# Targeted Application of Calcium Magnesium Acetate (CMA) Pilot Study Monitoring Report

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| **Client Contact Name:** | Will Fooks |
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| **Issued By:** | URS Corporation Ltd.<br>West One<br>114 Wellington Street<br>Leeds<br>LS1 1BA<br>Tel: +44 (0) 113 204 5000<br>Fax: +44 (0) 113 204 5001 |

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| Prepared by | David Deakin<br>Chuansen Ren | | July 2011 | Principal Air Quality Consultant<br>Senior Air Quality Consultant |
| Checked by | Helen Watson | Helen R Watson | July 2011 | Air Quality Consultant |
| Approved by | Garry Gray | | July 2011 | Associate Director |

# CONTENTS

**SECTION** **PAGE NO**

## CONTENTS

**SECTION** **PAGE NO**

**APPENDIX A CMA APPLICATION SCHEDULE**

## LIMITATIONS

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# 1. EXECUTIVE SUMMARY

Modelling suggests that $PM_{10}$ concentrations will meet the EU Limit Values across London in 2011. However, there remain some areas near the busiest roads in central London where the margin between modelled concentrations and the daily mean $PM_{10}$ limit value is very small. These areas are therefore considered at risk of exceeding the limit value. The Mayor of London's Air Quality Strategy includes a series of measures to reduce $PM_{10}$ emissions across London in addition to local measures to tackle $PM_{10}$ concentrations in priority locations[1]. The application of dust suppressants to road surfaces in priority areas is one of the local measures.

The application of dust suppressants to reduce roadside concentrations of $PM_{10}$ has been investigated overseas, primarily in Scandinavia and also Austria. The majority of studies did achieve beneficial results through the application of suppressants in relation to daily $PM_{10}$ concentrations. However, until this study no trials had been undertaken to assess the effectiveness of this mitigation measure in the UK.

There are three published studies undertaken in tunnels, three at motorway locations and one in an urban environment. There is therefore a limited amount of information concerning dust suppressants, with particular reference to urban environments. In addition, studies were undertaken in locations which are likely to utilise winter studded tyres (which increase re-suspended PM from the road surface) for part of the year and as such it is considered that the high percentage of improvements achieved in daily $PM_{10}$ concentrations observed in these studies (reductions up to 56%) are unlikely to be achieved in the UK. The literature review however, does suggest that in some locations, particularly in urban environments, that the application of dust suppressants could be one of the useful tools which may be used to reduce daily $PM_{10}$ concentrations.

Phase 1 of the monitoring of the impact of Cleaning and Application of Dust Suppressant trial (CADS) in London was undertaken in Victoria Embankment, which is one of the $PM_{10}$ hotspots identified by the Mayor's Air Quality Strategy. Baseline monitoring commenced on the 15th of October 2010 at Victoria Embankment. The test and control sites were selected to avoid areas with sources of particulates which could obscure the effects of any dust suppression (e.g. rail, congestion etc) and in particular a section of Victoria Embankment was selected. Monitoring was concentrated to make the best use of limited resources and to identify an understanding of the types of results which could be expected in one location before attempting to replicate effects in a number of locations.

Applications of the dust suppressant, Calcium Magnesium Acetate (CMA), commenced on the 18th of November 2010. CMA was selected as the suppressant by TfL on the basis of experience from the European Union (EU) Life funded project – CMA+. CMA was applied along Victoria Embankment between Waterloo Bridge and Byward Street.

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[1] Greater London Authority, 2010. Mayor of London. Clearing the air. The Mayor's Air Quality Strategy. Dated December 2010. www.london.gov.uk

The analysis of CMA effects has focused on a period of low intensity treatment between the 12th of January 2011 and 31st of January 2011 and also a more intensive period of treatment between the 1st of February 2011 and the 10th of March 2011.

In the low intensity period calculations suggest that an improvement in 24-hour $PM_{10}$ kerbside concentrations was achieved. The calculated improvement during this period was around 10%. However, improvements achieved in the smaller size fractions during this period are greater than expected based on literature review information. This suggests that the level of improvement during this low intensity period is likely to be less than calculated.

In the more intensive treatment period an overall reduction in 24-hour $PM_{10}$ kerbside concentrations was also identified. The level of improvement during this period has been calculated to be approximately 14%. Calculations for the smaller size fractions of $PM_{2.5}$ and $PM_1$ (24-hour kerbside averages) suggest that improvements of around 3% were also achieved during the intensive treatment period. Lower improvements in these size fractions, relative to $PM_{10}$, would be anticipated with the smaller size fractions. This is because CMA interventions are anticipated to affect larger sized particles primarily.

These CMA treatment figures are based on a first pilot study undertaken during a limited study period and in one study location. It is therefore suggested that the results should be considered, as only indicative of the environment studied, over the duration of study, and with the inherent limitations of a pilot study.

The percentage reduction achieved during the pilot study may, in part, be due to the partial canyon environment located at the main test site, as this will likely result in some re-circulation effects, which may maintain the available source of particulates on the road surface. This will increase the amount of particulate available for re-suspension relative to open environments and so lesser percentage improvements may be expected in these open environments.

Further work is now required to confirm these pilot study effects are replicated in other locations and environments. For example open environments, which may be less well suited to CMA applications or other environments, which may be even better suited to CMA applications (e.g. full canyons which are common in some urban environments). A range of detailed recommendations have been suggested for the next stage of works (e.g. measurement of road surface chemistry).

The study has not been undertaken with reference techniques, which are used to determine compliance with EU Limit Values. Therefore, these results cannot be used to demonstrate compliance with EU Limit Values. However, the results from the pilot study suggest that if the levels of change identified from the pilot study can be replicated elsewhere, that this technique has the potential to be useful in reducing $PM_{10}$ concentrations and the number of EU Limit Value exceedances. Albeit, this would be limited to periods where an exceedance was likely close to the EU Limit Value and where one of the key episode sources was local road traffic emissions. Dust suppressants will not be a useful abatement technique for preventing exceedences of the $PM_{10}$ EU limit Value where the key driver is long range pollution.

## 2. INTRODUCTION

There are some locations in London that have been identified as at risk of exceeding the $PM_{10}$[2] 24-hour EU Limit Value of 50 µg/m³ (not to be exceeded more than 35 times per year)[3]. Historically, days when exceedances have occurred have been primarily been monitored during the winter months, although in recent years significant numbers of exceedances have been recorded in the springtime and occasionally summer time.

The Mayor's Air Quality Strategy[1] acknowledges that many 24-hour exceedances are due to significant background contributions of $PM_{10}$, but that in some instances a combination of local measures could be utilised to avoid exceedances of the 24-hour $PM_{10}$ limit value.

In his Air Quality Strategy the Mayor of London has set out a series of policies to improve air quality in London, including age based limits for taxis and Private Hire Vehicles (PHVs); tighter Low Emission Zone (LEZ) standards; promoting smarter travel; and further improvements in the bus fleet. These measures are expected to deliver significant long-term reductions in air pollutant emissions and improvements in London's air quality and build on a number of initiatives implemented in previous years.

However, due to the need to consult stakeholders and other operational practicalities many of the new policies in the Mayor's Air Quality Strategy do not come fully into force until 2012 or later. This is after the extended deadline for meeting the EU limit value of 11 June 2011. Consequently, the Mayor's strategy identified the need for short-term local measures to help improve local air quality at the small number of priority action areas in central London most at risk of exceeding 24-hour EU limit values for $PM_{10}$.

In developing the local measures TfL reviewed best practice and innovative approaches from across Europe. One of the potential local measures identified was the use of dust suppressants. On the basis of studies which identified that dust suppressants reduced $PM_{10}$ concentrations up to 56%, including some peer reviewed articles, it was judged by TfL that a trial in the UK was justified.

This report details the first phase of trials undertaken in the UK to test the effectiveness of dust suppressants. In this study the effectiveness of Calcium Magnesium Acetate (CMA) has been utilised as the dust suppressant. The original objectives of the study provided by TfL were as follows:

- Assess the effectiveness of different methods of dust suppressant application (solution concentration, application area etc).
- Quantify the impact that the application of dust suppressant has on 24-hour average $PM_{10}$ and $PM_{2.5}$ concentrations in the trial areas over the trial period.

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[2] $PM_{10}$ is the size fraction of ambient particulates with an aerodynamic diameter of equal to or less than 10µm.

[3] The European Parliament and The Council Of The European Union, 2008. Directive 2008/50/EC of The European Parliament and of The Council of 21 May 2008 on ambient air quality and cleaner air for Europe.

- Understand what potential benefit the application of dust suppressants may have on reducing the number of $PM_{10}$ exceedences in hot spot areas if a dust suppressant programme was subsequently implemented.

The first phase of the study focused primarily on Victoria Embankment, part of the Mayor’s Priority Action Areas for 24-hour $PM_{10}$ concentrations. The Marylebone Road and Euston Road priority action area between was also treated during the trial. However, these areas are not included in this phase of the monitoring report as the trial aimed to focus limited resources. Marylebone Road has always been scheduled for inclusion in a later stage of work.

# 3. LITERATURE REVIEW

The performance of dust suppressants, including CMA, on paved surfaces has been tested in a number of Scandinavian and other European countries. Tests in these countries have typically been successful in reducing daily $PM_{10}$ concentrations and this success has resulted in the implementation of these trials.

The literature review initially discusses the sources associated with roadside particulates and how climatic variations and local conditions may affect the amounts and sources of particulates at roadside locations. This literature review also presents the findings from key dust remobilisation and dust suppressant studies, identifying the likely key factors which affect dust re-suspension. In particular, the possible differences in remobilisation potential and hence the associated level of likely performance of dust suppressants in the UK, relative to the European studies, is discussed. The techniques used to monitor and analyse dust re-suspension are also briefly reviewed.

## 3.1 Roadside Particulates

The total concentration of $PM_{10}$ at roadside locations is a combination of a variety of sources including: background components (local and regional) combined with direct vehicle exhaust emissions and non-exhaust vehicle emissions.

A report prepared by Barlow et al. 2007[4] includes a list of direct vehicle non-exhaust sources including: tyre wear, break wear and road surface wear. Barlow et al. 2007 also list other potentially direct vehicle non-exhaust emissions including: clutch ware, engine ware, abrasion of wheel bearings, corrosion of vehicle components, corrosion of street furniture and corrosion of crash barriers. Other potential direct non-exhaust emissions include dust introduced by dirty wheels and losses from truck loadings (Gehrig et al. 2010)[5]. Similar smaller losses could also be associated with dirt from vehicle undercarriages and in particular wheel arches and mudguards.

The last non-exhaust component of roadside $PM_{10}$ concentrations is re-suspended dust, which is a mixture of the deposited sources listed above and other background sources (e.g. sea spray, vegetation, desert dust events, construction site emissions, industrial site emissions, solid and liquid fuel heating or electricity plant emissions, domestic solid fuel emissions and road salt). Dust is re-suspended by the action of tyres, vehicle induced turbulence and the wind.

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[4] Barlow, T, J. Boulter, P, G. McCrae, I, S. Sivell, P. Harrison, R, M. Carruthers, D. and Stocker, J. 2007. Non-exhaust Particulate Matter Emissions from Road Traffic: Summary Report.

[5] Gehrig, R., Zeyer, K., Bukowiecki, N., Lienemann, P., Poulikakos, L.D., Furger, M. and Buchmann, B. 2010. Mobile load simulators - A tool to distinguish between the emissions due to abrasion and resuspension of $PM_{10}$ from road surfaces. Atmospheric Environment 44 (2010) 4937 – 4943.

The US Environmental Protection Agency (US EPA) (2006) [6] lists the erosion of soft verges adjacent to roads as a potential local source of dust which can be remobilised and also litter deposits as a potential source of particulates, including $PM_{10}$. Litter dropped from vehicles could also be a direct non-exhaust emission. However, Boulter et al. 2006[7] note that litter is unlikely to be a significant source of particulates, unless the litter is of a form that can rapidly break down and that erosion of verges is only likely to be significant in rural environments.

The proportion of $PM_{10}$ concentrations associated with each of the above components is variable, with variations due to:

- Distance from kerbside locations;
- Different climates; and,
- Different traffic conditions (e.g. speeds, vehicle types).

The proportion of $PM_{10}$ from different sources comprising total roadside concentrations suggested in the literature reviewed also varies between different authors. Thorpe et al. 2007[8] notes that, despite the growing number of studies that have attempted the quantification of re-suspension emissions, estimates are very variable and remain uncertain largely due to the difficulties in making direct measurements.

A further study was also undertaken in 2007 into the re-suspension of $PM_{10}$ by road vehicles by Abbott[9]. In this study Abbot investigated six monitoring locations, as listed in Table 3.1. In this study oxides of nitrogen, $PM_{10}$ and $PM_{2.5}$ data were analysed to try and assess the contribution of re-suspension. This was done by inferring emission rates from the measured data and comparing these to expected rates of emission from the National Atmospheric Emissions Inventory (NAEI). Abbott (op cit) concluded that at five of the six sites, the total inferred emission rate from monitored data was approximately equal to that expected from the NAEI and thus there was no evidence of an additional re-suspension emission for these sites for most hours of the year. The Marylebone Road site was not adequately described by comparison with NAEI factors, where the rate of inferred emissions was around 50% higher than the expected NAEI factors. Abbott (op cit) noted that at Marylebone Road this could relate to a re-suspension effect or congested flow

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[6] United States Environmental Protection Agency (US EPA), 2006. Draft Section 13.2.1 on paved roads from AP42.

[7] Boulter, P,G., Wayman, M., McCrae, I,S. and Harrison, R.M. 2006. A Review of Abatement Measures for Non-Exhaust Particulate Matter from Road Vehicles. Published Project Report PPR230. Final Version.

[8] Thorpe, A, J., Roy, M., Harrison, R, M. Paul, G. Boulter, P, G. Ian, S. McCrae, I, S. 2007. Estimation of particle re-suspension source strength on a major London Road. Atmospheric Environment Vol 41, issue 37, 8007-8020, 2007.

[9] Abbott, J. 2007. $PM_{10}$ resuspension by road vehicles. AEA report for the Department for the Environment, Food and Rural Affairs (Defra). Ref: ED-48209/R2388.

conditions. Abbott (op cit) also noted potential periods of higher emissions during high wind speeds at the Bexley 8 site which would be significant compared to modern HGV exhaust emissions, although road construction activity was listed as a potential confounding factor to this conclusion. Lastly, Abbott (op cit) also listed occasional incidental hours at all sites when the inferred emission rates were much higher than expected NAEI emission rates. The reasons for some of this effect were listed as measurement errors or gritting. Abbott (op cit) further noted that these occasional incidental emissions were relatively small, adding considerably less than 1 µg/m$^3$ to an annual average. No description of the results relative to 24-hour objectives was provided in the study.

**Table 3.1 Abbott (2007) Re-suspension Study Site Summary**

| Monitoring Site | Site Description | Site Type |
|---|---|---|
| Bexley 8 | 22m from the A206, Junction of Thames Road and Iron Mill Lane | Suburban |
| Ealing 2 | 3m from the A4020 in a canyon, close to the junction of High Street and the B490. | Roadside |
| Greenwich Bexley 6 | 1m from the A2 | Kerbside |
| Greenwich 9 | 5m from the A205, at the junction of Westhorne Avenue and Pinnell Road | Roadside |
| Marylebone Road | 1m from the A501 in a canyon location | Kerbside |
| M25 Site | Carriageway edge between Junctions 13 and 14 | Motorway |

Since the work undertaken by Thorpe et al. (op cit) Green et al. (2009)[10] have undertaken further work considering the chemical speciation of $PM_{10}$ at two sites in London. This work builds on the previous work of other workers, including Harrison et al. (2004)[11], where a mass closure model is created and particles are attributed to different chemical species. The Harrison et al. (op cit) study suggested a mean roadside $PM_{10}$ component of 11.5 µg/m$^3$ and for $PM_{2.5}$ a concentration of 8.0 µg/m$^3$ for four sites, including 3 in

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[10] Green, D., Tremper, A. and Fuller, G. 2009. Chemical Speciation of $PM_{10}$ at LEZ supersites.

[11] Harrison, R,M., Jones, A,M. and Lawrence, R,G. 2004. Major component composition of $PM_{10}$ and $PM_{2.5}$ from roadside and urban background sites. Atmospheric Environment 38, 4531–4538.

London and 1 Birmingham. In the Green et al. (op cit) study a number of chemical species were considered including: iron oxides, other metals, minerals, primary organic mass, elemental carbon, secondary organic mass, water, chlorides, sulphates and nitrates. Table 3.1 lists the chemical species and the mean concentration of each fraction identified at two sites. The potential sources of each chemical fraction suggested by the authors are also listed in Table 3.2.

**Table 3.2 Mean $PM_{10}$ Chemical species at Brent 4 and Tower Hamlets 4**

| **Chemical Species** | **Brent 4 (µg/m$^3$)** | **Tower Hamlets 4 (µg/m$^3$)** | **Suggested Sources** |
|---|---|---|---|
| Iron oxides | 1.9 (7%) | 2.3 (7%) | Break ware |
| Other metals | 0.2 (1%) | 0.3 (1%) | Tyre and brake wear |
| Minerals | 3.9 (13%) | 6.5 (20%) | Windblown dust and vehicular re-suspension |
| Primary organic mass | 2.1 (7%) | 3.9 (12%) | Direct organic gas emissions which form particles through nucleation or condensation (e.g. PAH's) as well as the organic components of soil or tyre wear which may be re-suspended by vehicles. |
| Elemental carbon | 6.7 (23%) | 5.2 (16%) | Direct vehicle exhaust emissions from incomplete combustion |
| Secondary organic mass | 3.2 (11%) | 3.4 (10%) | Non-traffic related organic compounds which have been oxidised in the atmosphere to form particles or condense onto pre-existing particles; this fraction may also contain organic components from soil which are not traffic related. |
| Water | 0.7 (2%) | 0.8 (2%) | Secondary or natural sources |
| Chlorides | 3.4 (12%) | 3.5 (10%) | Sea salts |
| Sulphates | 2.4 (8%) | 2.2 (7%) | Secondary or natural sources |
| Nitrates | 4.2 (14%) | 4.4 (13%) | Secondary or natural sources |
| Unidentified | 0.7 (2%) | 0.7 (2%) | |
| Total mean $PM_{10}$ | 29.4 | 33.2 | |

Note: Sampling undertaken in two phases. Sampling Period 1: 6th August 2008 to 29th September 2008. Sampling Period 2: 31st October 2008 to 26th December 2008. Percentages shown in brackets.

A key finding of the work by Green et al. (2009) was that around half of mean $PM_{10}$ concentrations were from natural or secondary sources i.e. $PM_{10}$ formed in the atmosphere from other pollutants rather than primary $PM_{10}$ which is emitted directly. In relation to re-suspension, Green et al. (op cit) did not identify a strong relationship between minerals and elemental carbon and therefore concluded this indicated no clear relationship between re-suspension and vehicle emissions, although noted that re-suspension is a complex process affected by a number of factors e.g. traffic composition, speed, meteorological conditions etc. Also the above conclusion, that there is no correlation between re-suspension and vehicle emissions, does not consider the potential influence of the re-suspension of a portion of deposited direct vehicle emissions or of a portion of other deposited particles from background sources (i.e. the iron oxide, other metals, and primary organic or secondary organic mass fractions). Another species which could potentially be re-suspended following deposition is elemental carbon, as although this is a primary exhaust emission of small particles (e.g. $PM_1$), these latterly increase in size through nucleation and growth as exhaust gases are dispersed and cooled. It is also important to note that the average concentrations reported by Green et al. (op cit) for different fractions relate to the mean of the two sampling periods and that individual 24-hour periods varied, particularly during pollution episodes.

