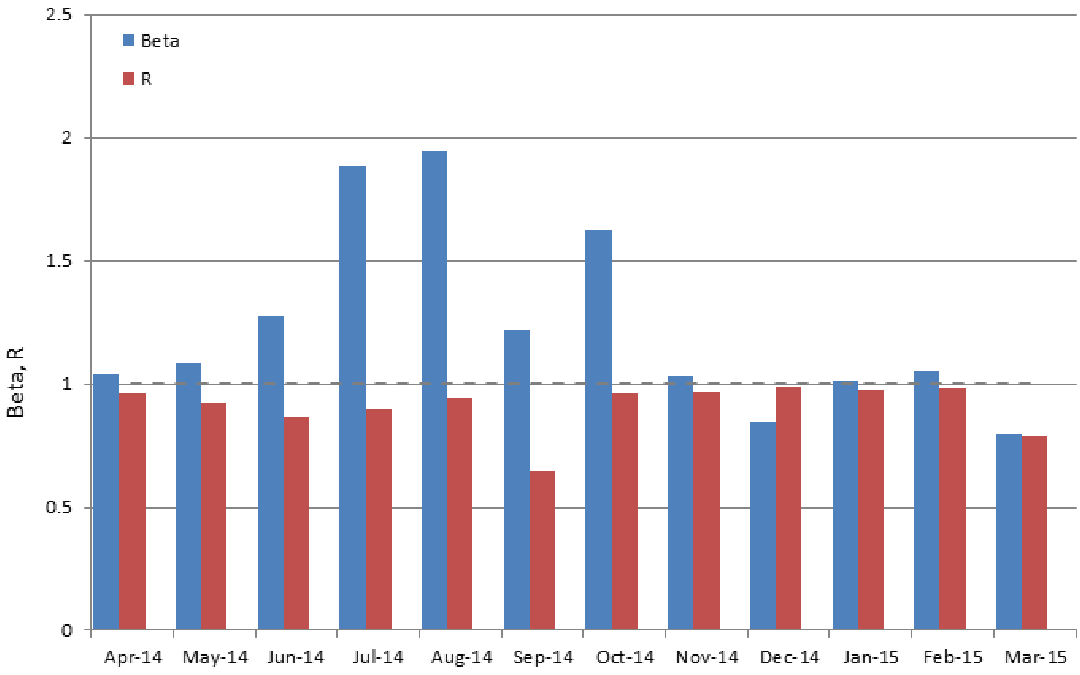

Figure 14 Monthly RMA regressions for instruments H and I. Regression gradient beta and correlation R are shown. Regressions were undertaken from Sundays.

Type II instruments

Figure 15 shows PM_{10} concentrations measured by two closely located instruments of type II. Good agreement was seen between the measurements, with gradient 1.017 (±0.004), intercept 0.068 (± 0.085) µg m^{-3}, R =0.99 with all data. However fewer examples of type II instruments were available when compared with the number of type I instruments in service around construction sites. This limited test does not mean that instruments of type II are not prone to in-service sensitivity drift.

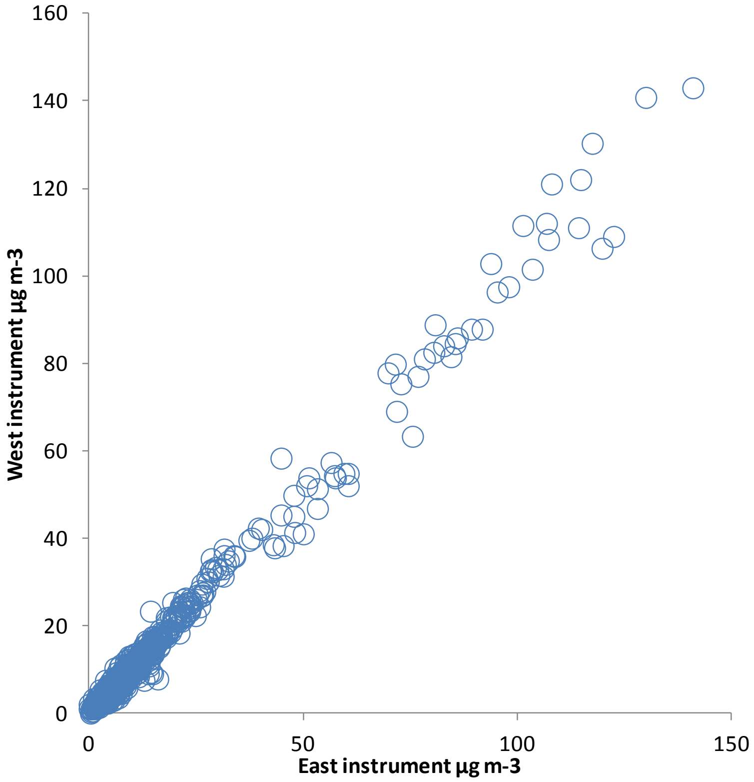

Figure 15 Regression of two closely located instruments of type II.

