Local Measures for PM_{10} Hotspots in London

Project 18447

Final Report

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1 Introduction

1.1 This report has been prepared by Air Quality Consultants (AQC) and TRL Ltd (TRL) on behalf of Transport for London. This report was completed to present a range of local measure options for consideration during an early stage of the Strategy development process, and accordingly does not take account of the MAQS that will be issued for public consultation in April 2010 or indeed the final MAQS, and nor does it take account of any revised modelling work that may supersede the studies cited in this report.

Background

1.2 The first Air Quality Strategy for London was published in 2002 (GLA, 2002). A draft revised Mayor's Air Quality Strategy (MAQS) (GLA, 2009d) has recently been published for consultation. This focuses on achieving the European Union (EU) limit values for air pollutants. Air quality in many areas of the UK and Europe does not currently meet the limits for nitrogen dioxide (NO_2) and particulate matter (PM) with an aerodynamic diameter of less than 10 µm (PM_{10}). The limit values for these pollutants are shown in Table 1. Defra has submitted a Time Extension Notification to the European Commission to extend the deadline for the PM_{10} limit value to 2011[1]. A similar process is currently underway to extend the limit value deadline for NO_2 to 2015. Many of the hotspots are likely to be the same for both pollutants and some of the control measures will be applicable to both pollutants.

Table 1: Air quality limit values for NO_2 and PM_{10}.

Pollutant	Averaging period	Limit value
NO_2	1-hour	200 µg/m^3 (not to be exceeded more than 18 times a year)
	Annual	40 µg/m^3
PM_{10}[a]	24-hours	50 µg/m^3 (not to be exceeded more than 35 times a year)[b]
	Annual	40 µg/m^3

[a] Measured by the European reference method or equivalent.

[b] The 24-hour mean objective is approximately equivalent to an annual mean of 31.5 µg/m^3 (Kent *et al*. 2007)

[1] The Commission issued a statement on 11 December 2009 announcing its' decision that the UK request for a time extension does not meet the minimum requirements of the Directive. The UK may put forward a further request based on new information.

1.3 Once improvements resulting from Transport for London's Business Plan and anticipated vehicle fleet changes are taken into account, the majority of London is expected to meet the PM_{10} limit by 2011 - based on modelling undertaken for TfL by the Environmental Research Group at King's College London (Westmoreland and Dajnak, 2009). However, the modelling also indicated five areas in London that would remain at risk of not meeting the EU limit values if no further action were taken. These locations, illustrated in Figure 1, are focussed on the central London road network. Of these locations, Marylebone Road is considered to be at "high risk" of not meeting the EU limit value by 2011, whilst the four other locations, Tower Hill, Victoria Embankment, Marble Arch and Euston Road are considered to be at "moderate risk" of not meeting the limit value by 2011.

Figure 1: Central London locations identified as at risk of not meeting the EU limit value for PM_{10} in 2011 (source: Mayors Air Quality Strategy, Consultation Draft, 2009)

1.4 It is noted that the monitoring and assessment requirements for checking compliance with the EU air quality Directive limit values exclude locations within 25 m of a major junction. The limit values will therefore not strictly apply to some of these hotspots, in particular Marble Arch. Nonetheless, it is recognised that it is still important to tackle poor air pollution at these locations for reasons of improved public health, and these hotspots have not been excluded from the study.

1.5 Various London-wide measures for improving air quality are mentioned in the Mayor's Air Quality Strategy, and a number of these relate specifically to road transport. Measures already proposed or underway include the following:

- Promoting modal shift to cleaner forms of transport.
- Bus emissions programme – from 2012 every new bus coming into the London fleet will be diesel-electric hybrid and the 'new bus for London' is expected to be hybrid.
- Encouraging car clubs, especially those using plug-in hybrid and electric cars.
- Improving road maintenance to reduce road surface wear.
- Smoothing traffic flows through better traffic management.
- Making it easier for boroughs to implement and enforce 20mph zones.
- The continuation of the Central London Congestion Charging scheme.
- Operation of the London Low Emission Zone (LEZ).
- Procurement and promotion of electric vehicles.

The Mayor is also proposing a further package of measures for transport. This package consists of:

- Encouraging smarter travel choices and sustainable travel behaviour.
- Promoting technological change and cleaner private vehicles.
- Reducing emissions from particular sources in the public transport fleet.
- Emission-control schemes (such as changes to the London Low Emission Zone).

1.6 However, whilst London-wide measures will help to deliver the necessary improvements, it is recognised that specific local measures are also required. Policy 3 of the draft MAQS sets out the Mayor's intent to implement ***targeted local measures at these hotspots***. The draft MAQS commits TfL to undertaking work to develop a detailed picture of each hotspot, to examine potential interventions for each location, and to then develop a tailored package of measures and action plan for each of the five priority hotspot areas. Whilst the focus is on the priority hotspots, the MAQS also recognises that there are potentially other locations in London where air quality is comparatively poor, including those areas identified by the boroughs' own monitoring and modelling assessments. It is therefore intended that the "tailored measures" could be adapted for these locations, as appropriate.

1.7 TfL has appointed Air Quality Consultants (AQC) and TRL Limited (TRL) to carry out a programme of work to identify local measures for each of these five hotspots. The outcome of this study, and the proposals arising from it, will be used to inform the public and stakeholder draft of the MAQS. It is important to note that this study focuses only on ***local measures*** that could be applied within each hotspot (and potentially transferred and implemented at other London hotspots). It is not the purpose of this study to identify or address wider-scale measures that may be implemented to reduce PM_{10} emissions and concentrations; such measures are being considered separately by Mayor.

1.8 In addition, the draft MAQS (Policy 6) also identifies the need to develop ***Air Quality Action Days and Special Measures*** that will focus on high pollution days as well as seeking to promote more lasting behavioural change. This report also considers the potential for employing such Special Measures.