The uncertainties associated with the magnitude of re-suspended dust $PM_{10}$ contributions, as described above, has resulted in difficulty in ascribing a re-suspended $PM_{10}$ emission factor to emission inventories. Therefore, re-suspended $PM_{10}$ is not typically explicitly included in dispersion modelling exercises, unless captured via model verification. For example the London Atmospheric Emissions Inventory (LAEI)[12] includes a total $PM_{10}$ emission for Central London of 125 tonnes, including break and tyre wear of 40 tonnes, but does not include a value for re-suspension or road ware.

The above discussion of roadside particles has focused on $PM_{10}$ concentrations, partly as it is due to the potential for non-compliance with the 24-hour $PM_{10}$ EU Limit Value that the Priority Action Areas within the study have been declared. However, smaller particle sizes such as $PM_{2.5}$ and $PM_1$ (particles with an aerodynamic diameter of less than 2.5 µm and 1 µm respectively) have also been considered, in order to establish whether these size fractions are a significant part of re-suspended $PM_{10}$.

The literature reviewed suggests that these smaller size fractions are not significantly associated with road dust re-suspension. A study in 2010[13] indicates that the dominant contribution of $PM_{2.5}$ and $PM_1$ is often from long-range transport, although road wear through the use of studded tyres appears to be an important source for smaller particle size fractions. Winter tyres are not typically used in the UK and so this will not be a

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[12] Greater London Authority, 2006. London Atmospheric Emissions Inventory.

[13] Sjödin, A., Ferm, M., Björk, A., Rahmberg, M., Johansson, C., Gudmundsson, A., Swietlicki, E., Mats Gustafsson, M. and Blomquist, G. 2010. Wear particles from road traffic. Transport Research Arena Europe 2010, Brussels.

significant source of smaller sized particulates. Amato et al. 2009[14] also suggests that total emissions of $PM_{2.5}$ are around 8% from non-exhaust emissions and 32% from exhaust sources. Barlow et al. 2007, in deriving emission factors for non-exhaust sources, assumed that there were no emissions of $PM_{2.5}$ from re-suspension. Workers, such as Thorpe et al. 2007, also use the particle sizes between $PM_{2.5}$-$PM_{10}$ to represent non-exhaust sources.

## 3.2 Climatic Variations

In colder climates the use of studded tyres is thought to generate a significant amount of road surface wear leading to a high proportion of $PM_{10}$ from this source. Norman and Johansson (2006)[15] concluded that local road abrasion due to the use of studded tyres was the most important mechanism responsible for the high $PM_{10}$ concentrations observed along some highways in Stockholm, with Omstedt et al. 2005[16] stating that exhaust emissions only marginally contribute to observed $PM_{10}$ concentrations in Sweden. Gustafsson et al. 2008[17] also indicate that studded winter tyres (used in colder climates) yield tens of times higher $PM_{10}$ concentrations compared to non-studded winter tyres. In addition to higher rates of road wear, winter tyres will also potentially generate a greater source term available for re-suspension. The use of grit to prevent routes freezing is also likely to contribute to re-suspension contributions.

Norman and Johansson (2006) also remark that this situation is in contrast to many other European cities where exhaust emissions may contribute 50% or more of local $PM_{10}$ concentrations (e.g. Querol et al. 2004[18]). Amato et al. 2009 also remark that Barcelona represents a typical Mediterranean scenario, where exhaust and non-exhaust emissions from road traffic have similar burdens on $PM_{10}$ concentrations. A recent study in Spain by Pay et al. 2011[19] also discusses the potential contribution of re-suspension to both annual

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[14] Amato, F., Pandolfi, M., Escrig, A., Querol, X., Alastuey, A., Pey, J., Perez, N., Hopke, P.K., 2009. Quantifying road dust resuspension in urban environment by multilinear engine: a comparison with PMF2. Atmospheric Environment 43, 2770–2780.

[15] Norman, M and Johansson, C. 2006. Studies of some measures to reduce road dust emissions from paved roads in Scandinavia. Atmospheric Environment 40 (2006) 6154–6164.

[16] Omstedt, G., Johansson, C., Bringfelt, B., 2005. A model induced non-tailpipe emissions of particles along Swedish roads. Atmospheric Environment Vol 39.

[17] Gustafsson, M., Blomqvist, G., Gudmundsson, A., Dahl, A., Jonsson, P., Swietlicki, E., 2009. Factors influencing $PM_{10}$ emissions from road pavement wear. Atmospheric Environment 43 (31), 4699 to 4702.

[18] Querol, X., Alastuey, A., Ruiz, C.R., Artinano, B., Hansson, H.C., Harrison, R.M., Buringh, E., ten Brink, H.M., Lutz, M., Bruckmann, P., Straehl, P., Schneider, J., 2004. Speciation and origin of $PM_{10}$ and $PM_{2.5}$ in selected European cities. Atmospheric Environment 38, 6547 – 6555.

[19] Pay, M. T., Jiménez-Guerrero, P. and Baldasano, J, M. 2011. Implementation of resuspension from paved roads for the improvement of CALIOPE air quality system in Spain. Atmospheric Environment 45 (2011) 802-807.

and peak period $PM_{10}$ concentrations noting that: ‘The re-suspended particles from paved roads (RPR) emission may have strong local effects on the modelled particle concentration in or near the largest urban zones (up to 7 $\mu gm^{-3}$ as the annual average and a contribution of 30 $\mu gm^{-3}$ to the rush hour peaks)’. These results may be higher than would be obtained in some other European countries, since regions with low precipitation climates favour the accumulation of paved road dust and the re-suspension of loose material on the road surface (Abu-Allaban et al., 2003[20]; Thorpe and Harrison, 2008[21]).

In Lille, France, a study by Anne Jaecker-Voirol and Philippe Pelt in 2000[22] concluded that re-suspension of $PM_{10}$ originating from loose material present on the paved road surface seems to be several times higher than vehicle exhaust gas emission.

In the UK, a study by Thorpe et al. (2007), concerning particle re-suspension source strength for Marylebone Road, lists previous work undertaken by Lenschow et al. (2001)[23] in Berlin and suggests that vehicle exhaust emissions and abrasion emissions are approximately equal to re-suspension emissions. Harrison et al. (2001)[24], working in the UK, also found that vehicle induced re-suspension, including other traffic-related coarse particles (such as brake and tyre wear emissions) provides a source strength which is approximately equal to that of exhaust emissions. However, Thorpe et al. (2007) suggest that a lower contribution of roadside increment $PM_{10}$ concentrations is from re-suspension, 20–22% of total $PM_{10}$ emissions. Thorpe et al. (op cit) further suggest that 19% can be attributed to coarse fraction abrasion source emissions, whilst the remaining 60% arises from vehicle exhaust and fine fraction abrasion emissions.

## 3.3 Road and Traffic Related Variations

The re-suspension of dust from road surfaces is due to three factors as described above including tyre action, wind and vehicle induced turbulence. Gehrig et al. 2004[25] in a study

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[20] Abu-Allaban, M., Gillies, J.A., Gertler, A.W., Clayton, R., Proffitt, D., 2003. Tailpipe, resuspended road dust, and brake-wear emission factors from on-road vehicles. Atmospheric Environment 37 (37), 5283 – 5293.

[21] Thorpe, A., Harrison, R.M., 2008. Sources and properties of non-exhaust particulate matter from road traffic: a review. Sci. Total Environ. 400, 279 to 282.

[22] Jaecker-Voirol, A., Pelt, P., 2000. $PM_{10}$ emission inventory in Ile de France for transport and industrial sources: $PM_{10}$ re-suspension, a key factor for air quality. Environmental Modelling & Software 15, 575 - 581.

[23] Lenschow, P., Abraham, H.J., Kutzner, K., Lutz, M., Preu, J.D., Reichenbacher, W., 2001. Some ideas about the sources of $PM_{10}$. Atmospheric Environment 35, 23–33.

[24] Harrison, R.M., Yin, J., Mark, D., Stedman, J., Appleby, R.S., Booker, J., Moorcroft, S., 2001. Studies of the coarse particle (2.5–10 mm) component in UK urban atmospheres. Atmospheric Environment 35 (21), 3667–3679.

[25] Gehrig, R., Hill, M., Buchmann, B., Imhof, D.,Weingartner, E., Baltensperger, U., 2004. Separate determination of $PM_{10}$ emission factors of road traffic for tailpipe emissions and emissions from abrasion and resuspensions processes. Int. J. Environ. Pollut. 22, 312 – 325.

in Switzerland indicate that sites with relatively undisturbed traffic flow, re-suspension and road abrasion are in the same range as exhaust emissions, but that at sites with disturbed traffic flow due to traffic lights, emissions from abrasion/re-suspension are even higher than those from exhausts. Latterly, Gehrig et al. 2010 also describe that the re-suspension mechanism is dependant on the intensity and speed of the circulating local traffic. Gustafsson et al. 2008 also indicate that wear is strongly dependent on speed; and in one of the simulator experiments every 10 km $h^{-1}$ increase yielded an increase of the $PM_{10}$ concentration of 680 $\mu gm^{-3}$, although this relates to studded tyres. As previously discussed studded tyres have greater potential to abrade road surfaces and hence generate greater direct emissions from road ware compared to normal tyres. The greater road abrasion associated with studded tyres may also generate a larger source of particles which is available for re-suspension relative to normal road tyres.

Barlow et al. 2007 indicate that vehicle induced turbulence resulting in re-suspension is in the vast majority of instances due to Heavy Duty Vehicles (HDV) and other authors also ascribe higher re-suspension emission rates to heavy vehicles relative to light vehicles (e.g. Düring et al. (2002))[26].

Gehrig et al. 2010 used Mobile Load Simulators to estimate $PM_{10}$ emission factors for pavement abrasion and re-suspension on different pavement types. These authors described several findings, with particular reference to road abrasion and re-suspension including: that particle emissions due to abrasion from pavements in good condition are quite low, in the range of only a few mg $km^{-1}$ per vehicle if quantifiable at all. The authors (op cit) also note that considerable abrasion emissions, however, can occur from damaged pavements. In relation to re-suspension, the authors (op cit) describe that deposited dust can cause high and extremely variable particle emissions depending strongly on the dirt load of the road surface and that the source term is the limiting factor to the amount of particulate that can be re-suspended. Lastly the authors (op cit) indicate that porous pavements seem to retain deposited dust better than dense pavements, thus leading to lower emissions due to re-suspension compared to pavements with a dense structure (e.g. asphalt concrete).

## 3.4 Local Meteorological Variations

One of the three re-suspension mechanisms listed previously is wind action. Thorpe et al. 2007 found that wind speed has an influence on re-suspension, although this was still secondary to the number of heavy-duty vehicles. This was noted by Thorpe et al. (op cit)

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[26] Düring, I., Jacob, J., Lohmeyer, A., Lutz, M., Reichenbacher, W., 2002. Estimation of the “non-exhaust pipe” $PM_{10}$ emissions of streets for practical traffic air pollution modelling. In: 11th Intl. Symposium on Transport and Air Pollution, Graz University of Technology, Institute for Internal Combustion Engines and Thermodynamics, vol. 1, pp. 309 - 316.

to be consistent with other workers who noted increased $PM_{2.5}$-$PM_{10}$ concentrations with increased wind speed (e.g. Harrison et al. 2001 and Charron and Harrison, 2005[27]).

Barlow et al. 2007 also suggest that there is a relationship between wind effects and vehicle induced turbulence, in which vehicle induced turbulence initially suspends particulates, then the wind keeps particulates suspended and that increased wind speeds therefore result in increased re-suspension.

Rainfall should be a significant factor in re-suspension as it has the potential to wash particles from road surfaces. However, Thorpe et al. 2007 did not identify a relationship between rainfall and re-suspension. This was noted by Thorpe et al. (op cit) to be in contrast to Charron and Harrison, 2005 who did note decreased $PM_{2.5}$ and $PM_{2.5}$-$PM_{10}$ concentrations following periods of rainfall and increases during drought conditions. Thorpe et al. (op cit) suggest that complicating factors, such as wind speed and heavy vehicles may mask rainfall effects and that a more sophisticated approach such as Omstedt et al. 2005 may be required to understand the influence of rainfall. Omstedt et al. (op cit) contend that road surface moisture is one of the most important parameters that controls the re-suspension based on a budget equation that takes into account precipitation, evaporation and runoff. Omstedt et al. (op cit) suggest that during wet conditions a road dust layer is built up from road wear which strongly depends on the use of studded tyres and road sanding [Swedish roads]. The dust layer is then reduced during dry road conditions and that the dust layer is reduced by wash-off due to precipitation.

## 3.5 Dust Suppressant Control

The literature review has identified that the re-suspension of dust from the road surface is likely to be a significant proportion of the non-exhaust sources of particulates.

A report prepared by Boulter et al. 2006 noted that dust suppressants appear to be an obvious choice for mitigating dust re-suspension. Boulter et al. (op cit) list fourteen dust suppressants including chloride salts, organic emulsions, polymers and adhesives.

A review of literature concerning dust suppressants has identified two papers which focus on the application of CMA and Magnesium Chloride by Norman and Johansson (2006) and Aldrin et al. (2007)[28] respectively. Both sets of authors also list various dust suppressant studies which have not been published in scientific literature including work

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[27] Charron, A., Harrison, R.M., 2005. Fine ($PM_{2.5}$) and Coarse ($PM_{2.5–10}$) Particulate matter on a heavily trafficked London highway: sources and processes. Environmental Science and Technology 39, 7768–7776.

[28] Aldrin, M., Hobæk Haff, I. and Rosland, P. 2008. The effect of salting with magnesium chloride on the concentration of particular matter in a road tunnel. Atmospheric Environment 42, 1762 – 1776.

by Værnes (2003)[29], Tønnesen (2006)[30], Berthelsen (2003)[31], Aldrin and Steinbakk (2003)[32] and Hafner (2007)[33]. The findings of the studies are summarised in Table 3.3.

**Table 3.3 Dust Suppressant Studies Summary**

| **Author(s)** | **Environment** | **Suppressant Type** | **$PM_{10}$ Percentage Reductions** |
|---|---|---|---|
| Norman and Johansson (2006)[1] | Highway or motorway | CMA | 35% daily Average |
| Aldrin et al. (2007)[2] | Tunnel | Unknown | 56% |
| Værnes (2003) | Tunnel | Unknown | 50% |
| Tønnesen (2006) | Tunnel | Unknown | 50% |
| Berthelsen (2003 | Highway or motorway | $MgCl_2$ | 17% daily average (dry days) |
| Aldrin and Steinbakk (2003) | Highway or motorway | Unknown | None |
| Hafner (2007) | Urban Roads | $MgCl_2$ | 29 – 43% |

Note: [1] Study extended over 1 year and so will have included periods of winter conditions and likely studded winter tyre usage. [2]Study undertaken in winter conditions and so results are likely to be influenced by studded winter tyres.

Three of the studies including work by Værnes (2003), Tønnesen (2006) and Aldrin et al. (2007) considered dust suppressant effects in tunnels. This environment is likely to be quite different to an open rural or urban environment, as within the centre of a tunnel particulates re-suspended by vehicle induced turbulence and tyre action may be deposited back on to the road surface more predictably than in an open environment.

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[29] Værnes, E., 2003. Measurements of particular matter in the Hell Tunnel late Autumn 2002 (only in Norwegian). Technical Report, Project No. 223181, Sintef, Trondheim, Norway.

[30] Tønnesen, D., 2006. Dust measurement in Festningstunnelen (only in Norwegian). Technical Report, Note 104020. Norwegian Institute for Air Research, Kjeller, Norway.

[31] Berthelsen, B,-O., 2003. The use of magnesium chloride as dust reducer at E6 through Trondheim (only in Norwegian). Report No. TM2003/2, Trondheim Municipality, Environment Division, Trondheim, Norway, ISBN:82-7727-087-9.

[32] Aldrin, M and Steinbakk, G, H. 2003. Effect of salting to particular matter. An analysis on data from the winters 2001/2002 and 2002/2003 (only in Norwegian). Technical Report SAMBA/19/2003, Norwegian Computing Centre, Oslo, Norway.

[33] Hafner, W. 2007. Effectiveness of fine-dust-reducing measures in KAPA GS. International Congress on the EU-LIFE-ENVIRONMENT Project KAPA GS29/03/2007 to 30/03/2007 Klagenfurt on Lake Wörthersee, Austria. Department of Environmental Protection, Klagenfurt.

However, tunnel ventilation systems and perhaps the piston effect of significant flows in tunnels could facilitate transport of particulates along and out of tunnels. The potential for wind blown removal may also be reduced relative to open environments. Rainfall removal of particulate matter is also not applicable to this type of environment, except potentially at portal locations. Tunnels could therefore be considered to be locations with a potentially high potential source of surface dust and as such represent environments where comparatively large reductions in re-suspension contributions could be observed from the application of dust suppressants. Significant changes in daily $PM_{10}$ concentrations were estimated by all three studies with approximately 50% for the Værnes (op cit) and Tønnesen (op cit) studies and 56% for the Aldrin et al (op cit) study. The Aldrin et al. (op cit) study also reported improvements of 70% on the concentration of the coarse particles $PM_{10}$–$PM_{2:5}$ and on the fine particles $PM_{2.5}$ of 17%.

Three of the studies, Aldrin and Steinbakk (2003), Norman and Johansson (2006) and Berthelsen (2003) were carried out in highway or motorway locations. These locations are likely to have a different potential for re-suspension compared to the tunnel and urban environments. In comparison to tunnel environments the source potential may be lower as particulates may not accumulate as readily due to prevailing winds and also the higher speeds of motorway traffic which will lift particles via turbulence. The Aldrin and Steinbakk (op cit) study was at a motorway in Oslo with a 50 mph speed limit and no significant effects on $PM_{10}$ concentrations were noted. In the second study, a four lane motorway with an approximate daily flow of 60,000 vehicles and similar speed of 55 mph, was treated with CMA (approximately 80% surface area coverage). In this study the daily average $PM_{10}$ concentration was 35% lower (statistical significant at 95% confidence interval) than untreated sections. The last study, on a route with a 50 mph speed limit, resulted in an average reduction of 17% on dry days (using a 15% magnesium chloride solution). The contention that there may be a less pronounced re-suspension source at motorway locations, with high consistent speeds relative to tunnels, is supported by the lower percentage reductions achieved relative to the tunnel studies.