Regression intercepts

The in-service regressions revealed some non-zero intercepts that were statistically significant. The maximum intercept was 8 µg m^{-3} between instruments H and I in September 2014. The remaining intercepts were less than 2.5 µg m^{-3}, with the majority being less than 1 µg m^{-3}.

Discussion

The in-service calibration checks provide a new way to control the sensitivity of indicative sensors placed around a construction site. Comparisons between paired instruments around a site will be a combination of two factors; differences between the performance of each instrument and differences between the locations. As shown from the in-service checks above, changes in gradient of ± 10% normally self-rectify and may therefore be indicative of variability between locations. Change of ± 20%, largely do not self rectify. For this reason it is not possible to recommend an action in response to a gradient change of ± 10%. Instead changes of ± 20% should be used as an indicator of an excessive drift in sensitivity and an instrument co-location should take place to determine if instrument drift of greater than ± 10% is present.

Zero tests

Introduction

In instrument trails in Barcelona (Viana et al 2015) several examples of a variant of the instrument type III was tested alongside a reference measurement device. Although good correlation between them was found sudden shifts in baseline concentration caused offsets between the type III instruments. At times these offsets, with one case being around 40 µg m^{-3}, caused uncertainties of over 200% in the ambient measurements. An offset of 40 µg m^{-3} would be around 20% at the trigger concentration of 190 µg m^{-3}.

Large instrument offsets should be identifiable using the in-service regression method but can be directly detected by passing filtered air through an instrument. This is carried out by fitting a high efficiency particle absorbing (HEPA) filter to the instrument inlet. This practice is routine on regulatory networks. The instrument response to filtered air can allow an assessment of signal noise, leaks and any instrument offsets.

Method

HEPA filters were fitted to three instruments of type I operating in the field close to three separate construction sites. Measured concentrations were recorded prior to fitting the filter, after one minute and then again after at least ten minutes.

Results

Results from HEPA filter tests on three instruments are shown in Table 5. In each case measured concentrations dropped to near zero. Although no leaks, offsets or substantial noise was found the instrument response demonstrates the ease of the field test.

Table 5 Results from HEPA filter field tests on three instruments of type I. Concentrations are given at µg m^{-3}.

Inst ID		Time	TSP	Dust	$PM_{2.5}$	$PM_{1.0}$
F	SAMPLE	10/05/2017 11:11	19.00	15.60	9.00	1.60
F	HEPA ON	10/05/2017 11:12	0.00	0.00	-0.02	-0.02
F	HEPA ON	10/05/2017 12:28	0.00	0.00	-0.01	-0.01
J	SAMPLE	10/05/2017 13:36	36.20	17.70	9.00	1.40
J	HEPA ON	10/05/2017 13:37	0.00	0.30	0.00	0.00
J	HEPA ON	10/05/2017 14:07	0.00	0.00	0.04	0.00
K	SAMPLE	10/05/2017 13:47	21.40	21.90	17.60	14.40
K	HEPA ON	10/05/2017 13:48	0.00	0.00	-0.04	-0.04
K	HEPA ON	10/05/2017 13:58	0.00	0.00	-0.04	-0.04

5 Conclusions and recommendations

This report has considered evidence on the real world performance of instruments used to measure PM_{10} around construction sites. When assimilating this evidence we need to remember that these are not reference quality instruments but, in the MCERTS terminology they are indicative. This means that they must perform within a 50% uncertainty window in field tests alongside the EU reference method.

Many practical reasons restrict the types of instruments that can be used around construction sites. These include the physical size of the measurement systems and their housing, their high electrical power demands and, in some cases, their sensitivity to vibration. The size of reference equivalent equipment often means that planning permission is required before installation. Smaller indicative measurement systems are therefore used in practice to measure construction PM_{10}. These indicative instruments allow measurements in locations that would simply not be possible with EU reference equivalent methods. They open up the opportunity for more comprehensive measurement programmes close to sensitive populations or close to construction sources. However, the use of indicative instruments introduces additional uncertainties.

As shown, the use of indicative samplers as part of near-real time management of construction dust such as that in the GLA guidance plays to the strengths of these types of instrument. These management strategies focus on identifying PM_{10} concentrations above trigger values. Concentrations of PM_{10} above the trigger values are dominated by coarse particles and contain a relatively low proportion of volatile PM. However improvements are needed in the way in which these instruments are operated. Bias in instrument sensitivity could lead to an increase in the number of false alarms and therefore work stoppages or missed dust events and a failure to control dust impacts.

An over read of 10% would increase the mean number of trigger events by 33% with the new trigger definition and 23% with the old one. A 20% over read caused an increase of 78% for the new threshold and 114% for the old one. For over reads greater than 20% the rate of false alarms exceeded the real events for trigger definitions.