Work programme

1.9 The work programme has been undertaken in three phases:

Phase 1 – Understanding the effectiveness of potential local measures. The first phase of the project involved a literature review of local measures which could potentially be introduced to address the high PM_{10} concentrations at the five hotspots. This has provided the basis for selecting measures for inclusion in the pilot programmes developed in Phase 2 of the project.

Phase 2 – Development of pilot programmes. The second phase of the project involved the development of pilot programmes of local measures tailored to each of the hotspots. To help with this, detailed profiles were developed for each hotspot, covering physical attributes, traffic characteristics and the pollution climate. Monitoring programmes have also been developed to allow TfL to make an informed judgement on the effectiveness of the local measures in a London context.

Phase 3 – Assessment of Options for Special Measures. The third phase of the project was carried out independently of Phases 1 and 2. It involved a literature review of special measures that have been employed in the UK and other European countries, and discussed the feasibility of options that could be implemented in London.

1.10 Chapter 2 of this report provides an overview of airborne PM and abatement. Chapter 3 sets out the limitations of the modelling studies used to identify the hotspots, principally to inform the subsequent assessment of measures. Chapter 4 describes issues related to monitoring data and pollution forecasting. Chapter 5 sets out the Detailed Profiles for each hotspot location. Based on these profiles, Chapter 6 then provides an evaluation of the measures that have been considered, which leads to the recommended Pilot Programmes for each hotspot as described in Chapter 7. Chapter 8 discusses monitoring, setting out the generic considerations and a recommended approach for each Pilot Programme. Finally, Chapter 9 provides a review of Special Measures and discusses the feasibility of options that could be implemented in London.

1.11 The Detailed Profiles for each hotspot are set out in Appendix 1. The literature review that was completed under Phase 1 of the project is included as Appendix 2 to this report.

1.12 A glossary of terms is provided at the end of the report.

2 Overview of Airborne Particulate Matter and Abatement

2.1 In order to reduce atmospheric concentrations of PM_{10} in London it is necessary to have an understanding of its characteristics, emission sources and formation mechanisms. A brief overview of the characteristics and sources of airborne PM – with particular reference to London - is given in this Chapter of the Report. Specific information on PM_{10} concentrations and sources within the five hotspots will be provided in Phase 2 of the project. An introduction to abatement techniques is also provided.

Characteristics and sources of airborne PM

2.2 Airborne PM is a complex mixture of organic and inorganic substances, in solid or liquid form, which undergoes modification or transformation in the atmosphere. It is derived from a wide variety of sources, both natural and anthropogenic, and displays a range of physical and chemical properties. Particles are termed either 'primary' where they are emitted directly into the atmosphere, or 'secondary' where they are formed by reactions between gas-phase components such as sulphur oxides, nitrogen oxides, ammonia, and organic compounds. Consequently, various terms and metrics are used to describe airborne PM (see Glossary).

2.3 Particles in the atmosphere range in size from less than 10 nm (0.01 µm) to around 100 µm. There are three recognised modes relating to the typical shape of the size distribution and corresponding sources: the nucleation mode, the accumulation mode, and the coarse particle mode. The contributions of different sources to mass concentrations in these different modes vary with many factors, including location, season, time of day, and both local and regional weather conditions.

2.4 The ***nucleation mode*** consists of particles emitted directly from combustion sources, such as road vehicle exhaust, waste incineration, and industrial and domestic burning. Nucleation mode particles typically have a diameter of less than around 0.05 µm. Even though such particles may be present in large numbers, each particle is so small that this mode usually forms only a small proportion of the total aerosol mass. Nucleation mode particles reside in the atmosphere for a few hours, and are transformed by coalescence and condensation into larger accumulation mode particles.

2.5 ***Accumulation mode*** particles range between around 0.05 µm and 1 µm in diameter, have atmospheric residence times of tens of days, and usually form a significant fraction of the total aerosol mass. They are also efficient at scattering light, and often dominate optical effects such as visibility. As well as being formed via the coagulation of nucleation mode particles, accumulation mode particles originate from primary emission sources and gas-to-particle transformations in the atmosphere.

2.6 The ***coarse particle mode*** includes those particles greater than about 1 µm diameter. These particles are typically generated through mechanical processes rather than nucleation and condensation. Within this size range the process of gravitational settling is significant, and atmospheric lifetimes are much shorter than for accumulation mode particles.

2.7 The PM generated by road transport activity (the most important source of PM emissions in London) can be categorised according to its mechanism of formation. It is often assumed that diesel exhaust is the main source of PM from road vehicles, and exhaust emissions have been well characterised in the laboratory under well-defined test conditions. However, there are a number of non-exhaust processes, involving mechanical abrasion and corrosion, which can also result in PM being released directly to the atmosphere. The main abrasion processes leading to the direct emission of PM are tyre wear, brake wear and road surface wear as well as emissions from wheel arches and open loads (such as close to construction sites). In addition to direct non-exhaust emissions, material previously deposited on the road surface can be resuspended in the atmosphere as a result of tyre shear, vehicle-generated turbulence, and the action of the wind. In the case of road transport, it is commonly assumed that most primary fine particles ($PM_{2.5}$) are emitted from the exhaust, whereas many of the coarse particles ($PM_{2.5\text{-}10}$) are considered to originate from non-exhaust sources. This over-simplifies the situation somewhat; whilst there is a general agreement that exhaust emissions can be classified as $PM_{2.5}$, there is evidence to suggest that non-exhaust particles contribute to both the fine and coarse modes (Boulter et al., 2007a).

PM_{10} emissions in London[2]

2.8 The total annual emissions of various pollutants in London are quantified in the London Atmospheric Emissions Inventory. The latest published data are available for 2006 (GLA 2009b).