The last study identified at the time of preparing this report was by Hafner (2007), using CMA at Klagenfurt indicating a 29 – 43% reduction in the concentration of $PM_{10}$. This study was undertaken in an urban environment similar to the locations under consideration in this study. Results from the Klagenfurt study yielded lower percentage reductions in $PM_{10}$ concentrations relative to the tunnel studies, but higher reductions in $PM_{10}$ relative to two of the three motorway studies. In comparison with tunnels, this result is consistent with the contention that tunnel environments have a greater source which can be mitigated via dust suppressants, as discussed above. This finding relative to motorway locations may be for a number of reasons, for example, the lower average speeds in urban locations may result in less efficient removal of dust via vehicle induced turbulence. Additionally, wind movements may be constrained by the built environment relative to motorway locations, which may also result in the retention of particulate matter on and around road surfaces. The retention of dust on road surfaces in urban environments combined with stop start traffic and heavy vehicles (e.g. buses) and other factors listed in Section 3.3 could result in a situation conducive to dust re-suspension and hence a situation in which dust suppressants could be effective. However, it should be noted that as all studies were not undertaken using the same suppressants, rates of application and application methodologies etc. direct comparisons are difficult. For example, some studies recorded any sweeping or jet washing events and some don't list if any sweeping or jet washing events occurred during the period of suppressant application.

Three of the studies included information concerning the longevity of dust suppressant effects and also the effects from days of consecutive treatment. In Norman and Johansson (2006) the authors noted that during the treated days the observed effect was lower in the afternoon, probably caused by removal of the CMA solution as it sticks to the tyres on passing vehicles and is transported away from the treated stretch, and also due to evaporation. Aldrin et al. (2007) note that dust suppressant effects are most pronounced immediately after application, with effects steadily diminishing with time, but estimate the duration of effect to 10 days, with a large uncertainty (95% confidence intervals between 3 and 16 days). Two studies also suggest that treating on consecutive days result in increased effects. Berthelsen (2003) note that effects are increased if treatment occurs over consecutive days and Norman and Johansson (2006) suggest that the reduction in the $PM_{10}$ levels slightly increases if CMA was applied several days in a row.

Norman and Johansson (2006) also suggested that the hygroscopic properties of CMA solutions, and hence the effectiveness of the solution to reduce $PM_{10}$ concentrations, may change with Relative Humidity (RH). However, the authors found no consistent relationship between the RH and the reduction in $PM_{10}$ levels. Another potentially significant suggestion by Aldrin et al. (2007) is that magnesium chloride may be a dust source in itself if used in too high a concentration.

## 3.6 Analysis Techniques

Investigations into re-suspension, dust suppressants and road cleaning or sweeping have used a number of techniques to support results and interpretations based on particulate data (e.g. $PM_{2.5}$, $PM_{10}$ and $PM_{10}$–$PM_{2.5}$). Workers such as Norman and Johansson (2006) have tried to isolate dust suppressant effects using statistical approaches which isolate dust suppressant application days from non-application days (e.g. 95% confidence limits). Norman and Johansson (op cit) also isolated certain weather conditions, trying and focus on dry days and days with appropriate wind directions (e.g. downwind of road surfaces).

Workers also use different pollutants to try and corroborate that changes in re-suspension observed in particulate data are due to mitigation strategies rather than changes in traffic or weather conditions. For example the absence of changes in oxides of nitrogen ($NO_X$) relative to changes in particulate has been used (Norman and Johansson (op cit)) and changes in trace metals and mineral content relative to carbon has also been used (Amato et al. 2009[34])

A recent study by Martuzevicius et al. (2011)[35] also discussed particle-bound Polycyclic Aromatic Hydrocarbons (PAHs) in relation to street dust. Abu-Allaban et al., 2003 also used scanning electron microscopy (SEM) to identify different source contributions in collected samples of particulates.

## 3.7 Summary

Dust deposited on road surfaces is a function of the various direct non-exhaust contributions and background contributions (local and regional) and is concentrated in size fractions greater than $PM_{2.5}$.

The source potential of dust available for mitigation via dust suppressants varies between locations and also countries. Countries with colder climates which use studded tyres are likely to have a high surface dust loading due to surface abrasion of road surfaces via studded tyres, whilst warmer countries are likely to have high dust loadings due to low precipitation rates. In the UK dust loadings are likely to be lower than these colder and warmer climates.

The proportion of roadside $PM_{10}$ concentrations in the UK from dust re-suspension is uncertain, with various estimates suggesting its importance is similar to or less than direct exhaust concentrations on average. However, considering that there are three potential mechanisms for mobilising surface dust including: vehicle induced turbulence, wind and tyre action this suggests that there could be significant variability in the importance of surface dust re-suspension, with potentially higher loadings in periods of higher wind speed and intensive traffic flows with stop start conditions etc. A recent study, albeit in Spain, suggested significant differences in the magnitude of dust re-suspension between peak periods and annual periods. Additionally, a recent study in France, with a similar climate to the UK (Lille), also suggested re-suspension concentrations of $PM_{10}$ could be several times higher than exhaust concentrations.

The review of dust suppressant trials identified that there are three published studies undertaken in tunnels, three at motorway locations and one in an urban environment. There is therefore a limited amount of information concerning dust suppressants, with particular reference to urban environments.

The majority of studies did achieve beneficial results through the application of suppressants in relation to daily $PM_{10}$ concentrations, with the greatest improvements

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[34] Amato, F., Querol, X., Alastuey, A., Pandolfi, M., Moreno, T., Gracia, J. and Rodriguez, P. 2009. Evaluating urban $PM_{10}$ pollution benefit induced by street cleaning activities Atmospheric Environment 43 (2009) 4472–4480.

[35] Martuzevicius, D., Kliucininkas, L., Prasauskas, T., Krugly, E., Kauneliene, V. and Strandberg, B. 2011. Resuspension of particulate matter and PAHs from street dust. Atmospheric Environment 45 (2011) 310 – 317.

shown in the tunnel studies (approximately 50% reductions), followed by the urban study (approximately 29% to 43% reductions) and the motorway studies (approximately 20%, although one of the motorway studies provided similar results to the urban study with 35% reduction). The one study which did not identify significant effects was also a motorway study. All the studies were undertaken in locations which are likely to utilise winter studded tyres for part of the year and as such the high percentage of improvements, up to 56%, observed in these studies are unlikely to be possible in the UK. However, the literature review does suggest that in some locations, particularly urban environments (e.g. canyon and/or congested locations), that the application of dust suppressants could be one of the useful tools which may be used to reduce daily $PM_{10}$ concentrations.

# 4. DUST SUPPRESSANT IMPLEMENTATION STRATEGY

## 4.1 Introduction

The targeted application of dust suppressants is designed to reduce 24-hour $PM_{10}$ concentrations arising from re-suspended road dust. This trial in London builds on a growing body of evidence concerning the effectiveness of targeted cleaning and the application of dust suppressants to reduce local $PM_{10}$ concentrations in areas of poor air quality. Dust suppressants have not previously been used in the UK but have been trialled across Europe, most notably in the EU Life funded project – CMA+. The project CMA+ has been underway since January 2009 and will expire at the end of September 2012. CMA+ has a total budget of € 2.7m with around € 1.3m being financed by the EU.

## 4.2 Dust Suppressant

Building on European experience, and the importance of looking for environmentally friendly solutions to problems, the trials in London used Calcium Magnesium Acetate (CMA) as a dust suppressant. CMA is a combination of dolomitic lime and acetic acid (a principal component of vinegar). When absorbed into the soil, CMA's calcium and magnesium components benefit the soil structure, just as liming a garden improves permeability. The acetate portion of CMA biodegrades naturally. CMA it is non-toxic and is no more harmful to handle than common table salt and it is also harmless to plants and water. CMA poses no significant risk of corrosion of steel, aluminium, or concrete.

## 4.3 Trial Period

Historically, days when exceedances have occurred have been primarily been monitored during the winter months, although in recent years significant numbers of exceedances have been recorded in the springtime and occasionally summer time. Therefore the pilot study aimed to target winter and spring months.

## 4.4 Location of Application

CMA was applied along Victoria Embankment between Waterloo Bridge and Byward Street and along Marylebone Rd/Euston Road.

## 4.5 Time of Application

The CMA solution was spread between the hours of 23:00 and 05:00 or during the interpeak period (outside of peak hours to reduce impact on other users). These periods were selected as the solutions did not appear to dry significantly during night time and the binder was in place before the morning peak period, when the effect is anticipated to be optimal.

No applications were undertaken on weekends during the pilot study.

Though CMA is an effective de-icer it was not used as a de-icer as this was outside the scope of the trial.

## 4.6 Frequency of Application

CMA was applied on a regular basis and applications were not timed to try and focus on those times of high 24-hour $PM_{10}$. Best practice suggested regular application of dust suppressant improves performance. CMA has been shown in Norway to improve performance when it is applied several days in a row Berthelsen (2003) and Norman and Johansson (2006). Furthermore, Aldrin et al (2008) found it to be more effective to repeat treatments more often than to increase the amount of material being used. Based on these reports and the lack of a suitable long-range forecasting tool, CMA was applied on a regular basis. This approach was consistent with international best practice.

CMA was not applied when it rained or snowed. When it snowed application of CMA conflicted with the requirement to maintain winter service.

During the initial months the frequency of application was intentionally low to ensure that any operational problems could be resolved. Later on in the trial the frequency of application was increased and varied to ensure that the results informed the future optimisation of the application on CMA. A summary of the frequency of application throughout the trials is as follows:

- In November and December treatments were undertaken 2-3 times per week though they were severely disrupted by rain and snow.
- In January the site was allowed to clear and a strategic review of the results was conducted.
- In late January, February and March the frequency of application was increased including trials of application within the inter peak.
- In April (up to the 18th) there were limited numbers of treatments with a night time application and an inter peak application on the 4th and 5th and one on the 18th.

A full schedule of treatments is provided in Appendix A.

## 4.7 Application

The CMA solution is spread as 25% CMA and 75% water. The rate of application was limited to an even spread of $10 g/m^2$. Visual checks were undertaken by TfL to check that excess CMA was not observed on road surfaces during the study. TfL also reviewed accident rates during the study to confirm there were no significant changes in accident rates.

The spreading equipment follows traditional pre-wet salting techniques utilised by gritting lorries, but with a more restrictive flow on solution passing onto the application dish. The dish has been adapted to spread the liquid at an application rate for CMA of $10 g/m^2$. The modified gritter vehicle is shown in Figure 4.1.

The specific gritter lorry modifications that have been implemented are as follows:

- Installed pre wet tanks to gritter body;
- Installed pipes to spinner;
- Installed regulating pumps to control spread rate;
- Installed control box within cab, including regulated control system;
- Regulated spinner speed;
- Adapted spinner angle; and
- Reconstructed spinner blade to create droplets.

**Figure 4.1 Modified Gritter Vehicle showing pre-wet tanks (left hand side) and application dish (right hand side)**

## 4.8 CMA Applications and Road Sweeping

To ensure that the application of CMA did not conflict with the relevant local authorities cleaning of the streets the trial included a sweeper which was only used when the borough sweeping was planned to be after the application of CMA. The treatment consisted of brushing and full width suction of the carriageway surface, to remove detritus and fine particles of dust. As the sweeping of most central London major road occurs daily it was not considered to impact of the results.

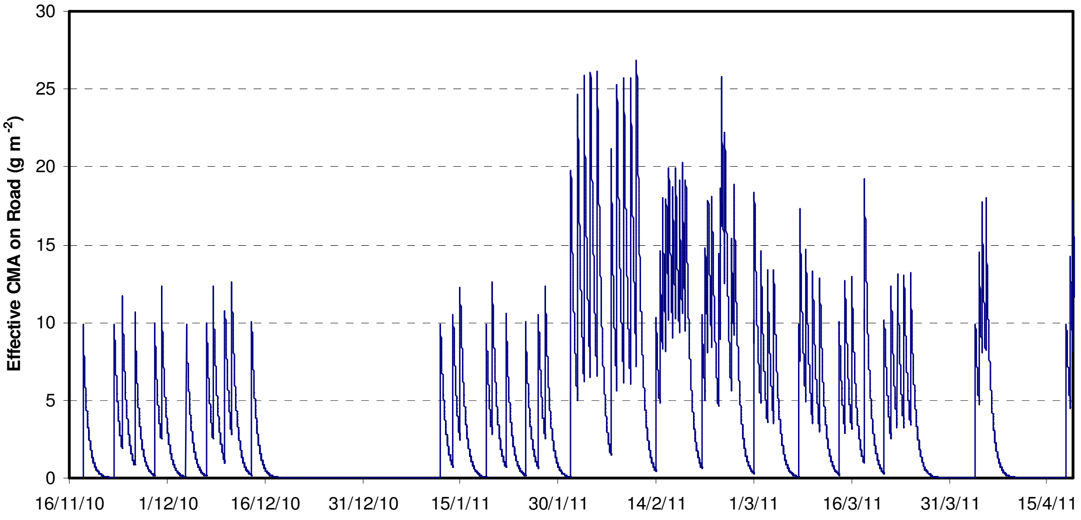
## 4.9 CMA Accumulation

The potential for CMA to accumulate on road surfaces has been considered, to try and establish during which periods of the pilot study CMA may have been present at or above 10g/m$^2$, above which CMA effects may be anticipated, based on European experience (e.g. EU Life funded project – CMA+).

There is currently limited information concerning the rate of removal of CMA from road surfaces, only estimates of duration of effects were available at the time of writing. This includes the work of Aldrin et al. (2007) in Norway, that dust suppressant effects are most pronounced immediately after application with effects steadily diminishing with time, with an estimate of the duration of effect to 10 days, with a large uncertainty (95% confidence intervals between 3 and 16 days).

In the absence of any alternate information it has been assumed that the removal of CMA from the road surface follows a natural decay curve. The decay curve utilising a half life of 0.5 day and 1 day are shown below in Figures 4.2 and 4.3 respectively. These curves are presented to show potential rates of CMA decay and are currently illustrative only.

**Figure 4.2 Natural decay curve for CMA applications on Victoria Embankments (0.5 day half life)**

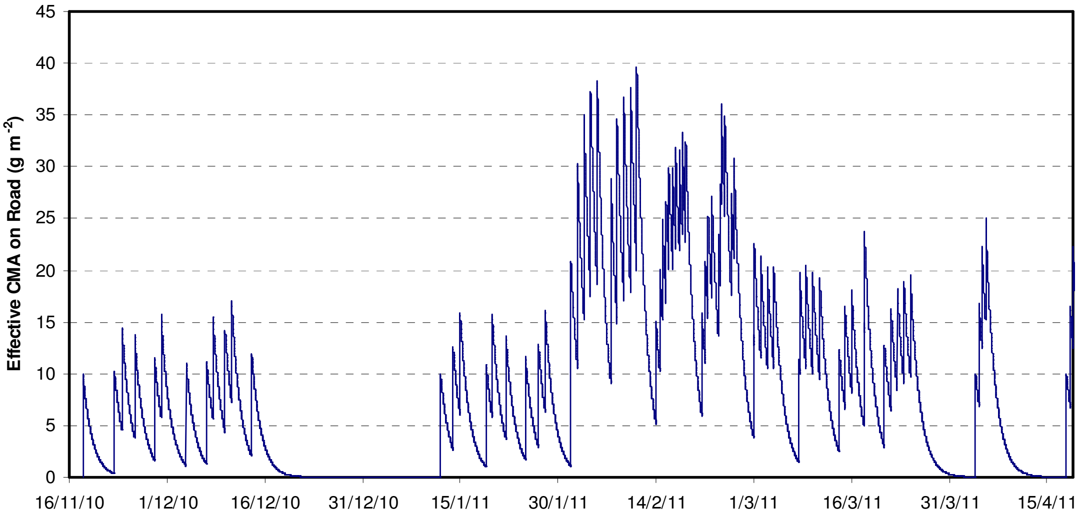


Assuming that CMA does decay following a similar profile and rate this suggests that during the initial treatment phases in November, December and January that CMA may not have been present at levels significantly above 10 g/m$^2$. In contrast, during periods where treatments were being undertaken twice a day, there may have been prolonged periods where CMA may have been present on the road surface at and above 10 g/m$^2$. The application of CMA can therefore be considered to have been undertaken at a low rate of intensity initially, with a higher rate of intensity in the latter stages of the pilot study.

The development of decay rates and effectiveness of CMA would be an important focus of future trials to optimise the amounts and frequencies of CMA application required.

Further chemical analysis of the build up of CMA on road surfaces will be undertaken in the next phase of works.

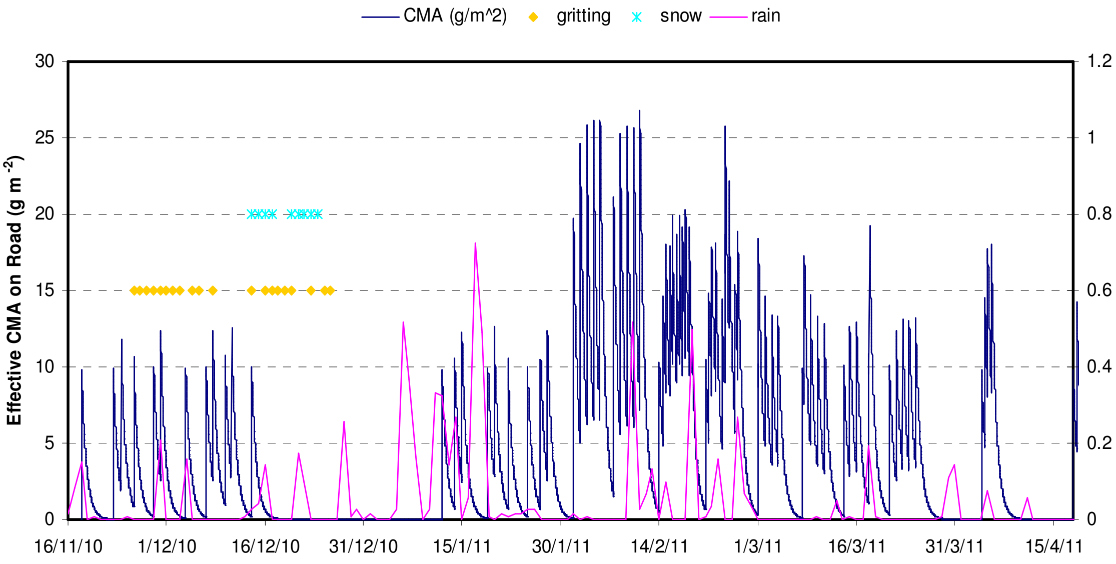
**Figure 4.3 Natural decay curve for CMA applications on Victoria Embankments (1 day half life)**



## 4.10 CMA Effects Uncertainty

The application of CMA was interrupted during the initial phase of treatment in December due to snow and gritting, as shown on Figure 4.4. During these periods CMA was either not applied or its frequency of application was reduced.

**Figure 4.4 Natural decay curve for CMA applications on Victoria Embankments (0.5 day half life) with gritting, snow and rainfall.**



There is currently limited information on how CMA has been applied in other countries in combination with gritting. Therefore, our pilot study has focused on the initial phase between 12th January and 31st January 2011 when low intensity treatments recommenced following the Christmas and New Year break. In the latter stages of the pilot study when more intensive treatments were being undertaken there were no snow or gritting events and so this has not affected the periods which can be considered. However, changes in the monitoring configuration at Victoria Embankment, with the removal of a monitor, have affected the period considered for intensive treatment. This is because a monitor was relocated from Victoria Embankment to commence data collection at Marylebone Road. This reduced the period of intensive treatment studied to the period between 1st February 2011 and 10th March 2011.