An under read of 10% resulted in a decrease in the mean frequency of triggers of 23% for the new definition, and a decrease of 25% for the old definition. A 20% under read produced a decrease trigger frequency of 38% for the new definition and 39% for the old definition. For under reads of 30% and more over half the trigger events would be missed. For indicative instruments to provide useful information for reactive dust management they need to be operated with uncertainties that are ideally less than 10% but certainly not more than 20%.

Analysis of existing datasets found that indicative instruments are susceptible to changes in:

- Sample flow between calibrations; with a mean change of -6% but changes of more than -10% were seen.
- In-correct heater operation or heater failure, which in the case of one instrument type, led to an over read of 100% during episodes of high volatile PM.
- Changes in instrument sensitivity that can result in bias of -50% to more than +200%. Many monthly bias changes of less than 10% self rectified meaning that an action limit of 20% is likely to be as low as practically possible in some situations. Evidence from the manufacture of instrument type I (Barton – personal communication) suggests that bias can also be detected in instruments returned for service.
- Changes in instrument offsets.

We therefore recommend the following minimum operational requirements

At the **start of a sampling** campaign instruments should be:

1) Set up in the same manner as in the MCERTS field tests. This point applies especially to sample heaters / systems and flow.

2) Either
    a. Co-located at the construction site or similar location for at least one week. Reduced (or standardised) major axis regression should be used and bias between instrument pairs should be less than 10% before deployment.

    or

    b. Calibrated by the manufacturer or a test house with traceability to national standards.

The following actions should be carried out **monthly** by the **field operator**:

3) Sample flow should be checked and adjusted with a traceable flow meter with an uncertainty of 5% or better. The field flow meter should be checked annually to ensure continued traceability of measurements.

4) The operation of the heater needs to be verified by continuous measurement of sample temperature or by manual verification of heater operation. A hand-held pyrometer was found to be practical for instrument type I.

5) HEPA filters should be fitted to the sample system and the measured concentration should quickly fall to within the signal noise or limit of detection for the equipment. Failure may indicate a fault which needs to be remedied.

In-service quality checks should be undertaken **monthly**:

6) PM_{10} concentrations should be compared during periods of low concentrations of local sources such as hours 1 to 3 each night or Sundays between pairs of instruments. Reduced (or standardised) major axis regression should be used.
    a. In the event of a bias (gradient) change of ± 20% (single month or cumulative change in bias between instruments):
        i. Equipment should be investigated for faults. If faults are found these should be remedied.
        ii. If a local overnight or Sunday PM_{10} source is found that would have interfered with the comparison, then no further action need be taken. A local source would be indicated by outliers in the regression or poor correlation.
        iii. The instrument should be placed in a collocation exercise on the construction site. If a bias of greater than 10% is found then the instrument should be subject to manufacturer or test house calibration.

Additionally:

7) Instruments must be serviced in accordance with manufactures recommendations. Servicing needs to include sampling systems.

8) Good record keeping is essential to track the performance of instruments over time. This should include records of field checks, pre and post service calibrations and the results from in-service cross checks.

The in-service calibration checks provide a new way to control the sensitivity of indicative sensors placed around a construction site. The proposed quality checks imply that spare equipment needs to be available to enable a full sampling programme to continue if equipment is withdrawn for repair or co-location checks.

Different instrument types will differ in their sensitivity to the various components of the PM mixture. In-service cross checks and co-locations need to be conducted with instruments of the same make and model.

Comparisons between paired instruments around a site will be a combination of differences between performance of each instrument and differences between the locations. Changes of ± 20% are recommended as an indicator of an excessive sensitivity drift to trigger a collocation. A collocation gradient of ± 10% is then recommended as a trigger for manufacturer recalibration. In this way uncertainties should be controlled at between 10% and 20%. This does not include the uncertainty from the manufacture calibration and also those induced by the variable sensitivity of equipment to different components of the PM mix.

It is clear that even with operational improvements beyond the current state of the art, uncertainty of up to 20% will remain in the measurement of PM around construction sites. With well characterised construction sites operators should tighten the in-service regression approach to take action with changes to 10% or 15%. This would reduce the potential for false alarms and also the number of missed dust events.

Real-time construction dust measurement strategies are limited by the capabilities of current measurement devices. Research into measurement methods and their application would improve construction dust management.

Given the uncertainty estimates, the performance of indicative instruments also needs to be better characterised through co-locations in construction environments.

The current MCERTS and European test methods of PM_{10} monitoring equipment focus on measuring concentrations and particle types that occur in typical urban areas. This is not the same as construction dust. There is a clear need for certification testing of indicative PM_{10} monitoring equipment in construction environments. There are three ways to achieve this:

- Construction activities and emissions could be simulated at existing equivalence testing platforms such as the one at the National Physical Laboratory.
- Paired reference equivalent and indicative monitoring equipment could be installed at construction sites and construction PM would be measured as they arose during the project.
- A mobile test platform could be used and taken around construction sites to test a range of site activities.

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