2.9 The majority of PM_{10} emissions in Greater London in 2006 and 2010 are from road transport and in particular diesel engines. Road transport is responsible for 66% and 64% of total PM_{10} emissions

[2] PM_{10} has been designed as an air quality metric. However, it is common practice for PM emissions in inventories to be classified according to such metrics, even though the methods used to measure emissions are not the same as those used to measure PM_{10}.

in 2006 and 2010 respectively. A detailed breakdown of the contribution of vehicle types to PM_{10} emissions is given in the 2004 inventory full report (Mattai and Hutchinson, 2008). This shows that in this version of the inventory, taxis, cars and LGVs are the largest contributors to the total PM_{10} emissions from road transport in Central London (24%, 25% and 18% respectively in 2010, as shown in Figure 2).

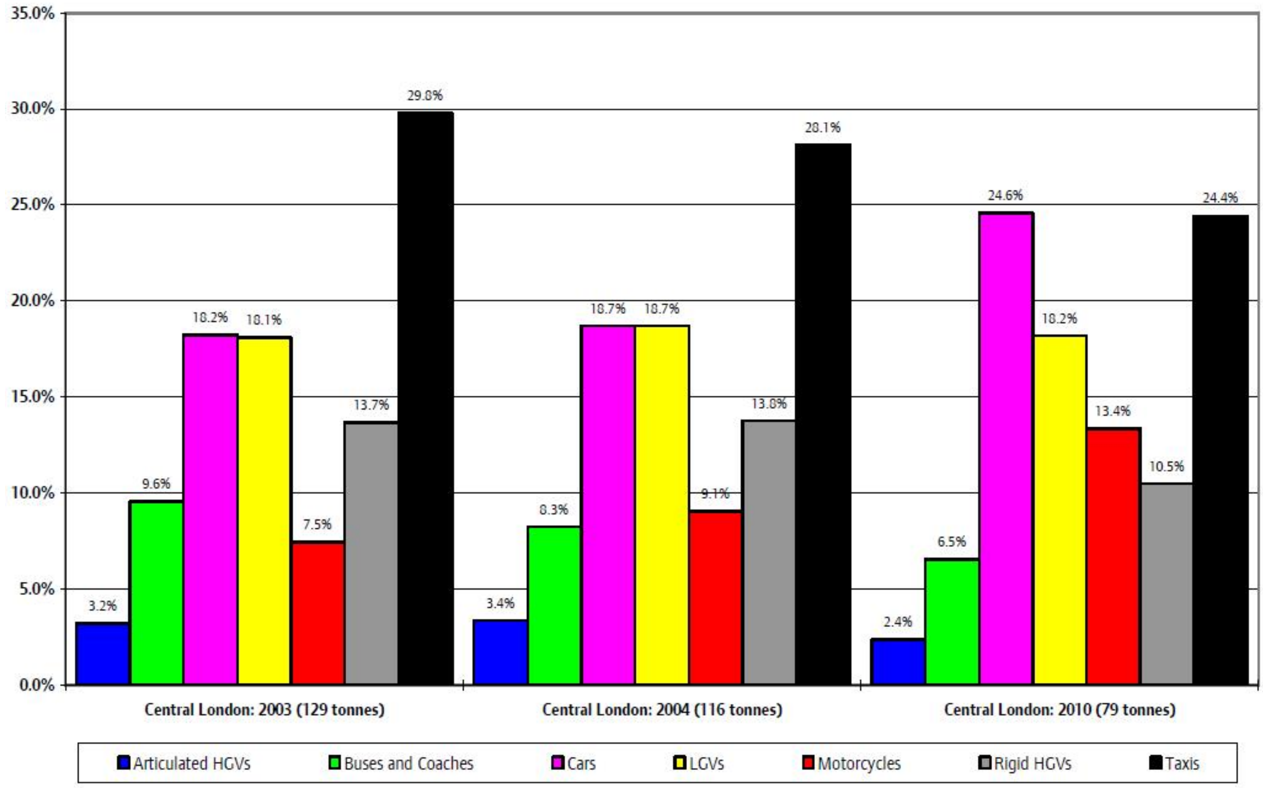

Figure 2: Proportion of total PM_{10} emissions from road transport in Central London by vehicle type in 2003, 2004 and 2010 (Mattai and Hutchinson, 2008).

2.10 The vehicle related emissions in the London Atmospheric Emissions Inventory include exhaust emissions and brake & tyre wear. No allowance made for the role of vehicle induced resuspension. This is due to the absence of agreed emission factors. Nevertheless, the study by Thorpe et al. (2007) of PM_{10} resuspension on Marylebone Road concluded that around 20% of the road contribution to roadside concentrations was due to resuspension, with 60% due to vehicle exhaust and around 20% to abrasion sources (brake, tyre and road surface). Further details of this work are available in a series of publications detailing the findings of the major research project for Defra[3].

[3] www.airquality.co.uk/archive/contracts/project1.php?project_id=158&action=project

PM_{10} concentrations in London

2.11 Annual mean concentrations of PM_{10} in London decreased during the 1990s, but in the last decade the decline has been much slower (GLA, 2009). Although the EU annual mean and daily air quality standards are met at background sites, they are regularly exceeded close to the busiest parts of London's trunk road network and near waste management sites (Fuller et al., 2007). This study is particularly concerned with identifying measures to deal with levels of PM_{10} at five areas in Central London which have been identified as being at risk of exceeding the daily mean PM_{10} limit value in 2011. It is recognised that significant reductions in concentrations are required at some sites to meet the 24-hour limit value of no more than 35 exceedences of 50 µg/m^3. This limit value equates approximately to an annual mean of 31.5 µg/m^3 (Kent et al. 2007) and at kerbside locations on Marylebone Road (the worst-case hotspot), it is predicted that a reduction in annual mean PM_{10} of between 4.1 µg/m^3 and 10.3 µg/m^3 is required in 2011 to meet the limit value. This is equivalent to a reduction in emissions from road traffic along Marylebone Road of between 19 to 48% (Westmoreland and Dajnak, 2009).