The micro-scale performance characteristics of CMA are also relatively uncertain currently, with workers suggesting some linkage with relative humidity (e.g. Norman and Johansson, 2006). There is also the potential for temperature to affect CMA performance via changes in evaporation and also through rainfall, as this could reactivate or dilute CMA layers. Relative humidity, temperature and rainfall data have been considered against the periods when treatments have been undertaken at both a low rate of intensity and a higher rate of intensity and no clear effects have been observed. This may be because of the number of factors which affect re-suspension, including wind speed and vehicle movements, which are difficult to disaggregate from the effects of these meteorological parameters.

# 5. MONITORING STRATEGY

The key elements of the monitoring strategy which has guided the study are described in the following sub-sections.

## 5.1 Existing Particulate Monitoring Sites

A review of existing monitoring sites within the Victoria Embankment Upper Thames Street priority action area was undertaken as p[art of the development of the monitoring strategy. The review was undertaken to identify whether locations were already in-situ which could be used to test the effectiveness of CMA applications.

One continuous particulate monitor is located along the Upper Thames Street section of the route. The monitoring site has been active since 2007. The analyser is located underneath London Bridge (National Grid Reference: 532829, 180694) and is classed as a kerbside site. Particulates are listed as measured via a TEOM monitor but there is no Filter Dynamics Measurement System (FDMS) at this location. TEOM monitors are not an EU 'reference method'; as the heat they use to eliminate water also loses the volatile component of $PM_{10}$. However a Volatile Correction Method (VCM) has been derived (on behalf of Defra) to bring the TEOM measurements in line with those of FDMS. TEOM Data on the London network is adjusted using VCM. Quality assurance for the site is to London Air Quality Monitoring Network standards.

No particulate monitoring sites are located along the Victoria Embankment and Tower Hill sections of the route.

## 5.2 Study Interferences

The Upper Thames Street monitoring location identified in Section 5.1 is in a fairly complex location with respect to air quality, due to its location under a bridge. Similarly, the Marylebone Road location was not utilised, in the pilot study, due to concern that congestion effects could obscure CMA effects.

Additionally, neither the Upper Thames St or Marylebone Road routes include a second monitoring site which could be utilised as a control site. Therefore, both routes would have required the installation of a reference $PM_{10}$ monitoring technique to allow comparable data to be collected. The purchase and installation of a reference technique would have required the majority, if not all, of the pilot study budget for air quality. The timescales required to procure and install a reference technique were also not available for the study.

Therefore additional monitoring areas were selected in addition to the existing location identified above, in order to avoid areas with sources of particulates which could obscure the effects of any dust suppression, as listed below:

- Busy road junctions with associated queue effects, acceleration and deceleration profiles;

- Car parks;
- Rail sources – stations and tracks;
- Underground vents;
- Point source impacts e.g. vents and generators;
- On-road car parking spaces;
- Building effects;
- Vegetation effects;
- River boat moorings;
- Tunnel portals; and
- Construction sites (e.g. cross rail).

It is recognised that, due to the nature of central London some of the above potential sources are difficult to avoid. However, where additional sources can be avoided this increases the opportunity to observe dust suppressant effects and so these interferences were avoided as much as possible. Construction works and road closures are inevitable and as such TfL provided data concerning disruption to the road network from construction or closures etc.

## 5.3 Victoria Embankment Test Configuration

The final configuration of kerbside monitors utilised along Victoria Embankment is shown in Figure 5.1. This configuration was selected to minimise study interferences as listed above. Kerbside monitoring sites (less than 1m from the kerb of a busy road), rather than roadside sites (typically between 1 to 5m from a busy road, but up to 15m)[36] were utilised to minimise the potential for the dispersion of road contributions and to further minimise the potential for interferences from other local sources.

The monitors used in the trial were Osiris monitors. Each monitor was fitted with a wind direction and speed mast. Osiris monitors are small portable or semi-permanent monitors manufactured by Turnkey Ltd, which can be powered by solar cell, battery or mains electricity. The monitors were located on lamp posts at an approximate height of 3.5m, well above head height. Osiris monitors utilise a light scatter technique to measure TSP (Total Suspended Particulates), $PM_{10}$, $PM_{2.5}$ and $PM_1$. The Osiris monitors provided an average reading every fifteen minutes. The Osiris measurement technique is not a reference equivalent technique and so $PM_{10}$ data cannot be used for EU compliance purposes. In particular the heated inlet, which draws in air for sampling operates at $60^oC$

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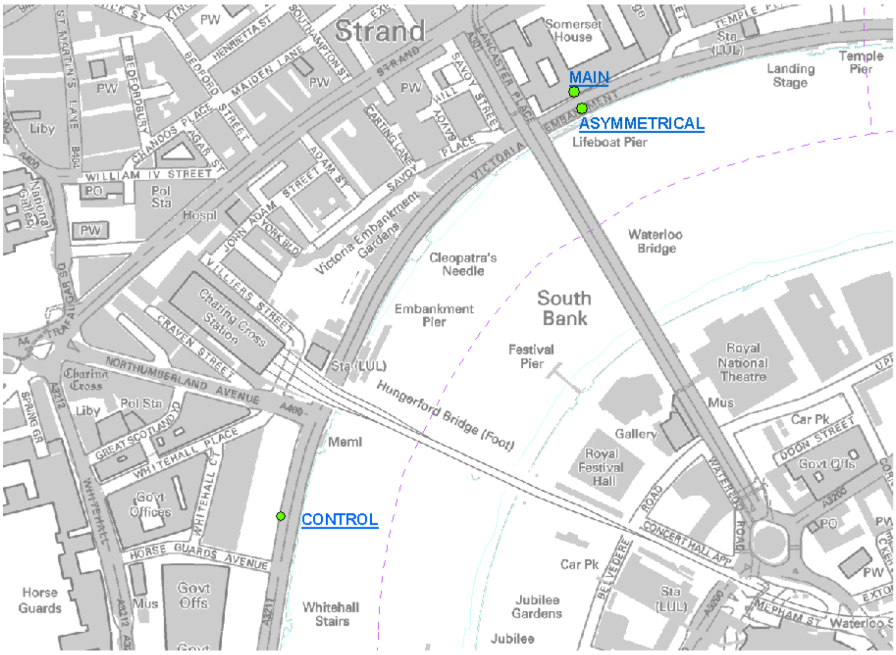
[36] Department for Environment, Food and Rural Affairs (DEFRA) (2009); Local Air Quality Management Technical Guidance LAQM.TG(09).

to minimise interferences from water vapour, will likely destroy some volatile particulate components. This potentially could lead the Osiris monitor to under read total $PM_{10}$ concentrations relative to reference techniques e.g. TEOM-FDMS. However, light scatter techniques, including Osiris, are used by local authorities, consultancies and academic institutions in monitoring campaigns and the Osiris monitor has achieved the Environment Agency's MCERTS certification[37] (Monitoring Certification Scheme). Additionally, volatile particulates are unlikely to be a significant component of re-suspended dust.

Two of the monitors installed at Victoria Embankment were loaned from Camden Council. This provided a significant cost savings given the small budget of the programme. A third Osiris monitor owned by Camden Council, that was already located at London Bloomsbury, was also used within the study to provide urban background data. Osiris based urban background data was required as it would not be appropriate to use a particulate background from a different monitoring technique (e.g. TEOM). Other Central London locations were also reviewed to identify any other potential Osiris urban background sites but none were identified.

**Figure 5.1 Victoria Embankment Monitoring Locations**



The configuration includes one control location and two test sites (Main and Asymmetrical). The control site and main test site were located on the same side of Victoria Embankment. The asymmetrical site was selected to provide an indication of any differences between concentrations with the main test site. The London Bloomsbury

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[37] Sira Certification Service and Environment Agency, 2009. Product Conformity Certificate. Osiris Airborne Particle Monitor MCERTS Performance Standards for Indicative Ambient Particulate Monitors, dated July 2009.

site was used to provide background data. Traffic data was utilised from an automatic count location on Victoria Embankment, north of Northumberland Avenue (A308).

## 5.4 Monitoring QA/QC

In October 2010 the three monitors loaned from the London Borough of Camden were serviced and calibrated by Turnkey. The fourth Osiris monitor was purchased as part of the study and so was calibrated ready for use.

During the study the filter in the Osiris monitors were replaced on the 10th of March 2011. This filter is required to protect the monitors pump from larger particulates. The flow rate achieved at each monitor was also checked during this site visit. All four sites had a flow rate of between 0.55 and 0.6 litres per minute. The voltage at the control site was adjusted to match 0.6 litres per minute. During these site visits the inlet was blown through with air to clear any debris.

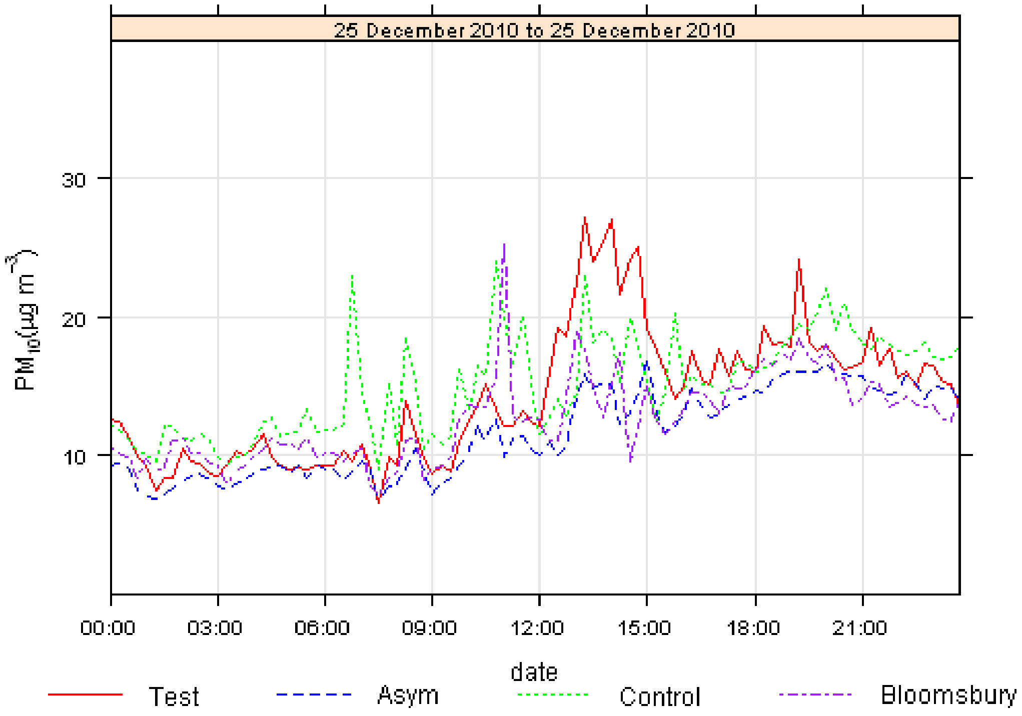
A further site visit was also undertaken on the 6th May, following the pilot study period. The flow rates at Victoria Embankment remained as observed at the test and control sites a month earlier.

Data has been processed to remove unusual values such as zero or negative values. Following data processing data capture of greater than 95% was achieved for the main test site, the control site and the asymmetrical site.

The data collected at each monitor has also been reviewed on occasions when there should be limited local variations in particulate contributions to establish how comparable monitored data is following calibration. In particular the data for the mid point of the Phase 1 study on Christmas day has been reviewed (see Figure 5.2). The data indicate that the monitors all reproduce very similar $PM_{10}$ concentrations for the majority of the day. This indicates that the monitors at this mid-point of the study continued to provide consistent data between monitors.

It has also been possible to compare data from the asymmetrical Osiris monitor, which was removed from Victoria Embankment on the 10th of March 2011 with an Osiris monitor owned and operated by a third party. This Osiris monitor was located at the Marylebone Road Supersite and concentrations at this monitor were compared with those obtained for the Victoria Embankment asymmetrical monitor when it was relocated to Euston Road. The monitored concentrations at the relocated monitor compared well with those obtained by the third party Osiris monitor, with average 24-hour $PM_{10}$ concentrations of around 40 µg/m³ at both monitors.

**Figure 5.2 $PM_{10}$ 15 minute averages from Christmas Day 2010**



## 5.5 Meteorological Data

Liaison undertaken by TfL with the London Boroughs, within which the priority action areas are located, identified three above ground level meteorological stations (wind speed and direction) which were suitable for use within the trials, to help interpret CMA effects including:

- The Council House roof in Westminster,
- Camley Street Natural Park in Camden,
- Walbrook Wharf in City of London and
- Yorkway in Camden

The Camley Street station also collects rainfall and relative humidity data.

## 5.6 Traffic Data

Automatic Traffic Count (ATC) data was collected from a permanent traffic counter located along Victoria Embankment north of Northumberland Avenue (A308) operated by TfL. The ATC utilises inductive loops to detect the presence of vehicles in the carriageway. TfL consider this type of equipment to be above 95% accuracy, however accuracy does fall in heavily congested traffic.

## 5.7 Analysis

The relationship between the Victoria Embankment Test and Control Sites have been investigated through graphical data analysis, including:

- Time-varying 24-hour and 15 minute $PM_{10}$ averages;
- Polar plots; and
- Particulate ratio analysis.

Summary statistics have also been calculated to identify differences between sites.

# 6. RESULTS AND DISCUSSION

In this section the results from the pilot study are presented and discussed for the baseline period and the key treatment periods identified in Section 4.10 including:

- Baseline Period: 15th October 2010 to 17th of November 2010
- Low Intensity Treatment Period: 12th January 2011 and 31st January 2011
- Higher Intensity Treatment Period: 1st February 2011 and 10th March 2011

The atypical construction activities and pollution episodes that occurred during the study are also identified in this section. Where relevant, these construction activities and episodes are discussed as part of our analysis.

## 6.1 Victoria Embankment Road or Pavement Construction Activity

A review of construction activity provided by TfL indicates that during the trials there were some periods of activity along Victoria Embankment including:

- Civil works in November, including Kerb realignment and tactile paving replacement. These works included areas within 100m of the test and control monitoring locations. No obvious effects from these works were noted in the data for November.
- Stump Grinding and planting is listed for Victoria Embankments for the start of January. These works were undertaken up to Blackfriars Bridge and so these small works are unlikely to have affected either the test or control monitoring locations.
- Two other small repairs are listed for the 15th of April towards the end of the trials, including the repair of a manhole cover and the repair of a paving defect. The duration of works for both tasks was 24-hours. The small amount of works is unlikely to have affected either monitoring location.

## 6.2 Air Quality Episodes

A review of the London Air Quality Network (LAQN)[38] indicates that there were eight pollution episodes issued for London or parts of London during the study including the following:

- Episode 1 was the Guy Fawkes and Diwali events 2010 listed for the 05/11/2010 to 08/11/2010, with the worst $PM_{10}$ concentrations around bonfire night events.

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[38] Environmental Research Group, King's College London, 2011. London Air Quality Network. http://www.londonair.org.uk/london/asp/default.asp.

- Episode 2 was a $PM_{10}$ and $NO_2$ event in mid November on the 15/11/2010 to 16/11/2010. The LAQN indicates this $PM_{10}$ and $NO_2$ pollution episode was mainly due to the poor dispersion of air pollution emitted from within London.
- Episode 3 was a $PM_{10}$ event in late February 2011 occurring between 18/02/2011 to 23/02/2011. The LAQN indicates that this event was a result of light easterly winds bringing an influx of particulate matter from continental Europe.
- Episode 4 was a $PM_{10}$ event in early March (02/03/2011 to 09/03/2011). The LAQN noted that on the 2nd this was due a high pressure system centred over the Baltic which resulted in an influx of industrial emissions from continental Europe. Greater input from continental urban sources resulted in a change of concentration and composition on the 3rd and 4th with greater concentrations of volatile $PM_{10}$.
- Episode 5 was an event in mid March between the 15/03/2011 to 17/03/2011. The LAQN noted that this event was due to a large influx of $PM_{10}$ particulate from Europe and that this included a large volatile component.
- The sixth $PM_{10}$ event occurred in late March on the 21/03/2011 to 22/03/2011. The LAQN noted that the elevated pollution levels were due to low wind speeds leading to poor dispersion after the morning rush hour with some contribution from airflow from the continent. In comparison to other recent episodes, the LAQN noted that the higher particulate levels evident at roadside and industrial locations suggest a significant local component.
- The seventh episode was a $PM_{10}$ event at the end of March between the 25/03/2011 to 31/03/2011. The LAQN suggest that this was due to transport emissions and pollution transported from continental Europe.
- The last event during the study was a smog event on the 17/04/2011 to 24/04/2011. This pollution episode was caused by a combination of both UK pollution sources and pollution from continental Europe brought into south east England on an easterly air flow.

The presence or absence of the above pollution episodes at the Victoria Embankment monitoring sites is discussed in the following sub-sections.

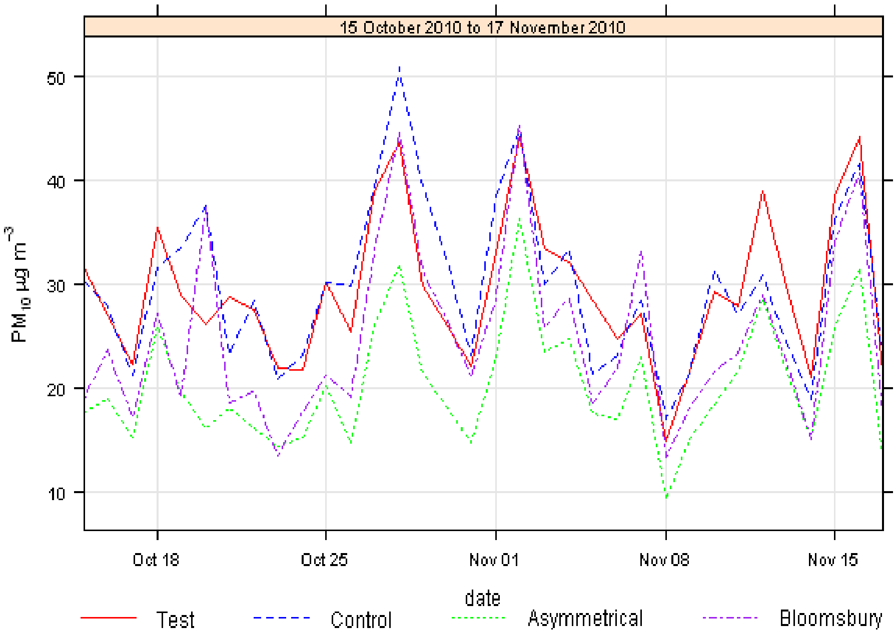
## 6.3 Background Review

The original test configuration was devised assuming that the 24-hour $PM_{10}$ concentrations from the London Bloomsbury Osiris monitor could be subtracted from the Victoria Embankment monitoring sites to provide a measure of local contributions at these sites. However, a review of the 24-hour background concentrations at the London Bloomsbury Osiris indicates that these are periodically higher than those recorded at the main test site.

The 24-hour results for the Baseline period are shown in Figure 6.1. This suggests that the London Bloomsbury Osiris site is potentially affected by local sources of $PM_{10}$, which are likely to be the local roads, including the A4200 located approximately 20m to the east and 40m to the north of the site. Therefore, the London Bloomsbury site is not the most appropriate location to provide urban background concentrations.

The original intention to remove urban background $PM_{10}$ concentrations (recorded via Osiris) was therefore not implemented, as this would have generally resulted in negative road contributions along Victoria Embankment.

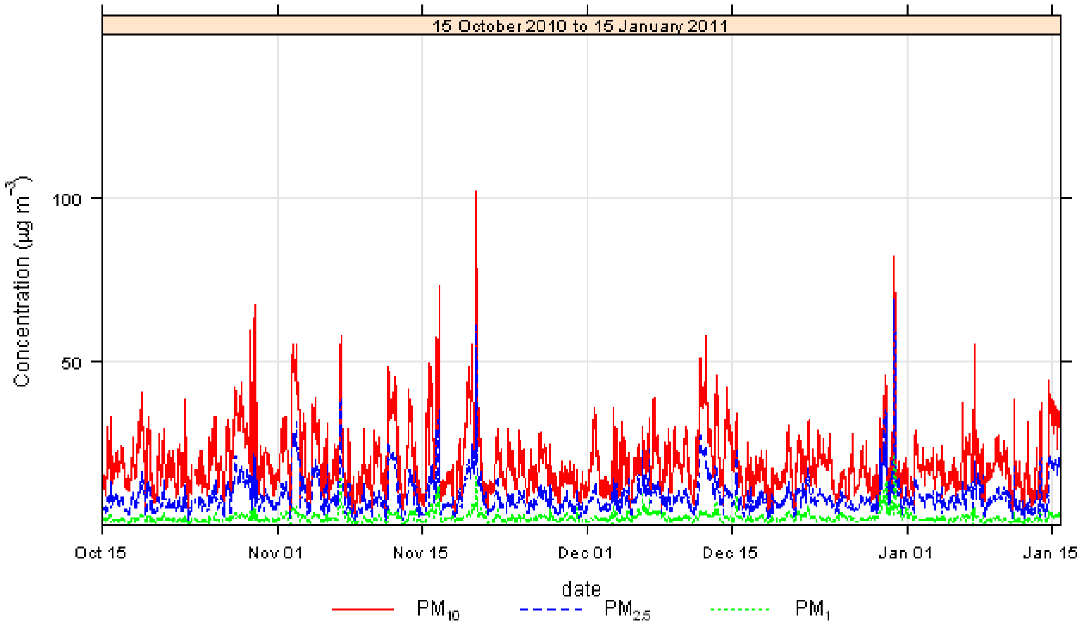
**Figure 6.1 London Bloomsbury and Main Test Site 24-hour $PM_{10}$ Concentrations**

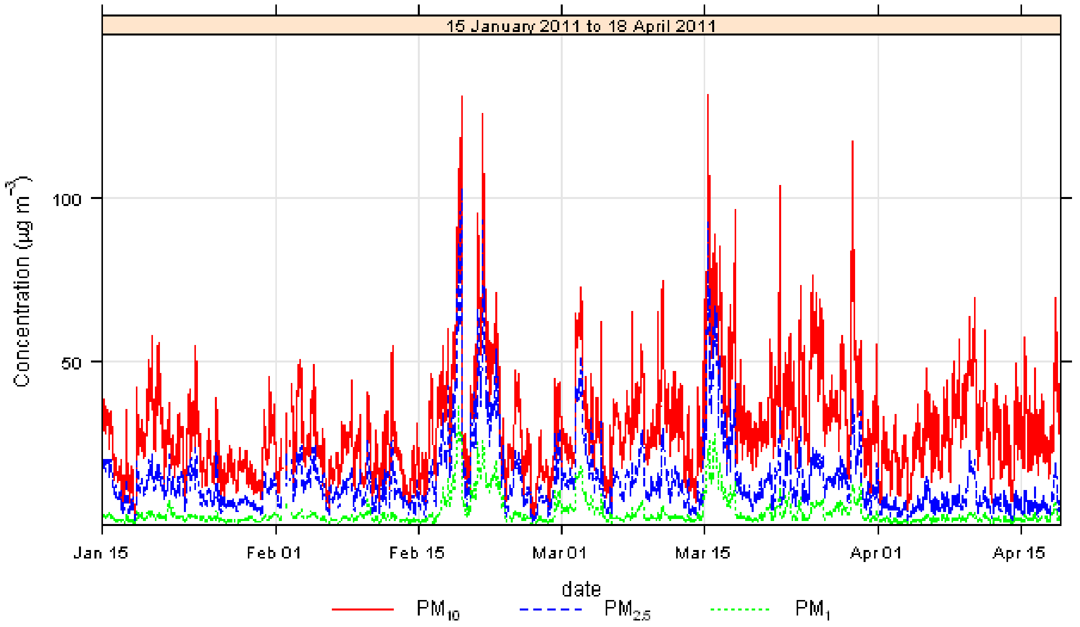


An alternate location to provide background data for Victoria Embankment was identified, away from notable A-Roads and rail sources within the River Corridor, but there was insufficient time to install a monitor at this location in the first phase of works. It is recommended this River Corridor background site is installed in the next phase of works.

In the absence of an ideal background site, the data from the remaining three Osiris monitors was analysed to identify the lowest PM concentration recorded at each monitor for every 15 minute average collected. The lowest of these values was then utilised to provide a measure of local background at Victoria Embankment. The resultant background value for the Victoria Embankment site over the study period is shown in Figure 6.2.

**Figure 6.2 Victoria Embankment Local Background ($PM_{10}$, $PM_{2.5}$ and $PM_1$)**

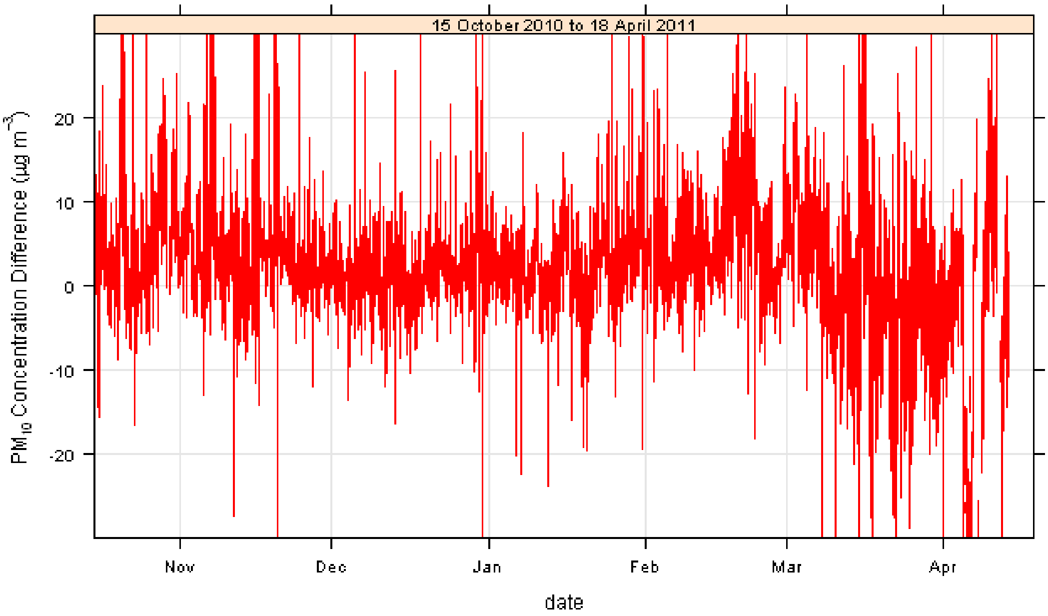




This approach is likely to over-estimate background concentrations when a local source, such as Victoria Embankment traffic, contributes equal amounts to the three monitoring sites. Additionally, when large scale background (e.g. pollution episodes) contributes different amounts to each of the three sites, these differences will be observed as variations in local contributions, unless this type of effect is resolved through additional analysis e.g. ratio analysis. However, even with these inherent limitations, this approach still consistently yields a background value which is lower than that observed from London Bloomsbury, as demonstrated in Figure 6.3. This figure indicates that typically London Bloomsbury 15 minutes $PM_{10}$ averages are higher than the local background concentration utilised for Victoria Embankment up to the 10th of March.

After the 10th of March the Asymmetrical site was moved from Victoria Embankment. Following this date the difference between the Victoria Embankment local background and the London Bloomsbury site is less clear, with the $PM_{10}$ concentrations at the local Victoria Embankment background sometimes higher than the London Bloomsbury site and vice versa. This is because higher local contributions will have been monitored at the two remaining sites, as the Asymmetrical site was in a far more open location than the two other Victoria Embankment monitors. The relationship between the three monitoring sites is discussed further in the following sub-section.

**Figure 6.3 London Bloomsbury Osiris with the Local Victoria Embankment Background ($PM_{10}$) Removed**



## 6.4 Local Meteorology

The Victoria Embankment test location is lined with trees on both sides of the road and this will affect air flow below the level of the canopy of the trees, less so in the winter months when the trees have lost their foliage. This will affect all three of the monitors located on Victoria Embankment, as the wind speed and direction masts attached to the Osiris units are located around 4.5m above ground level. This is well within the canopy of the trees.

At the main test site there is a further significant feature which is likely to affect local meteorological conditions, as the site is located approximately 5 metres from Somerset House. Somerset House is a large tall building formed in two tiers and appears to significantly affect local air flows forming a half canyon, as shown in the polar plots for the main test site. The asymmetrical site is also located within around 20 metres of Somerset House, opposite the main test site.

The meteorological data collected from the Victoria Embankment sites indicates that these sites are all affected by their local surroundings. In this instance, as the objective of the pilot study is to investigate changes in dust re-suspension from Victoria Embankment, this is appropriate. The polar plots for each site showing the $PM_{10}$ concentration data from each site together with the wind speed and direction data from the other Victoria Embankment site have been reviewed to demonstrate that this approach is appropriate. In order to focus on local sources the local background identified in the previous section has been removed from the $PM_{10}$ concentrations presented.

A further test has also been undertaken with ‘neighbourhood scale’ wind speed and met data. In this test the neighbourhood scale data has been used in conjunction with the $PM_{10}$ data for each Victoria Embankment site. This would be the alternate approach to utilising co-located wind data. This type of neighbourhood approach is as utilised by Barratt et al. (2010)[39] in a review of titanium oxide ($TiO_2$) paint used as a tool for $NO_2$ control. In the Barratt et al. (op cit) study the authors note that the use of wind speed and direction from a mast co-located with a monitor can provide valuable information, but that micro-scale topography can obscure source distribution. The authors further note that neighbourhood scale data representing general urban conditions can often be more useful. In the $TiO_2$ study, located in a courtyard, co-located data indicated no dependence on wind direction, with high concentrations during calm periods, as would be expected in a sheltered courtyard. Utilising regional wind data a source of $NO_x$ was noted to affect the site during north westerly winds. This regional effect corroborated an earlier desktop study at the courtyard that utilised computational fluid dynamics to predict this effect. Additionally, this regional effect could be further explained as appropriate by a review of the site’s physical surroundings.

However, the physical surroundings are different in the CMA pilot study. In our experiment we expect to observe enhanced local $PM_{10}$ concentrations on a polar plot when the wind is blowing from a local source e.g. Victoria Embankment. The wind speed and direction data that best replicates these local sources is therefore preferable for our pilot study.

The polar plots for each of the three Victoria Embankment sites are shown in Figures 6.4, 6.5 and 6.6.

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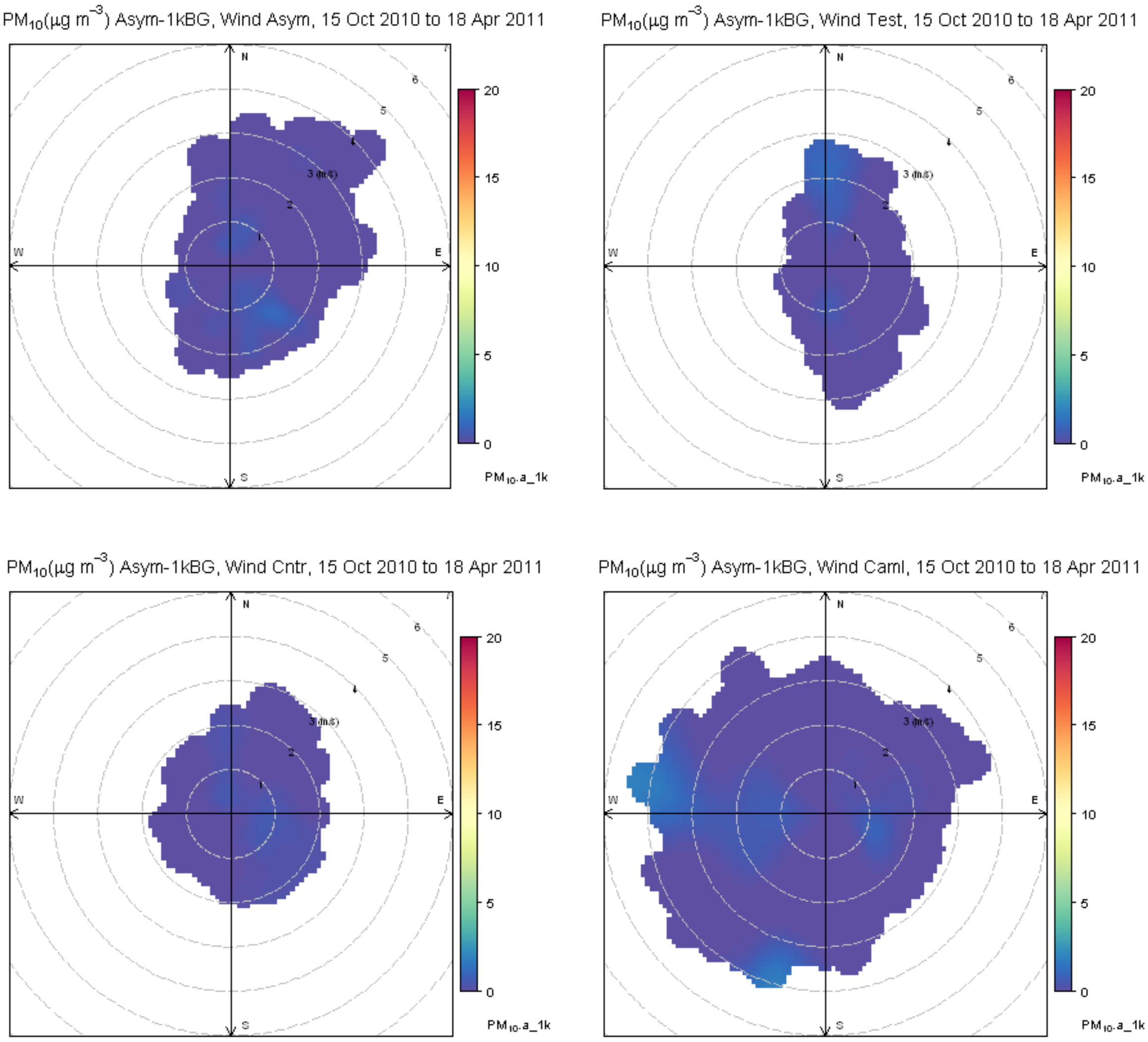
[39] Barratt, B., Carslaw, D. and Green, D. 2010. High Holborn D-NOx Paint Trial – Report 3. Kings College London Environmental Research Group. Date June 2010.

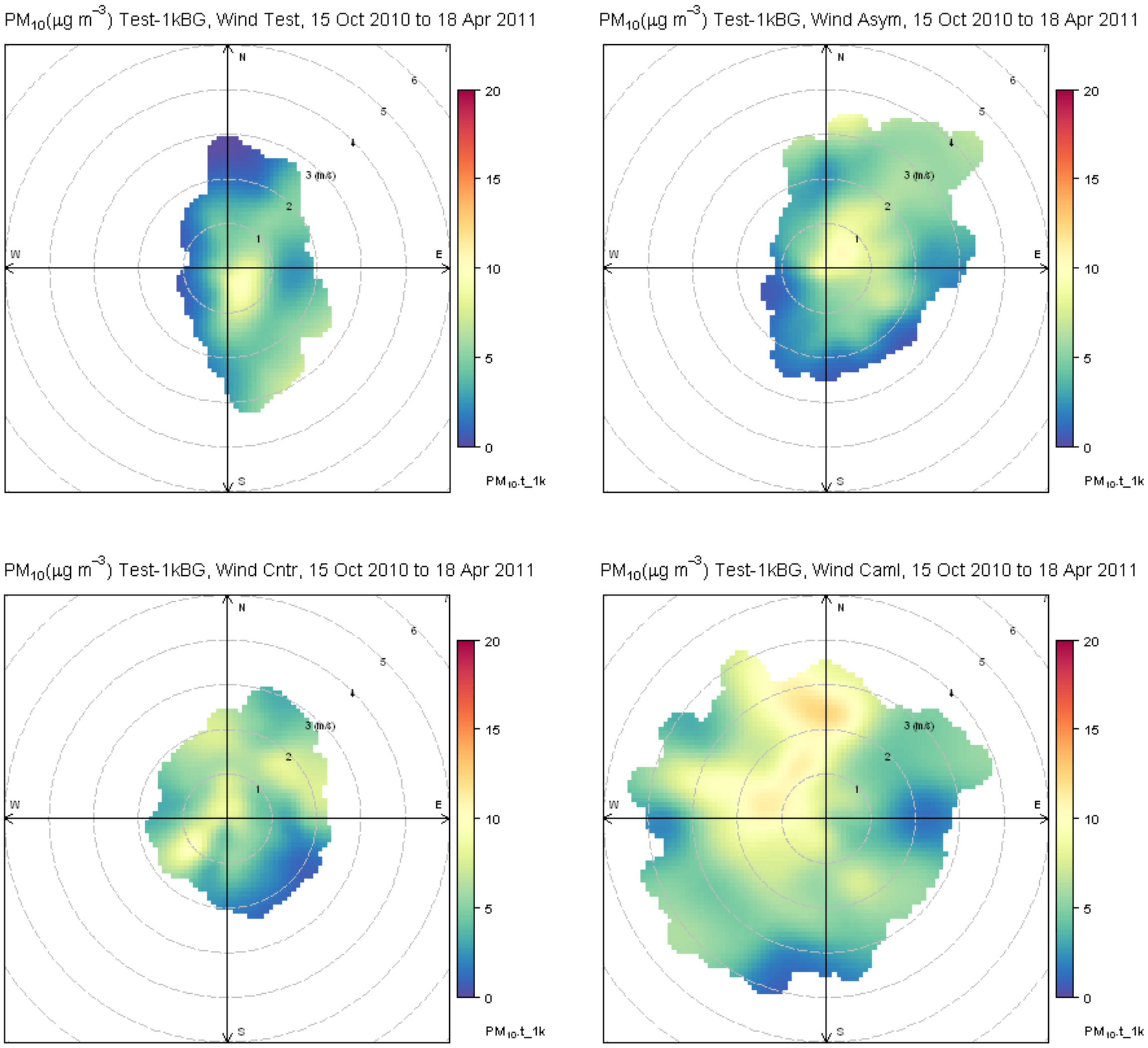
The polar plots for the asymmetrical site indicate that low local contributions of local $PM_{10}$ are recorded from all wind directions. This is likely because of local influences, such as Somerset House and also from exposure to wind movements which are upwind of Victoria Embankment emissions, and as such this site is often the site which provides the local Victoria Embankment background.