2.12 Although there have been many measures implemented on a UK and European scale to reduce emissions of PM_{10}, $PM_{2.5}$ and their precursors, they appear to be having little effect on PM_{10} concentrations measured in London. Indeed, there is evidence to suggest that PM_{10} emissions from local sources in London have increased in the last few years, despite information to the contrary in the London Atmospheric Emission Inventory. Fuller and Green (2006) applied a source apportionment technique to separate PM_{10} concentrations into primary sources (from road transport emissions and stationary sources) and non-primary sources (including secondary PM_{10} from long-range sources and natural sources). The study found that although background concentrations decreased slightly over time, there were increases in the primary component, which resulted in a slight overall increase in measured PM_{10} concentrations.

2.13 The contribution of these different sources to the total PM_{10} in the vicinity of a road therefore provides a theoretical maximum limit to the reduction in concentration which can be achieved by local measures. For example, the background concentration and the contribution of non-primary particles will not be affected by local measures.

2.14 Studies have also shown that roadside PM_{10} appears to be more toxic than PM_{10} at background locations, and that particle mass concentrations are associated with short-term increases in respiratory health effects while changes in particle number concentrations are associated with increases in cardiovascular effects. Measures introduced on a local or London-wide scale to abate

PM_{10} could therefore be effective in reducing both the particle mass concentration and associated health effects of PM_{10} (Fuller et al, 2007).

2.15 It is important to note that although there are these exceedences at these hotspot areas, PM_{10} concentrations tend to fall off rapidly, on average, with increasing distance from the road, although on individual days the rate of fall off depends on the wind direction and speed. Zhu et al. (2009) found that PM concentrations returned to background concentrations within 100 m of a road, with the smaller fractions ($PM_{2.5}$) decaying faster than coarse fractions. The Air Quality Expert Group in the UK, on the other hand, reported monitoring data which showed that beyond 20–50 m from the edge of the road, concentrations are essentially indistinguishable from the local background, taking account of measurement uncertainty and the normally high background contribution to measured roadside concentrations (AQEG, 2005). AQEG also reported no difference in the fall off between PM_{10} and $PM_{2.5}$.

Abatement

2.16 Knowledge of the effectiveness of abatement measures for PM_{10} is needed to develop practical strategies for reducing ambient pollutant concentrations. Compliance with air quality standards for PM_{10} requires control of both fine and coarse particles. As the two modes tend to have different sources and formation mechanisms, different tyres of control are required (Boulter et al., 2007a). The compounds which are precursors to secondary particles also need to be controlled. Potential abatement options for PM_{10} therefore include a mixture of technical and policy approaches, and can relate to both vehicles and the infrastructure.

2.17 Primary fine particles from combustion sources are subject to regulation. For example, all new light-duty vehicle models and heavy-duty engine models sold in Europe must be type approved with respect to exhaust emissions in accordance with European Union Directives. The measurement of total exhaust particulate mass has been defined in regulation for diesel engines and vehicles since 1988. Regulations also govern the formulation and quality of road fuels. Commencing with the introduction of Euro V standards (in force from 2009), limits will also be placed on the allowable number of particles emitted in the exhaust of specific vehicle classes. The technologies which are being used to enable vehicle manufacturers to comply with the exhaust emission legislation include improved engines and exhaust after-treatment systems - such as three-way catalysts, oxidation catalysts, exhaust gas recirculation, selective catalytic reduction, diesel particulate filters and regenerative traps.

2.18 As noted earlier, much is already being done in London to reduce exhaust emissions from road vehicles, including the Low-Emission Zone, the fitting of diesel particulate filters to all 8,000

London's buses and the Taxi Emissions Strategy. Further technological solutions to address vehicle exhaust emissions are considered to be beyond the scope of this work.

2.19 The control of coarse particles is less straightforward (Harrison et al., 2001), as such particles arise from natural and anthropogenic disruption and attrition processes which are difficult to characterise (*e.g.* non-exhaust emissions, resuspension, dust from industrial processes, quarrying). In terms of controlling resuspension from paved roads, measures can either be designed to prevent material from being deposited onto the surface in the first place (preventive controls) or to remove any material that has already been deposited (mitigative controls). Improvements in vehicle technology are essentially preventative in nature, in that they reduce the primary generation or release of abrasion products, whereas policies (e.g. road sweeping programmes) tend to be mitigative in nature. Another potential type of measure involves 'adaptation' to reduce exposure to existing levels of pollution. Measures of this type might include improved sealing of vehicle passenger compartments and buildings, or re-routing main roads away from areas of population.

2.20 Clearly, the most effective measures are likely to be those which target with high efficiency those sources making the largest contribution to PM. It should also be noted that the 24-hour limit value for PM_{10} is more likely to be exceeded than the annual mean, even though the latter is more important from a public health viewpoint. This may alter the focus of the measures selected, as it may be appropriate to focus on reducing emissions on those days when the 24-hour limit is likely to be exceeded.

2.21 The contributions of the different sources to the total PM_{10} in the vicinity of a road restricts the reduction in concentration which can be achieved by local measures. For example, the background concentration and the contribution of non-primary particles will not be affected in a significant way by local measures.

3 Limitations of Modelling

3.1 This section briefly discusses the various limitations of the modelling assessment that has been used to identify the five hotspots in London. The intent of this exercise is not to provide a critical review of the modelling work carried out by the King's College Environmental Research Group (ERG), but rather to inform the Detailed Profiles and the selection of measures included within each Pilot Programme.

3.2 There are inherent uncertainties within any modelling assessment, particularly where future year predictions are carried out. There are also additional uncertainties that arise when a regional scale model (such as that used by ERG to predict pollutant concentrations across Greater London) is applied at a very detailed, local scale. Some of these issues, and the associated implications for identifying local measures to reduce PM_{10} concentrations, are set out below.

- It is widely accepted that it is difficult to predict 24-hour mean concentrations of PM_{10}, and the approach used both by Defra for national modelling assessments, and by ERG for the assessments to support the MAQS, is to rely on an empirical relationship between the annual mean and the number of 24-hour mean exceedences of 50 µg/m^3. This relationship indicates that the 24-hour mean limit value is at risk of being exceeded where the annual mean exceeds 31.5 µg/m^3. An important implication for this study is that measures to reduce the number of days on which PM_{10} concentrations exceed 50 µg/m^3 (and which is required to achieve the 24-hour mean limit value) may be different to those that would be used to target a reduction in the annual mean concentration. A further important consideration is that the source apportionment information provided, and the assumed 'background contribution'[4] to the modelled concentrations, is based on the annual mean. In practice, on exceedence days (when 24-hour mean concentrations are above 50 µg/m^3), the background contribution is often elevated above the mean value, and may closely approach, or even exceed the limit value threshold. On such days it will be impossible to reduce PM_{10} concentrations below the limit value by local measures.

- All modelling studies are dependant on a variety of input data, and the accuracy of these data will be reflected in the accuracy of the model output. A critical input parameter is the traffic data, which have been derived by King's College ERG for specific links within the London

[4] In the context of this report, the background contribution is defined as that arising from sources other than the immediate road link at which the hotspot is located. This contribution will include emissions from other, nearby road, a 'regional' contribution from across London, and a transboundary contribution.

Atmospheric Emissions Inventory. These "link lengths", where uniform traffic flows, speeds and vehicle mix are applied, are relatively long – for instance, the traffic flows around Marble Arch are the same on all arms of the gyratory, including the bus lane across the middle, and are the same as flows along Park Lane. In preparing the Detailed Profiles (which are discussed in greater detail in Section 4) it was apparent that flows may not be uniform along the whole link, although this had to be the assumption. An important implication arising from this observation is that in some cases, the application of a uniform measure along the whole of the identified hotspot would be inappropriate.

- There are limitations with the traffic data, which are based on counts in different years. This is illustrated in the results for the Marylebone Road hotspot. This is made up of two traffic links, with one covering 760 m the other covering 130 m at the eastern end of the hotspot. The traffic flows are similar, 66,500 and 65,700 veh/day respectively, but the composition is very different, for example LGVs for 13.2% and 0.5% of the traffic respectively, and rigid HGVs 3.1% and 17.8%. As this is effectively one road, such differences cannot be occurring in practice. The count for the 130 m section was made in an earlier year.

- The ERG model does not include any component for road vehicle resuspension, i.e. material on the road surface resuspended by passing vehicles. It is difficult to derive accurate estimates of this component, but many studies suggest that vehicular resuspension is as important, if not more important, than emissions of PM from the tailpipe (AQEG, 2005). This omission is important in the context of this study, as a number of the measures are focussed on suppressing resuspension.

- The emissions related to brake & tyre wear have been derived from EMEP/CORINAIR which provides emission factors for different vehicle types expressed separately for low and high speeds. There is significant uncertainty associated with these brake & tyre wear emission factors.

- Other uncertainties, albeit probably relatively minor, are that the model takes no account of the uneven distribution of vehicles across the road, in particular the presence of bus lanes, which means that bus emissions occur close to the pavement (at least on one side of the road), nor does it account for gradients.

3.3 Despite the model limitations as set out above, there are consistent messages which arise in terms of source contributions, the local road contribution, and the magnitude of improvement that is required. In addition, the development of a "package" of local measures to reduce PM_{10} emissions and concentrations provides a valuable approach that could be applied to other parts of London that are found to experience poor air quality. For example, the measures identified in this report could be implemented by the boroughs, selecting those interventions most appropriate to local conditions.

4 Monitoring and Forecasting PM_{10}

4.1 As previously described in Section 3, in order to move towards compliance with the limit value, the measures need to focus on those days where the 24-hour mean PM_{10} concentration is above 50 µg/m^3. This does not mean that measures to reduce long-term average PM_{10} concentrations will not be beneficial, but that both short-term and long-term measures need to be considered together, particularly where concentrations are well above the limit value. In order to focus on measures to tackle these 24-hour exceedences it will be essential to be able to reliably forecast the occurrence of these events several days in advance.

4.2 There is only one hotspot with a PM_{10} monitoring site, which is Marylebone Road. This is also the priority site for introducing measures, as the PM_{10} concentrations are higher at this location than any other. This section looks in more detail at the measured PM_{10} concentrations at this site, and also provides a review of the various PM_{10} forecasting services that are available.

Monitoring Data

4.3 When assessing PM_{10} monitoring data, it is essential to define the measurement method that has been used. The EU Directive specifies that measurements of PM_{10} concentrations, for comparison with the limit value, should be carried out using a reference method or equivalent. For practical reasons, the European reference method (a filter-based gravimetric sampler) is not routinely used in UK networks. Historically (including at Marylebone Road) monitoring has been carried out using a TEOM[5] analyser; a default correction factor of 1.3 (TEOM*1.3) was applied to the measured concentrations to provide an indicative "gravimetric equivalent" result. More recently, the TEOM data have been adjusted using the Volatile Correction Method (VCM) which is believed to provide a more accurate representation of "gravimetric equivalent" concentrations. In February 2009, a FDMS[6] analyser was installed at Marylebone Road – this instrument has been shown to be equivalent to the European reference sampler, and no adjustment of the data is required.

4.4 The 2008 and 2009 data for Marylebone Road are shown in Table 2, adjusted using the 1.3 factor and the VCM approach (in 2008), and the VCM approach combined with FDMS data (2009). The number of days above 50 µg/m^3 is dramatically reduced in 2008 from 151 (based on TEOM*1.3) to 58 days (based on VCM). The number of exceedence days in 2009 appears to be broadly similar

[5] Tapered Element Oscillating Microbalance: A type of analyser used for measuring concentrations of PM_{10}.
[6] Filter Dynamics Measurement System: A modified version of the TEOM, that reduces the loss of semi-volatile particles, and has been shown to be equivalent to the European reference method.

to that in 2008 with the TEOM $_{VCM}$, although there are still two winter months data to be included to provide a full year's worth of data.