**Figure 6.4 Asymmetrical Site Polar Plot – using asymmetrical data (top left), main test site data (top right), control site data (bottom left) and Camley Street data (bottom right).**



In the main test site polar plot, utilising wind speed and direction data with the main test site, a clear source is shown to the east/south east of the monitor, associated with low wind speeds. This feature is likely to be associated with Victoria Embankment. In the polar plot using the asymmetrical data, the feature to the east/south east is less clearly defined and generally shifts and expands to the north east. Utilising the wind data from the control site results in a higher source contribution with a range of wind speeds associated with winds from the south west. The last polar plot using wind speed and direction data from Camley Street shows large source contribution associated with winds from the north west.

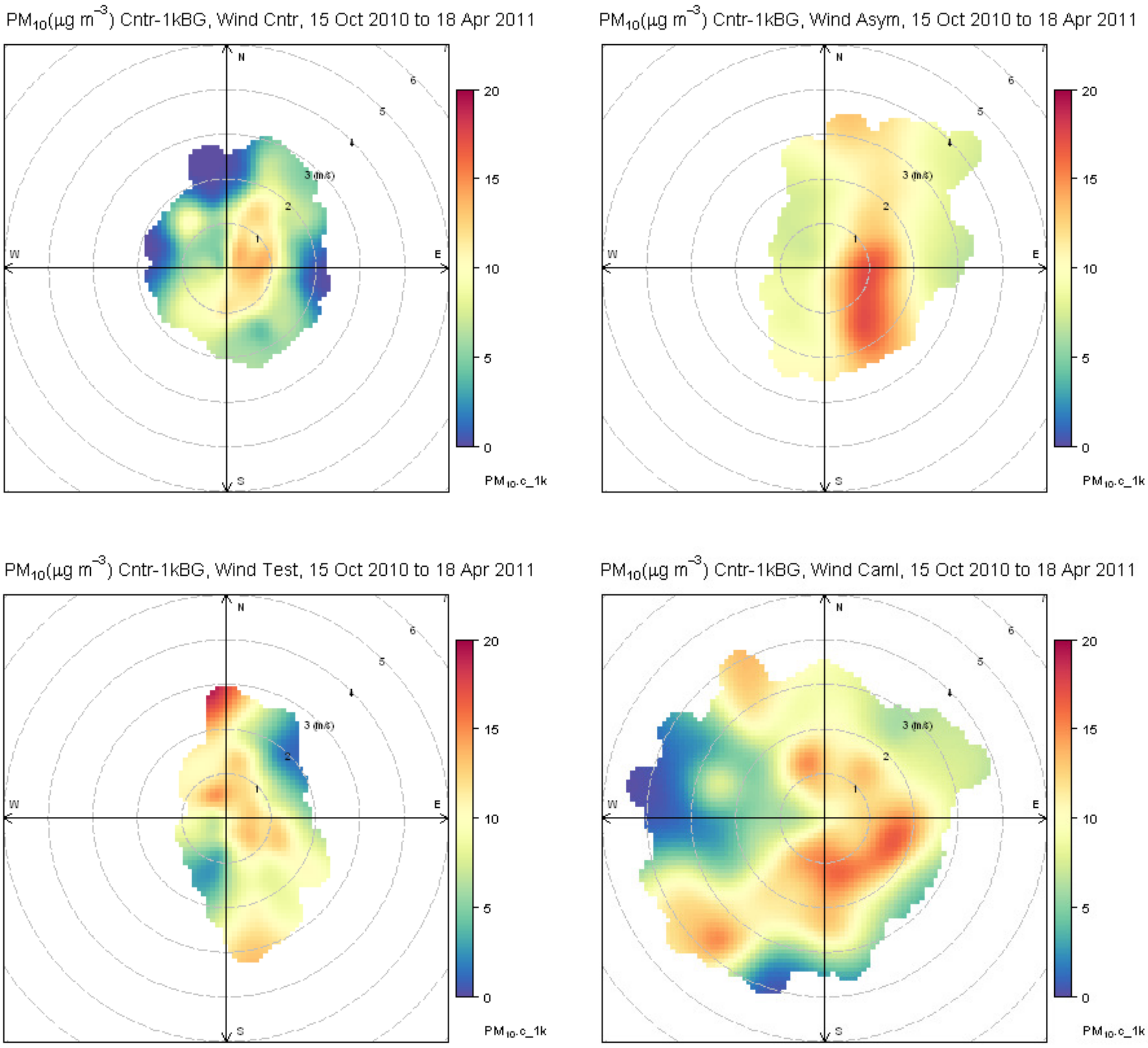
**Figure 6.5 Main Test Site Polar Plot – using main test data (top left), asymmetrical site data (top right), control site data (bottom left) and Camley Street data (bottom right).**



In the control site polar plot, utilising wind speed and direction data with the control site, a clear source is shown to the east of the monitor, associated with low wind speeds. This feature is likely to be associated with Victoria Embankment. In the polar plot using the asymmetrical data the feature to the east is extended between the east and west and the wind speed associated with this feature also increases. Utilising the wind data from the test site results in a less clear source contribution associated with Victoria Embankments than either the control or asymmetrical wind data.

The last polar plot, using wind speed and direction data from Camley Street, shows large source contribution associated with winds from the south east. The clear source contribution at low speeds feature which is observed with control wind speed and direction data is not observed using Camley Street data.

**Figure 6.6 Control Site Polar Plot – using control data (top left), asymmetrical site data (top right), main test site data (bottom left) and Camley Street data (bottom right).**



In summary, based on the information currently available, the most plausible particulate source distribution for Victoria Embankment is provided by the wind speed and direction information co-located with the Victoria Embankments monitors, rather than neighbourhood scale data. However, it is recommended that further wind speed and direction data is collected in locations local to Victoria Embankment, away from local features to compare with co-located data in any future phase of work.

## 6.5 Study Periods Review

In the preceding two sections the approach utilised to isolate local contributions and approach to wind speed and direction have been discussed. In this section the approach to isolate CMA effects is discussed. In particular the periods selected for inclusion in the analysis are discussed and the effects of pollution episodes within each period are analysed. These have been analysed using polar plots and three types of ratio analysis. Each type of ratio analysis is listed below:

- $PM_1/PM_{10}$ ratio analysis;
- $PM_{2.5}/PM_{10}$ ratio analysis; and
- $PM_1/PM_{10}$ at the main test site minus $PM_1/PM_{10}$ at the control site.

The $PM_1/PM_{10}$ ratio analysis for individual sites is particularly useful to try and identify long range pollution episodes, as these will include a large proportion of $PM_1$. The analysis will show if any pollution episode has affected the sites to differing amounts. For example it is likely that the main test site will be less affected by long range pollution episodes due to its relatively sheltered aspect, compared to the other Victoria Embankment sites.

The $PM_{2.5}/PM_{10}$ ratio analysis has been presented because one of the objectives of the pilot study is to consider the influence of CMA applications on the $PM_{2.5}$ size fraction. This plot has therefore been prepared to check that pollution episodes have not significantly affected this size fraction. This is necessary before any analysis is undertaken to establish the level of change which may be attributable to CMA.

The ratio analysis which subtracts the ratio of $PM_1/PM_{10}$ between the main test and asymmetrical sites with the $PM_1/PM_{10}$ ratio from the control site ratio is intended to further highlight any differences between the main test site and the asymmetrical site.

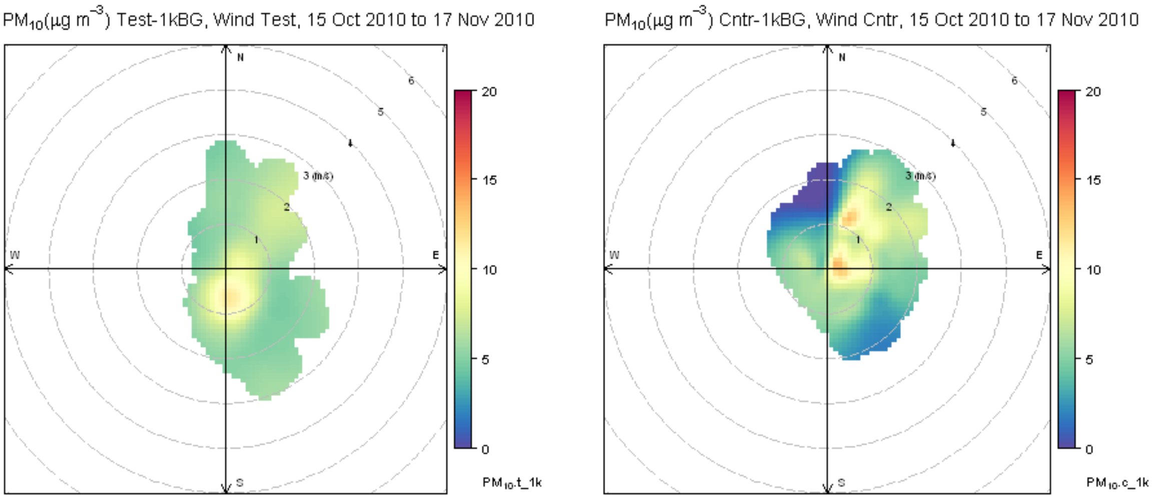
If the analysis indicates that there is a difference in the level of $PM_1$ or $PM_{2.5}$ contributions from long range pollution episodes at the main test and control sites this will have to be addressed before the effectiveness of CMA can be established.

### 6.5.1 Polar Plots

The polar plots for the main test site and the control site for the baseline period, low intensity period and higher intensity treatment period are shown in Figures 6.7, 6.8 and 6.9 respectively.

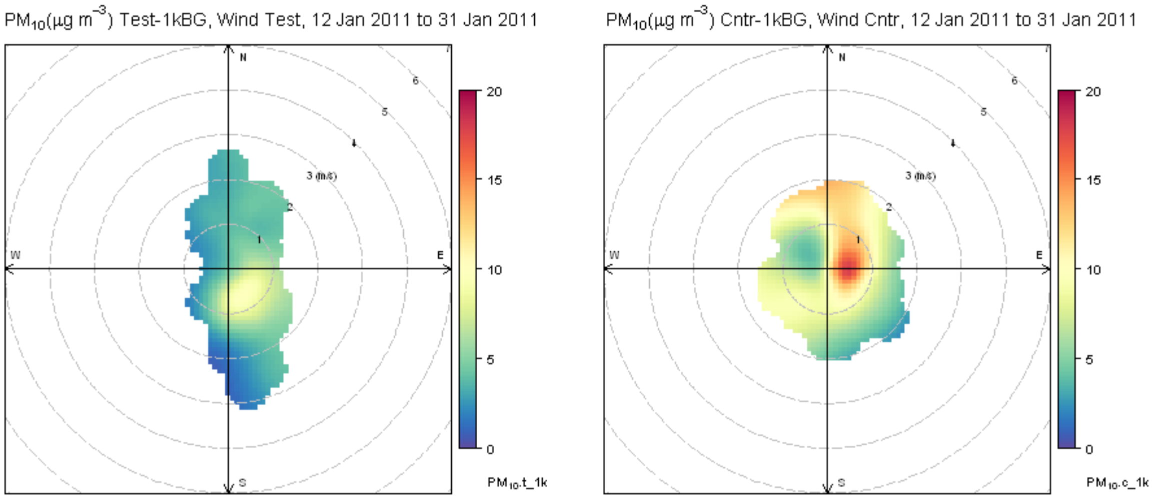
The polar plots have been prepared following the removal of the local background as previously described. In the baseline polar plots the average $PM_{10}$ local contributions at the two sites are very similar at around 10 µg/m$^3$, with some higher contributions of 15 µg/m$^3$ at low wind speeds at the control site.

**Figure 6.7 Baseline Period: Main Test and Control polar plot without local background**



The test site polar plot from the low intensity period (Figure 6.8) shows a very similar $PM_{10}$ contribution from Victoria Embankment as observed in the baseline period (Figure 6.7), with $PM_{10}$ contributions of around 10 µg/m³. In contrast, the contribution of $PM_{10}$ at the control site from local sources is higher than observed in the baseline period with concentrations greater than 15 µg/m³ being shown. This suggests that there may be some influence of additional local or regional sources at the control site that are not present at the test site and additionally potentially not present during the baseline phase. The difference observed could also, in part, be due to CMA effects.

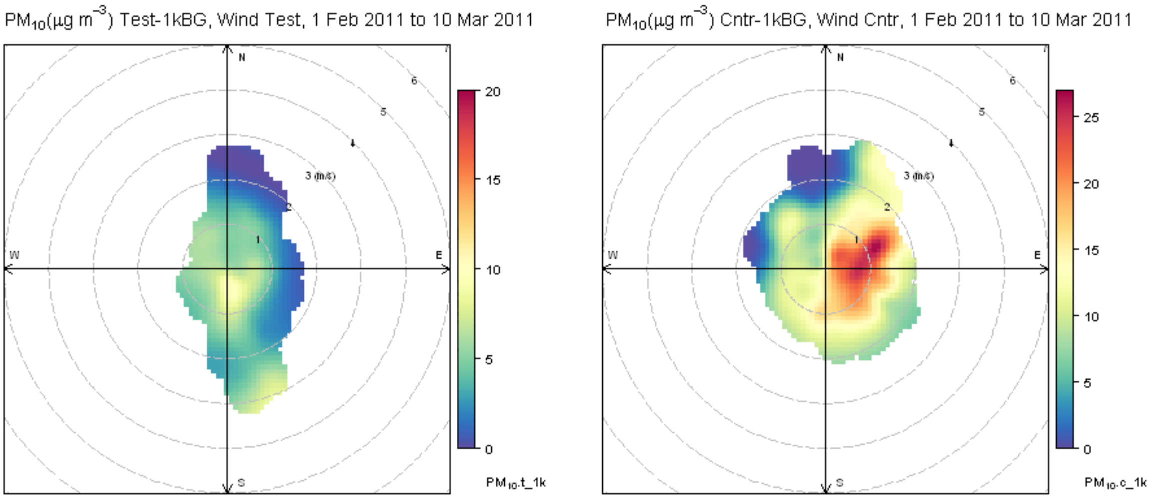
**Figure 6.8 Low Intensity Application Period: Main Test and Control polar plot without local background**



The main test site polar plot from the higher intensity period (Figure 6.9) shows a very similar $PM_{10}$ contribution from Victoria Embankment as observed in the low intensity and baseline period, with $PM_{10}$ contributions of around 10 µg/m³. In contrast, the contribution of $PM_{10}$ at the control site from local sources is higher than observed during the baseline and low intensity period. In the higher intensity period, concentrations of more than 25 µg/m³ local contribution are shown. The high contributions at the control site are likely to have been increased relative to the test site by the two pollution episodes which occurred during this period (Episodes 3 and 4, see Section 6.2). These episodes were associated with long range pollution from Europe. These additional contributions are noted more clearly at the control site, due to the more open aspect of the control site relative to the main test site. This effect will therefore mask any potential reductions in particulate concentrations between the two sites.

The potential influence of pollution episodes on the main test site and control site are discussed using ratio analysis in the following sub-sections.

**Figure 6.9 Higher Intensity Application Period: Main Test and Control polar plot without local background**



## 6.5.2 $PM_1/PM_{10}$ and $PM_{2.5}/PM_{10}$ ratio analysis for individual sites

In the three periods which this report focuses, namely the baseline period, low intensity treatment period and the higher intensity treatment period, the London Air Quality Network lists four particulate episodes. This section utilises a ratio analysis approach for the main test site, asymmetrical and control sites to illustrate how these episodes were observed on Victoria Embankment.

The first set of ratios considered are the ratio of $PM_{2.5}$ with $PM_{10}$ from each of the monitors (Figures 6.10, 6.11 and 6.12). The ratios for the baseline period do not show a clear separation of the ratios during the first two episodes. The lack of any clear difference in the ratio of $PM_{2.5}/PM_{10}$ suggests that these two episodes did not include a significant proportion of $PM_{2.5}$. The third and fourth episodes, associated with long range pollutant transport, are observed in the Osiris data at Victoria Embankments, as shown on Figure 6.12 with increased ratios of $PM_{2.5}/PM_{10}$. The clearest event is the third episode which is observed around the 21st of February.

**Figure 6.10 Baseline Period $PM_{2.5}/PM_{10}$ ratios Victoria Embankment Monitors**

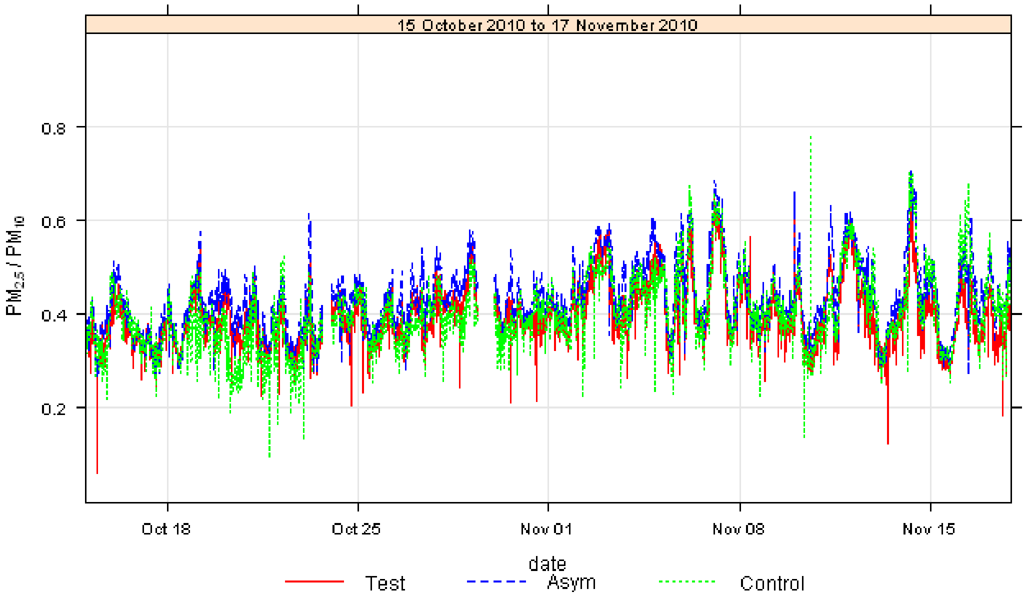


**Figure 6.11 Low Intensity Treatment Period $PM_{2.5}/PM_{10}$ ratios Victoria Embankment Monitors**

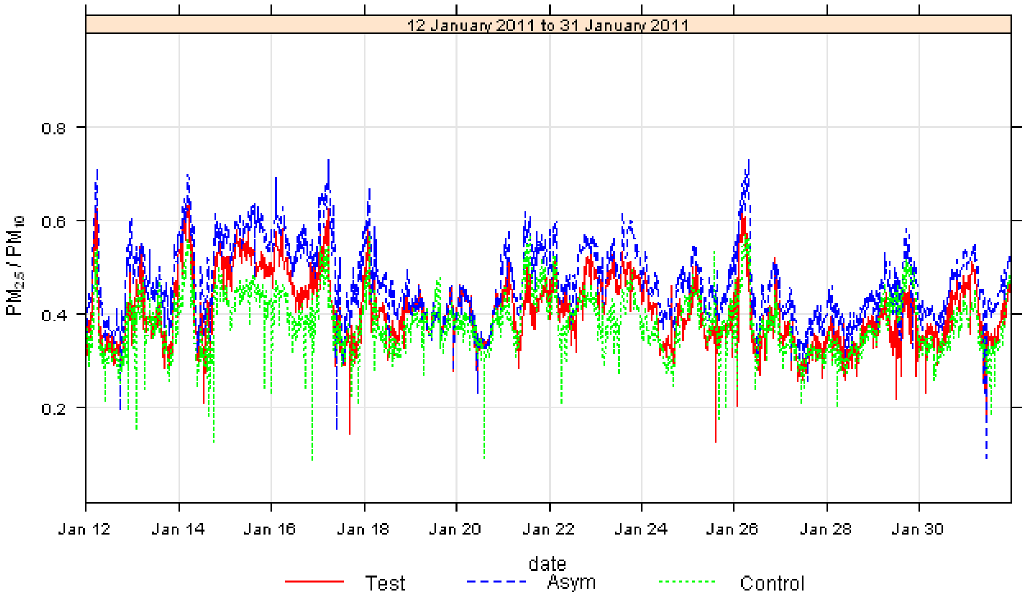
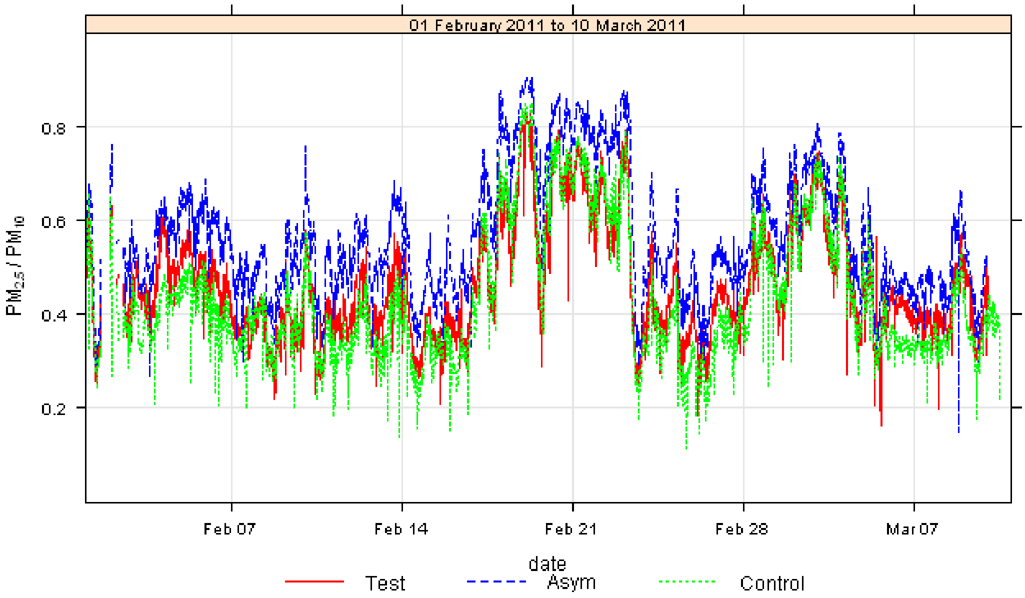