Table 2: 2008 Monitoring Data at Marylebone Road

Method	2008	2009
	Annual Mean	Period Mean 1 Jan-9 Nov
TEOM x1.3	46.8	-
TEOM $_{VCM}$	38.0	-
TEOM $_{VCM}$ (01/01/09 – 19/03/09) FDMS (20/03/09 – 09/11/09)	-	35.2
	No. Days >50 µg/m^3	No. Days >50 µg/m^3 1 Jan-9 Nov
TEOM*1.3	151	-
TEOM $_{VCM}$	58	-
TEOM $_{VCM}$ (01/01/09 – 19/03/09) FDMS (20/03/09 – 09/11/09)	-	42

4.5 Further analysis of the 24-hour mean PM_{10} exceedences at Marylebone Road is provided in Figures 3 to 5. Figure 3 shows a time series plot of 24-hour mean concentrations in 2008, with the exceedence days (>50 µg/m^3) highlighted above the grey shaded area. The area above the red shaded area contains 35 days>50 µg/m^3 (i.e. just compliant with the limit value). If the exceedence days within the red shaded area were to be eliminated then the limit value would be met. This would require a maximum reduction in the 24-hour mean PM_{10} concentration on these days of about 5 µg/m^3. This should be lower in 2011 than 2008, although recent trends would suggest that this may not occur. It is thus safest to assume the required reduction in 2011 will also be about 5 µg/m^3 on exceedence days.

4.6 It is also a feature of the data that the majority of "exceedence days" for PM_{10} occur during the winter months, with relatively few exceedences during the summer.

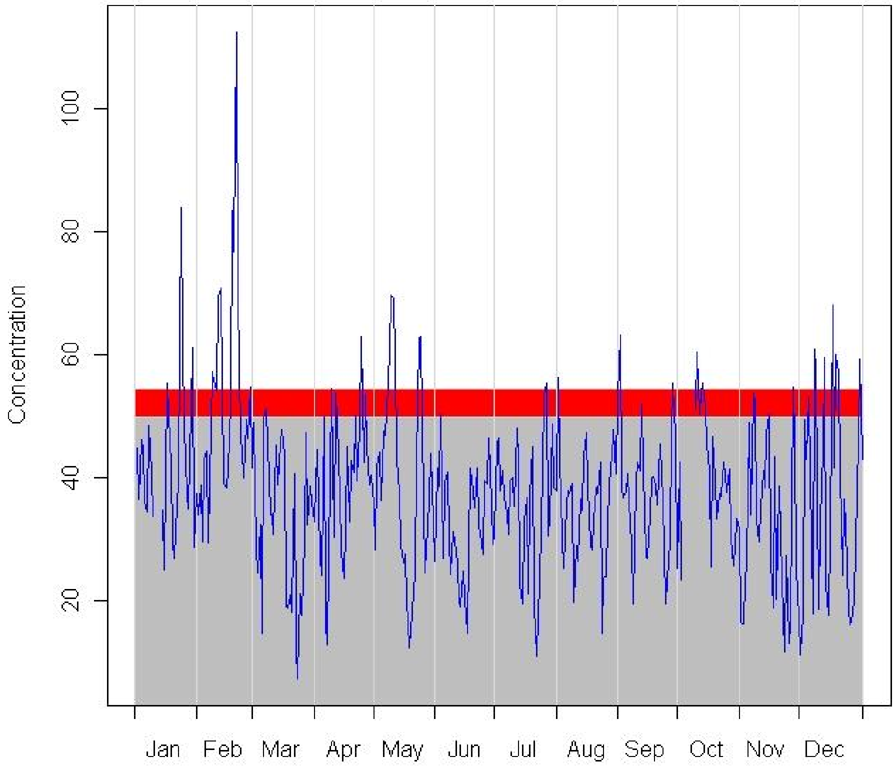

Figure 3: Time series distribution of 24-hour mean PM_{10} concentrations ($\mu g/m^3$, VCM corrected) in 2008 at Marylebone Road

4.7 Figures 4 and 5 provide information on the pattern of exceedences. Figure 4 shows a frequency distribution of the duration of exceedences i.e. 16 exceedences lasted for only 1 day, whilst 14 exceedences occurred over seven, 2-day episodes. Two exceedences lasted for 5 days (i.e. 10 exceedence days), while a further two exceedences lasted for 6 days (i.e. 12 exceedence days); an important conclusion is that 22 exceedences days were associated with episodes that extended over 5 or 6 days.

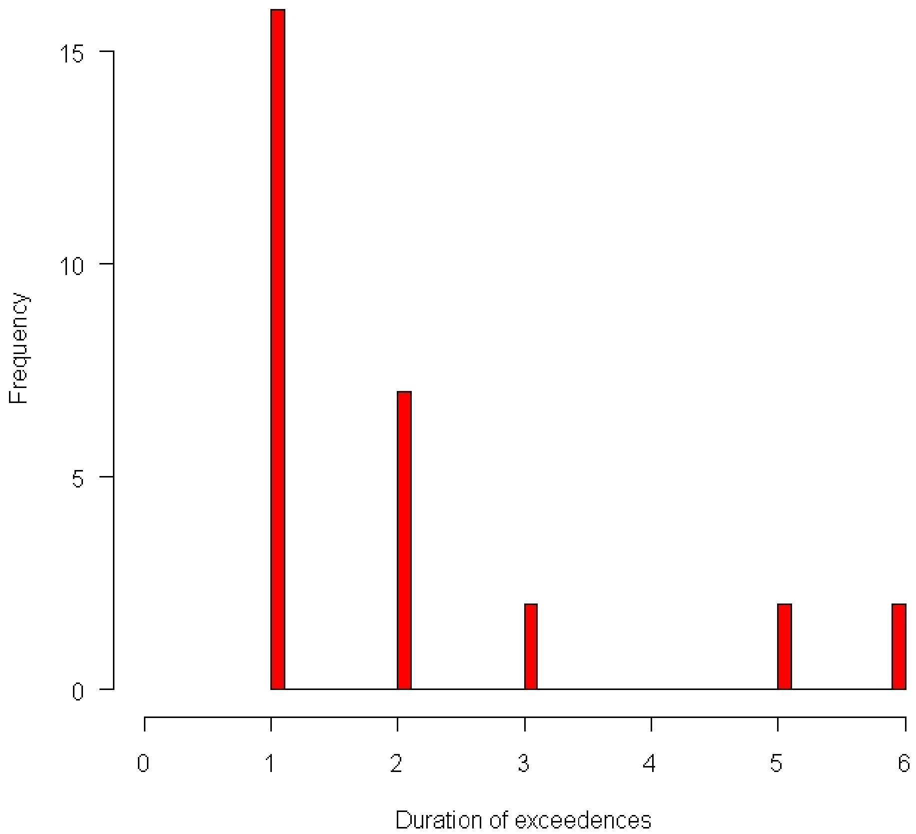

Figure 4: Frequency distribution of the duration of exceedences (24-hr mean PM_{10} concentration > 50µg/m^3, VCM corrected) in 2008 at Marylebone Road

4.8 Figure 5 shows a frequency distribution of the number of days between exceedences. This confirms the information from Figure 4, showing that exceedence days are "clustered" together. This has important implications for the potential use of forecasting to drive the application of local measures.

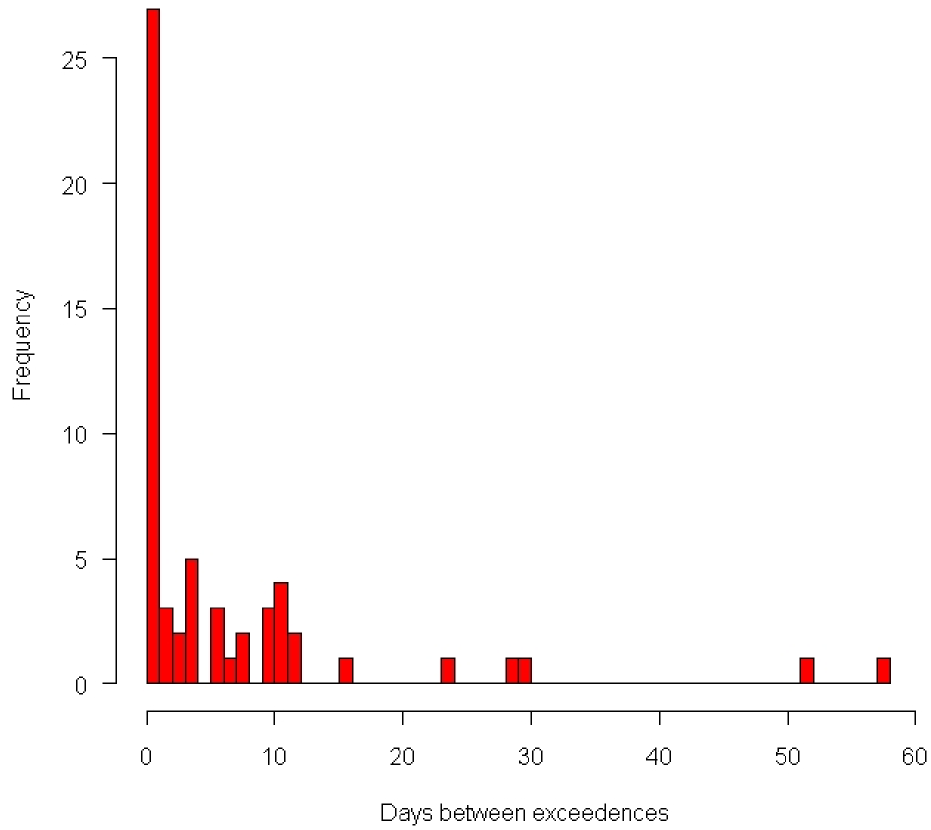

Figure 5: Frequency distribution of the number of days between exceedences (24-hr mean PM_{10} concentration > 50µg/m^3, VCM corrected) in 2008 at Marylebone Road

Forecasting PM_{10} Exceedence Days

4.9 If some local measures are to be successfully targeted at exceedence days, then it will be important to have knowledge in advance of when these days will occur, i.e. to forecast days on which PM_{10} concentrations will exceed 50 µg/m^3. Such forecasting is carried out by various organisations including AEA, CERC and the Met Office; King's College ERG also carries out forecasting, but currently on a very limited basis.

4.10 The forecasts carried out by AEA and CERC are based on the UK Air Pollution Indices published by Defra. These categorise days as being "Low", "Moderate", "High" or "Very High" based on measured pollutant concentrations. For PM_{10}, the thresholds are defined as shown in Table 3:

Table 3: UK Air Pollution Indices for PM_{10}

Band	Index	PM_{10} 24-hour Mean Concentration ($\mu g/m^3$)[1]
LOW	1	0-19
	2	20-40
	3	41-62
MODERATE	4	63-72
	5	73-84
	6	85-94
HIGH	7	95-105
	8	106-116
	9	117-127
VERY HIGH	10	≥128

1. The thresholds given are for gravimetric equivalent concentrations as measured by FDMS
2. Similar bandings are provided for other pollutants. The banding is assigned for the pollutant with the highest Index Level.

4.11 It can be seen from Table 3 that the 24-hour mean exceedence level (50 $\mu g/m^3$) lies within Index Level 3, categorised as "Low". To identify all potential exceedence days it would be necessary to forecast those days with an index of 3 or above.

4.12 The AEA forecasts are carried out on a national basis on behalf of Defra. The principal forecasts are made at 10 am and 2pm each day, for the following 24 hours. The emphasis of the forecasting is to provide health information to sensitive members of the public (e.g. those suffering from asthma or other respiratory problems). Forecasts are therefore provided for "Moderate", High" and "Very High" pollution days.