**Figure 6.12 Higher Intensity Treatment Period $PM_{2.5}/PM_{10}$ ratios Victoria Embankment Monitors**



The second set of ratios is the ratio of $PM_1$ with $PM_{10}$ from each of the monitors (Figures 6.13, 6.14 and 6.15). The ratios for the baseline period and the higher intensity treatment period show a clear separation of the ratio during all four episodes. This indicates that, as would be expected, these episodes included a significant proportion of $PM_1$.

The separation of the episodes using the $PM_1$ size fraction is clear enough to allow a comparison with the London wide dates observed by the London Air Quality Network (LAQN). The periods when these episodes affected the Victoria Embankment monitors are detailed below.

Episode 1 is listed by the LAQN to have occurred between the 5th - 7th November 2010, with the episode observed at Victoria Embankment on the 6th and 7th of November.

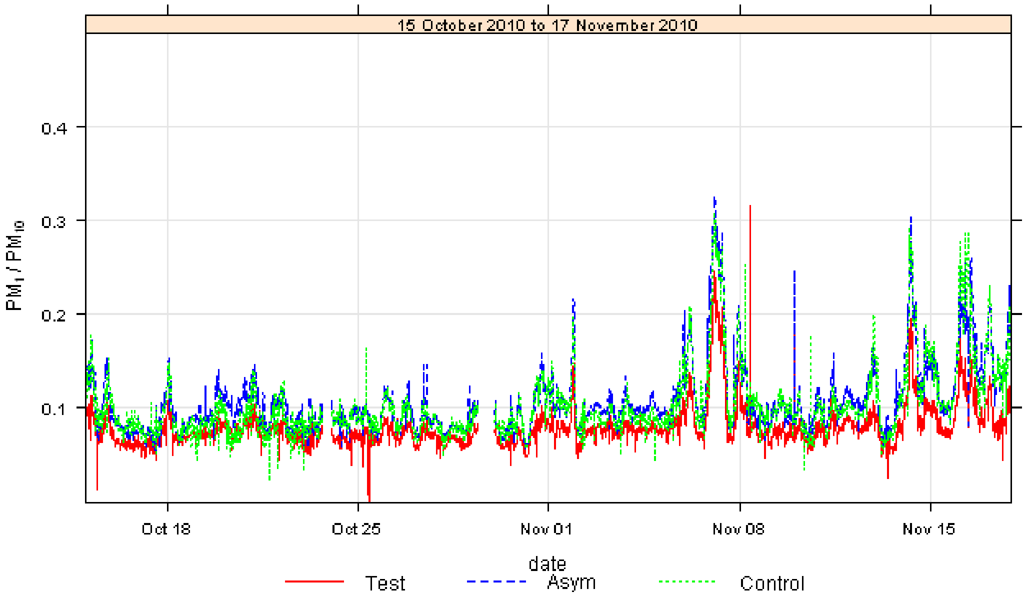
The second episode is listed as lasting between the 15th - 16th November 2010 on the LAQN, but this was only observed on the 16th November at the Victoria Embankment monitors.

The third episode listed on the LAQN is noted to have taken place between the 18th - 23rd February 2011, compared to the 17th - 23rd February 2011 at the Victoria Embankment monitors.

The fourth episode listed on the LAQN web-page between 2nd - 9th March 2011 was observed at the Victoria Embankment monitors between 25th February and 5th March 2011.

The dates between the LAQN and the Osiris monitors compares favourably with those of the LAQN.

**Figure 6.13 Baseline Period $PM_1/PM_{10}$ ratios Victoria Embankment Monitors**



The $PM_1$ size fraction plots also allow any differences in the ratios between sites to be identified. In general, the lowest $PM_1$ size fractions are observed at the main test site, followed by the control site. The highest proportion of $PM_1$ is consistently identified in the asymmetrical site. This demonstrates that the asymmetrical site is located in the most open aspect of all three sites and hence is most readily affected by long range transportation episodes and general background contributions.

This contention is reinforced by the magnification of this effect during long range pollution episodes where the gap in $PM_1$ ratios clearly increases between the highest ratio at the asymmetrical site and the lowest at the main test site. It appears the main test site is least affected by long range pollution episodes because it is located in a sheltered half canyon-like environment, which is less well mixed than the asymmetrical and control sites.

The proposition that long range air flows mix less well at the main test site than at the other sites is supported by a review of the two pollution episodes which were related to pollutants or local meteorological effects in London. In these two earlier episodes the separation between the $PM_1/PM_{10}$ ratios at all three sites are not as wide as in the long range pollution incidents.

**Figure 6.14 Low Intensity Treatment Period $PM_1/PM_{10}$ ratios Victoria Embankment Monitors**

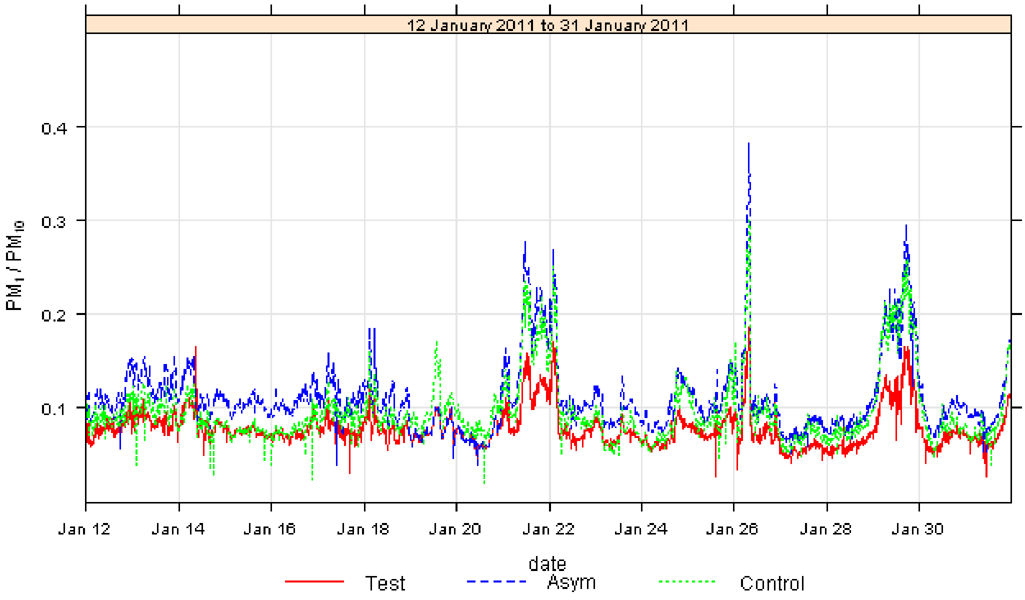
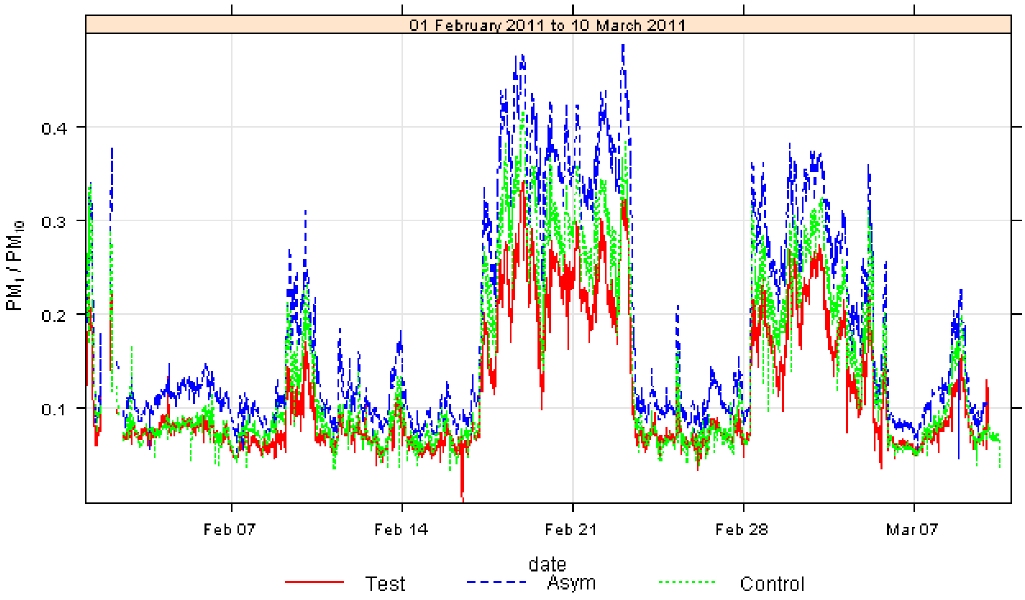


**Figure 6.15 Higher Intensity Treatment Period $PM_1/PM_{10}$ ratios Victoria Embankment Monitors**

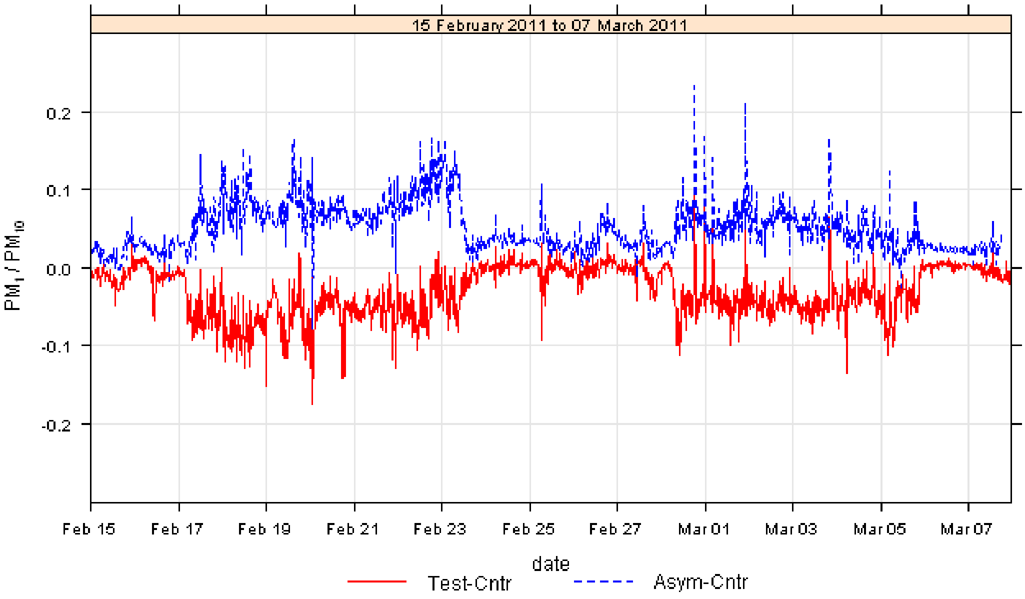


### 6.5.3 $PM_1/PM_{10}$ at the main test site and asymmetrical site minus $PM_1/PM_{10}$ at the control site

In this section the increase in asymmetry in the proportion of $PM_1$ monitored between the main test and asymmetrical site during pollution episodes is illustrated. This effect is likely to be due to the differences in aspect of the two monitors, with higher amounts of $PM_1$ monitored at the more open asymmetrical site relative to the more sheltered half canyon like main test site.

In Figure 6.16 this effect is illustrated by removing the ratio of $PM_1/PM_{10}$ monitored at the control site from the ratio of $PM_1/PM_{10}$ at both the main test and asymmetrical sites. The plot clearly shows that during pollution episodes 3 and 4 the difference in $PM_1$ ratios is higher at the asymmetrical site relative to the main test site. This provides further evidence of a canyon like environment and also further evidence that long range pollution episodes have lower effects at the main test site.

**Figure 6.16 $PM_1/PM_{10}$ at the main test site minus $PM_1/PM_{10}$ at the control site during pollution Episodes 3 and 4**



### 6.5.4 Ratio Analysis Summary

The ratio analysis has shown the following:

- The Osiris monitors at Victoria Embankment have consistently captured similar pollution episodes to those monitored by the LAQN.
- The ratio analysis also shows that, during long range pollution incidents, the difference in $PM_1$ concentrations can be exaggerated between the test and

control sites. This is due to the more enclosed situation of main test site in a half canyon, which appears to hinder mixing with long range air flows.

- The last observation is particularly important as this indicates that efforts to isolate these episodes should be employed when establishing the level of effectiveness to be ascribed to CMA effects, as otherwise effects could be overstated.

## 6.6 Traffic Effects

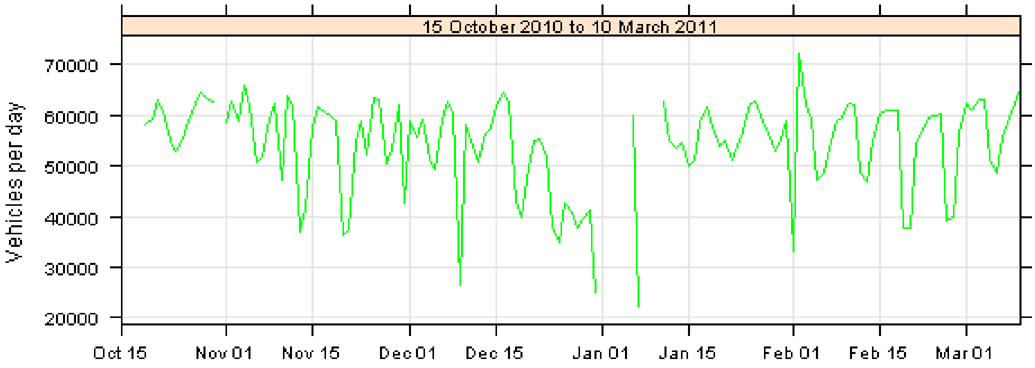
Previous studies of dust re-suspension have noted the importance of intense traffic flows in the re-suspension of dust, and therefore the influence of traffic has been considered in this pilot study.

In this study it is clear that the difference in 24-hour $PM_{10}$ concentrations between sites is reduced as traffic flows reduce and other local and background sources become a higher proportion of total $PM_{10}$ concentrations (see Figure 6.17). It therefore follows, that changes in $PM_{10}$ road contributions (exhaust and non-exhaust) should be related to changes in road traffic. However, at this stage, this is difficult to discern. Similarly no clear relationship between local contributions of $PM_{10}$ and heavy goods vehicles has been identified.

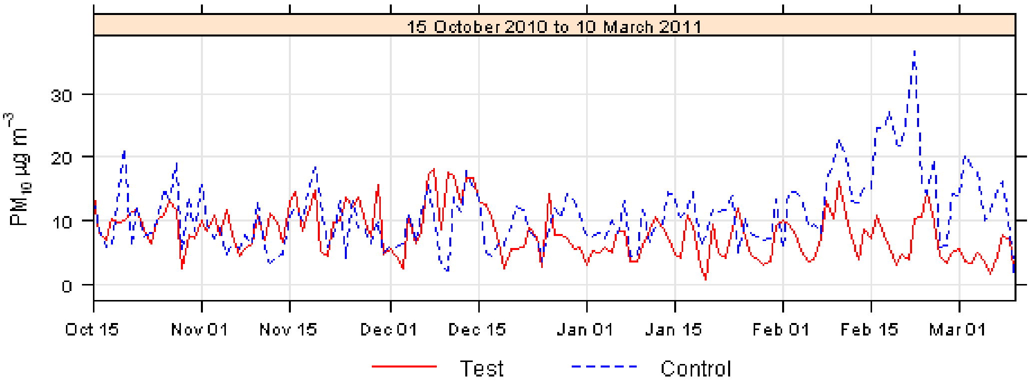
In later stages of work an improved background location may assist in resolving traffic effects. Additionally, dispersion modelling may be used to further partition $PM_{10}$ between local road contributions and background contributions.

**Figure 6.17 Traffic Flows and Local Contributions of $PM_{10}$**

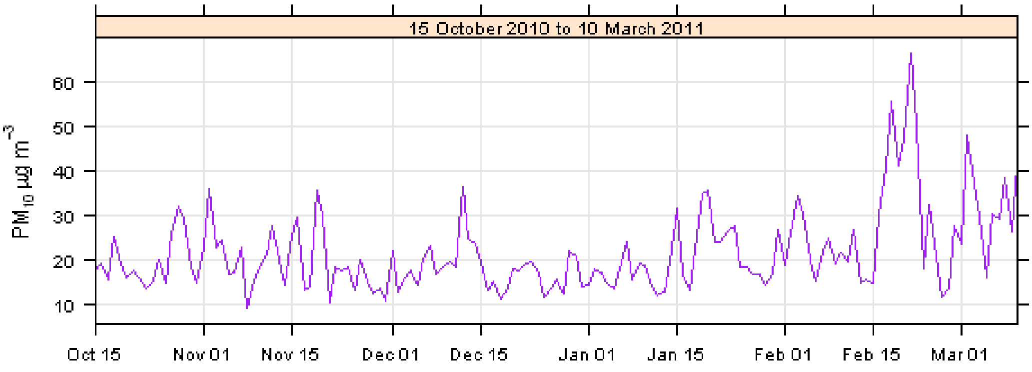
Two-way traffic



24-Hour Average $PM_{10}$ Concentrations from Local Sources



24-Hour Average $PM_{10}$ Concentrations from Background



## 6.7 Review of CMA Effectiveness

In this section the effectiveness of CMA applications in reducing 24-hour PM averages is discussed by comparing results obtained at the main test site with the control site. The analysis has not been undertaken on the Asymmetrical site versus the control site. This is because previous stages of analysis have indicated that the Asymmetrical site (located on the opposite side of Victoria Embankment to both the main test and control site), behaves very differently to the main test site likely due to half canyon effects.

The analysis has utilised the relationship between the 24-hour concentrations obtained during the baseline situation between the main test site and the control site. In particular, a forecast has been generated to show what concentration of particulates should have been expected at the main test site during the study period had CMA not been applied. In all instances this forecast concentration is higher than the unadjusted main test site monitored concentration. The main test forecast was calculated by multiplying the monitored particulate concentrations at the control with a factor of 0.98 for $PM_{10}$, 0.98 for $PM_{2.5}$ and 0.78 for $PM_1$. Utilising this approach it is the difference between the forecast particulate concentrations and the actual monitored test particulate concentrations that represents the effects of CMA application on 24-hour concentrations.

The review has also considered the previous stages of analysis which have shown that that elevated particulate concentrations were monitored at the control site relative to the main test site during pollution episodes, again due to the more enclosed half canyon effects at the main test site. Care has therefore been taken to isolate these periods as otherwise these location effects would overstate CMA effects.

In the baseline period the control site recorded slightly higher concentrations than the main test site, as shown in Table 6.1. This pattern is reversed in the low intensity test period and also in the higher intensity test period.

**Table 6.1 24-hour Main Test and Control Particulate Concentrations**

| Pilot Study Period | Control 24-hour Concentration (all units µg/m³) | | | Test 24-hour Concentration (all units µg/m³) | | | Forecast Test 24-hour Concentration (all units µg/m³) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $PM_{10}$ | $PM_{2.5}$ | $PM_1$ | $PM_{10}$ | $PM_{2.5}$ | $PM_1$ | $PM_{10}$ | $PM_{2.5}$ | $PM_1$ |
| Baseline | 29.8 | 11.8 | 3.0 | 29.3 | 11.6 | 2.3 | 29.3 | 11.6 | 2.3 |
| Low intensity | 31.6 | 11.9 | 2.9 | 27.9 | 11.3 | 2.1 | 31.1 | 11.7 | 2.3 |
| Higher Intensity | 44.8 | 21.4 | 7.4 | 35.8 | 17.5 | 4.7 | 44.1 | 21.0 | 5.7 |
| Higher Intensity without Episode 3 | 38.7 | 15.7 | 4.6 | 32.0 | 14.0 | 3.2 | 38.1 | 15.4 | 3.6 |

| Pilot Study Period | Control 24-hour Concentration (all units µg/m³) | | | Test 24-hour Concentration (all units µg/m³) | | | Forecast Test 24-hour Concentration (all units µg/m³) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $PM_{10}$ | $PM_{2.5}$ | $PM_1$ | $PM_{10}$ | $PM_{2.5}$ | $PM_1$ | $PM_{10}$ | $PM_{2.5}$ | $PM_1$ |
| Higher Intensity without Episodes 3 & 4 | 37.0 | 13.6 | 3.3 | 31.4 | 12.9 | 2.5 | 36.4 | 13.3 | 2.6 |

Table 6.2 presents the percentage and absolute changes calculated for the low intensity and high intensity periods. In the low intensity period a percentage reduction of 10.3% is calculated for $PM_{10}$, with a 3.2% reduction for $PM_{2.5}$ and a 6.1% reduction for $PM_1$. However, as CMA effects are anticipated to be more effective for coarser size fractions it is considered to be unrealistic to identify notably higher percentage improvements in $PM_1$ over $PM_{2.5}$. This suggests that there may be some interference which has affected the comparison, perhaps from a local or regional source. This would suggest that the percentage reductions in $PM_{10}$ should be lower than the 10.3% calculated.

**Table 6.2 Main Test CMA Effectiveness Summary**

| Pilot Study Period | Percentage Change | | | Absolute Difference in 24-hour Concentration (all units µg/m³) | | |
|---|---|---|---|---|---|---|
| | $PM_{10}$ | $PM_{2.5}$ | $PM_1$ | $PM_{10}$ | $PM_{2.5}$ | $PM_1$ |
| Baseline | 0.0% | 0.0% | 0.0% | 0.0 | 0.0 | 0.0 |
| Low intensity | -10.3% | -3.2% | -6.1% | -3.2 | -0.4 | -0.1 |
| Higher Intensity | -18.6% | -16.7% | -17.8% | -8.2 | -3.5 | -1.0 |
| Higher Intensity without Episode 3 | -15.9% | -9.3% | -10.8% | -6.0 | -1.4 | -0.4 |
| Higher Intensity without Episodes 3 & 4 | -13.6% | -3.3% | -3.4% | -5.0 | -0.4 | -0.1 |

During the higher intensity treatment period, high percentage reductions in $PM_{10}$ of 18.6 % were calculated. However, these were also accompanied by unrealistically high percentage reductions in $PM_{2.5}$ and $PM_1$ of 16.7% and 17.8% respectively. This reflects the disparity in how the long range pollution episodes affected the control and main test site, with higher contributions of $PM_1$ monitored at the control site relative to the main test site.

This interpretation is corroborated by the smaller reduction in $PM_{10}$ of 15.9% calculated following the removal of pollution episode 3 (17th - 22rd February 2011) from our analysis and the large reduction in $PM_{2.5}$ and $PM_1$ improvements. However, a reduction of 10% in $PM_1$ and $PM_{2.5}$ is still considered to be unrealistically high given the findings of the literature review.

In removing pollution episode 4 (28th February - 5th March 2011) further reductions in both $PM_{10}$ and $PM_{2.5}$ and $PM_1$ improvements are calculated. The reduction in $PM_{10}$ is calculated to be 13.6%, with improvements of 3.3% and 3.4% for $PM_{2.5}$ and $PM_1$ respectively. This result is considered to more adequately reflect the anticipated types of improvements from the application of CMA for the different particulate size fractions.

The percentage reduction achieved during the pilot study may, in part, be due to the partial canyon environment located at the main test site, as this will likely result in some re-circulation effects, which may maintain the available source of particulates on the road surface. This will increase the amount of particulate available for re-suspension relative to open environments and so lesser percentage improvements may be expected in these open environments.

Further work is now required to confirm if these effects are replicated in other locations and environments. For example open environments, which may be less well suited to CMA applications or other environments which may be even better suited to CMA applications (e.g. full canyons).

# 7. SUMMARY AND CONCLUSIONS

The first trials of Calcium Magnesium Acetate (CMA) dust suppressant on paved roads in the UK have been undertaken in London. The performance of the suppressant was monitored using Osiris continuous particulate monitors.

Baseline monitoring commenced on the 15th October 2010 at kerbside locations on Victoria Embankment. Applications of CMA commenced on the 18th November 2010. The study was undertaken over a period of approximately six months ending on the 18th April 2011. The analysis of CMA effects has focused on a period of low intensity treatment between the 12th January and 31st January 2011 and also a more intensive period of treatment between the 1st February and 10th March 2011.

The results show a consistent baseline situation where very similar results were obtained between the test and control sites.

In the low intensity period calculations suggest that an improvement in 24-hour $PM_{10}$ kerbside concentrations was achieved. The calculated improvement during this period was around 10%. However, improvements achieved in the smaller size fractions during this period are greater than expected based on literature review information. This suggests that the level of improvement during this low intensity period is likely to be less than calculated.

In the more intensive treatment period an overall reduction in 24-hour $PM_{10}$ kerbside concentrations was also identified. The level of improvement during this period has been calculated to be approximately 14%. Calculations for the smaller size fractions of $PM_{2.5}$ and $PM_1$ (24-hour kerbside averages) suggest that improvements of around 3% were also achieved during the intensive treatment period. Lower improvements in these size fractions, relative to $PM_{10}$, would be anticipated with the smaller size fractions. This is because CMA interventions are anticipated to affect larger sized particles primarily.

These CMA treatment figures are based on a first pilot study undertaken during a limited study period and in one study location. It is therefore suggested that the results should be considered, as only indicative of the environment studied, over the duration of study, and with the inherent limitations of a pilot study.

The percentage reduction achieved during the pilot study may, in part, be due to the partial canyon environment located at the main test site, as this will likely result in some re-circulation effects, which may maintain the available source of particulates on the road surface. This will increase the amount of particulate available for re-suspension relative to open environments and so lesser percentage improvements may be expected in these open environments.

Further work is now required to confirm these pilot study effects are replicated in other locations and environments. For example open environments, which may be less well suited to CMA applications or other environments, which may be even better suited to CMA applications (e.g. full canyons which are common in some urban locations).

The study has not been undertaken with reference techniques, which are used to determine compliance with EU Limit Values. Therefore, these results cannot be used to demonstrate compliance with EU Limit Values. However, the results from the pilot study suggest that if the levels of change identified from the pilot study can be replicated elsewhere, that this technique has the potential to be useful in reducing $PM_{10}$ concentrations and the number of EU Limit Value exceedances. Albeit, this would be limited to periods where an exceedance was likely close to the EU Limit Value and where one of the key episode sources was local road traffic emissions.

Dust suppressants will not be a useful abatement technique for preventing exceedences of the $PM_{10}$ EU limit Value where the key driver is long range pollution. This is because CMA targets local road re-suspension contributions.

# 8. SUGGESTED RECOMMENDATIONS FOR FURTHER WORK

## 8.1 Overall Approach

The first pilot phase of these CMA trials has yielded positive outcomes. The results of the trials suggest that CMA applications could be beneficial in reducing 24-hour $PM_{10}$ concentrations. Further works are recommended to confirm pilot findings, optimise application approaches and to target areas of uncertainty.

Further works are also recommended to test different environments to Victoria Embankment potentially including:

- Canyon situations, as these are often sites with elevated particulate concentrations;
- Higher speed urban routes, as these may have greater potential to remobilise particulates than lower speed routes; and
- High flow locations for heavy goods vehicles, as these may have the potential for greater remobilisation than light vehicles.

Roads close to construction and industrial sites could also be considered as at these sites there will potentially be a large potential non-exhaust source of particulates which could be remobilised from tracking out.

Ideally the best potential locations (canyon, higher speed, high HGVs or construction) inside or outside of the Priority Action Areas would have:

- The minimum of confounding factors;
- The best available existing air quality monitoring for particulates and $NO_X$;
- The best available traffic data including HGVs/ LGVs; and
- The best potential for installing new monitoring equipment.

## 8.2 Recommendations

The detailed recommendations to address areas of uncertainty in the findings of the first phase of works and to test different road environments are listed in Table 8.1. These recommendations aim to build on the findings of the pilot study and optimise the future application of CMA to enable it to play one part in achieving the objectives of the Mayor's Air Quality Strategy.

**Table 8.1 Detailed Recommendations**

| Recommendation | Reason |
|---|---|
| Increased periods of baseline data collection. | Existing baseline data for the Victoria Embankment site covers a period of one month (mid October to mid November 2010). Additional data is required to capture different baseline meteorological conditions. This could be achieved by collecting additional months of data in different seasons. The collection baseline data in different seasons would also be suggested for any new locations. |
| Obtain improved meteorological data. | Particularly for the control location at Victoria Embankment to provide 'neighbourhood data' unaffected by micro-environmental effects. Also for any other locations investigated. |
| Installation of a background River Corridor site. | To provide a more appropriate background site for Victoria Embankment. |
| Installation of an urban background site unaffected by significant A-Road or B-Road $PM_{10}$ emissions. | To provide a more appropriate background site for any additional urban routes tested. |
| Identify opportunities to co-locate Osiris monitors with $NO_X/NO_2$ analysers. This may be possible utilising existing $NO_X/NO_2$ monitors. | Consistent with scientific literature this approach helps to identify instances where changes in $PM_{10}$ concentrations are related to dust suppressant and when changes are due to meteorological effects. For example if a reduction in $PM_{10}$ concentration was associated with a reduction in $NO_x/NO_2$ this may indicate a meteorological cause, but if $PM_{10}$ concentrations fall and $NO_x/NO_2$ concentrations remain consistent this suggests a local effect. |
| Identify appropriate techniques to measure salt/ CMA build up on road surfaces. | To confirm that periods of CMA effects are accompanied by CMA build up on road surfaces, ideally using continuous methods. |
| Review of existing forecast tools to establish if suitable for use. | In order to identify if existing tools will allow the correct periods for deployment to be identified. |
| Review of different road surfaces utilised by TfL. | To establish if there are significant physical differences which could affect the potential for tyre wear and whether road surfaces fabrics could also affect re-mobilisation. |
| Continued development of analysis approaches. | To identify if improved approaches could be utilised to characterise CMA effects. |
| Engagement of specialist support | In order to utilise existing knowledge on CMA |

| Recommendation | Reason |
|---|---|
| as advisors. | applications and/or road surface remobilisation. |
| Further engagement with London Air Quality Groups e.g. The Air Pollution Research in London network (APRIL). | In order to obtain feedback from the air quality community and potentially establish if any other monitoring can be pooled. Potential opportunities to collaborate with studies which complement the further investigation of CMA effects may also be identified through engagement e.g. dust speciation studies. |

# Appendix A CMA Application Schedule

| Date | Start Time | Finish Time | Rate (g per m2) | Notes |
|---|---|---|---|---|
| 18/11/2010 | 02:00am | 02:45am | 10 | |
| 22/11/2010 | 21.30pm | 21.55pm | 10 | |
| 24/11/2010 | 02:00am | 02:45am | 10 | |
| 26/11/2010 | 00:00am | 00:45am | 10 | |
| 29/11/2010 | 02:00am | 02:45am | 10 | |
| 30/11/2010 | 02:00am | 02:45am | 10 | |
| 03/12/2010 | 22.15 pm | 23.30pm | 10 | |
| 07/12/2010 | 01:00am | 02:00am | 10 | |
| 08/12/2010 | 01:00am | 02:00am | 10 | |
| 09/12/2010 | 21.45pm | 22.30pm | 10 | |
| 10/12/2010 | 21.30pm | 21.55pm | 10 | |
| 13/12/2010 | 23.15pm | 23.45pm | 10 | |
| 11/01/2011 | 23.00pm | 23.25pm | 10 | |
| 13/01/2011 | 21.15pm | 21.35pm | 10 | |
| 14/01/2011 | 23.00pm | 23.25pm | 10 | |
| 18/01/2011 | 23.00pm | 23.30pm | 10 | |
| 19/01/2011 | 21.00pm | 21.20pm | 10 | |
| 21/01/2011 | 23.30pm | 23.55pm | 10 | |
| 24/01/2011 | 23.20pm | 23.50pm | 10 | |
| 26/01/2011 | 23.15pm | 23.45am | 10 | |
| 28/01/2011 | 00.15am | 00.45am | 10 | |
| 31/01/2011 | 23.30pm | 00.25am | 10 | Two applications |
| 01/02/2011 | 23.30am | 00.30am | 10 | Two applications |
| 02/02/2011 | 23.35pm | 00.30am | 10 | Two applications |
| 03/02/2011 | 23.45pm | 00.40am | 10 | Two applications |
| 04/02/2011 | 00.01am | 00.55am | 10 | Two applications |
| 07/02/2011 | 02.00am | 02.50am | 10 | Two applications |
| 08/02/2011 | 01.20am | 02.10am | 10 | Two applications |

| Date | Start Time | Finish Time | Rate (g per m2) | Notes |
|---|---|---|---|---|
| 09/02/2011 | 02.00am | 02.50am | 10 | Two applications |
| 10/02/2011 | 03.15am | 04.00am | 10 | Two applications |
| 11/02/2011 | 01.30am | 02.15am | 10 | Two applications |
| 14/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 14/02/2011 | 00.30am | 0.1.00am | 10 |  |
| 15/02/2011 | interpeak |  | 10 | exact treatment time not listed |
| 15/02/2011 | 00.00am | 00.30am | 10 |  |
| 16/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 16/02/2011 | 00.00am | 00.25am | 10 |  |
| 17/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 17/02/2011 | 00.50am | 01.15am | 10 |  |
| 18/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 18/02/2011 | 00.30am | 00.55am | 10 |  |
| 21/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 21/02/2011 | 01.00am | 01.25am | 10 |  |
| 22/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 22/02/2011 | 00.45am | 01.15am | 10 |  |
| 23/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 23/02/2011 | 22.30pm | 23.30pm | 10 |  |
| 24/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 24/02/2011 | 00.1.20am | 01.50am | 10 |  |
| 25/02/2011 | Interpeak |  | 10 | exact treatment time not listed |
| 25/02/2011 | 23.20pm | 23.50pm | 10 |  |
| 28/02/2011 | 23.30pm | 23.55pm | 10 |  |
| 01/03/2011 | 02.30am | 03.00am | 10 |  |
| 02/03/2011 | 02.00am | 02.25am | 10 |  |
|  | 02.40am | 03.10am | 10 |  |

| Date | Start Time | Finish Time | Rate (g per m2) | Notes |
|---|---|---|---|---|
| 03/03/2011 | | | | |
| 04/03/2011 | 02.00am | 02.30am | 10 | |
| 07/03/2011 | 21.00pm | 21.30pm | 10 | |
| 08/03/2011 | 02.00am | 02.30am | 10 | |
| 09/03/2011 | 00.00am | 00.25am | 10 | |
| 10/03/2011 | 01.00am | 01.30am | 10 | |
| 11/03/2011 | 03.00am | 03.30am | 10 | |
| 14/03/2011 | 02.30am | 03.00am | 10 | |
| 15/03/2011 | 00.35am | 01.00am | 10 | |
| 16/03/2011 | 01.00am | 01.25am | 10 | |
| 17/03/2011 | 21.30am | 22.10am | 10 | |
| 18/03/2011 | 00.00am | 00.25am | 10 | |
| 21/03/2011 | 01.30am | 02.00am | 10 | |
| 22/03/2011 | 01.45am | 02.15am | 10 | |
| 23/03/2011 | 01.00am | 01.25am | 10 | |
| 24/03/2011 | 01.30am | 02.00am | 10 | |
| 25/03/2011 | 01.00am | 01.30am | 10 | |
| 04/04/2011 | 01.00am | 01.25am | 10 | |
| 04/04/2011 | 14.00pm | 14.40pm | 10 | |

| Date | Start Time | Finish Time | Rate (g per m2) | Notes |
|---|---|---|---|---|
| 05/04/2011 | 00.30am | 01.10am | 10 | |
| 05/04/2011 | 14.00pm | 14.45pm | 10 | |
| 18/04/2011 | 00.00am | 00.35am | 10 | |
| 18/04/2014 | 14.00pm | 14.40pm | 10 | |