4.13 An analysis of the performance of the forecasting service has been carried out by AEA, specifically to inform this project (personal communication Andrew Cook, AEA, December 2009). This compared the daily numerical forecast issued for the London urban area with the highest numerical index value attained (i.e. measured) for PM_{10} at three roadside stations in central London (Marylebone Road, Haringey Roadside and Camden Kerbside). The analysis was carried out for two calendar years, 2007 and 2008. This analysis provides some evidence as to how well daily exceedences of the limit value might be predicted, but it is constrained by:

- The forecasting is carried out using the bands described in Table 3. As Band 3 covers the range 42 to 61 µg/m^3, it is not possible to precisely evaluate exceedences of the limit value (50 µg/m^3);

- The daily numerical forecasts are "unspeciated", i.e. they describe the maximum index value forecast for all of the pollutant species monitored (ozone, nitrogen dioxide, PM_{10}, sulphur dioxide and carbon monoxide); to put this in context, on a day when Band 4 is forecast, it is not possible to determine from the historical data which pollutant this referred to;

- The 2007 and 2008 monitoring data for these three sites were based on the use of TEOM analysers. As described in Para 4.4 above, this is likely to have significantly overestimated the number of "exceedence days".

4.14 The analysis has focused on days on which Band 4 or above where forecast (all days were forecast to be Band 3 or above, so use of days with Band 3 or above criterion would not be helpful for this analysis). The following general conclusions can be drawn from the analysis, which covered 730 days over the two-year period:

- 152 days (20.8%) were "False Positive" (i.e. Band 4 or above was forecast, but measured PM_{10} levels were Band 3 or below)

- 53 days (7.3%) were "Correct" (i.e. Band 4 or above was forecast and measured for PM_{10})

- 79 days (10.8%) were "False Negative" (i.e. Band 3 or below was forecast, but measured PM_{10} levels were Band 4 or above)

- 446 days (61.1%) were also "Correct" (i.e. Band 3 or below was forecast and measured for PM_{10}).

4.15 This analysis indicates that forecasting exceedences of the daily mean limit value for PM_{10} is challenging e.g. for 2007 and 2008 combined, there were 205 days forecast at Band 4 or above, of which only 53 days (26%) were correct.

4.16 It must be emphasised that a number of the "measured" indices at Band 4 or above will have been related to ozone episodes, during which time PM_{10} may have been low (Band 3 or below). A small number of other "measured" indices at Band 4 or above were known to be related to Saharan dust events or Bonfire Night celebrations, both of which are very difficult to predict (and of course could not be controlled by local measures). There is potential for the forecasting accuracy to be improved if it were focused specifically to PM_{10}. It is also understood that the AEA forecasting system could easily be adapted to forecast days with PM_{10} of 50 µg/m^3 or above.

4.17 Forecasting is also used to support the airTEXT service, which again provides information to sensitive members of the population. Pollution forecasts are generated twice daily (at 7am and 7pm) by CERC for the rest of the day, and all of the following day. The predictions are provided for individual boroughs, and airTEXT alerts are sent to subscribers on days where “Moderate” air pollution, or above, is predicted over more than one-tenth of the selected zone. Maps are also provided indicating forecast levels for each Index Level.

4.18 The airTEXT service does not publish routine reports on forecasting performance. CERC has been contacted to provide details, but no information had been made available at the time of drafting this report.

4.19 The national air quality forecasts broadcast by the BBC are based on information provided by the Met Office. These forecasts are carried out using the NAME model, and are intended to provide a UK-wide perspective, although within the near- term it is understood that “city level” forecasts are also to be provided.

5 Detailed Hotspot Profiles

5.1 The first stage of developing the targeted local measures was to provide Detailed Profiles for each hotspot, describing the physical attributes, traffic characteristics, and the pollution climate. These Detailed Profiles were compiled from both site visits, examination of digital maps and satellite images, and discussions with King's College ERG who provided information relating to emissions inventories, modelling assessments and source apportionment.

5.2 The *physical attributes* included parameters such as the road width, pavement width, presence of bus lanes, cycle lanes and red routes, pedestrian crossings and junctions, the location and type of vegetation, street canyons etc. The *traffic characteristics* defined the vehicle composition, traffic flows and speeds, and observations regarding congestion. The *pollution climate* was defined by the background contribution, and the source apportionment of the local (road traffic) sources including specific contributions from different vehicle types. A further consideration was the magnitude of PM_{10} reduction required at each hotspot, as this has an important bearing on how many different measures may be necessary.

5.3 Due to the length and/or configuration of the hotspots, each hotspot area was divided into a number of links. These individual links were selected to represent important changes in the characteristics of the hotspot e.g. relating to physical changes (such as the width of the pavement, presence of major junctions etc) or changes in traffic flow and composition. The complete Detailed Profiles for each hotspot are provided in Appendix 1 to this document. Each hotspot is broken down into a series of links, each of similar character. These links are shown in the Maps in Appendix 1. A summary of each Profile is provided below.

Marylebone Road

5.4 The hotspot comprises a section of Marylebone Road over a total length of 890 metres, extending from Baker Street (west) to Osnaburgh Street (east). The road has 3 lanes in each direction (including a bus lane), separated by a central reservation. The pavement width varies considerably from about 3 metres (north side) occasionally extending to 9 metres (south side). There are a number of major and minor junctions. There is mature tree planting along many sections of the road. The buildings along the road make it canyon-like along most of its length. The traffic composition and source apportionment data are summarised below.

Table 4: Traffic Characteristics – Marylebone Road

Link	Traffic Speed (km/hr)	Traffic Flow (AADT)	Traffic Composition (%)							Features Causing Congestion
			Motorcycles	Taxis[a]	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	25	66542	5.5	10.3	64.1	3.4	13.2	3.1	0.4	Bus stop on northern side; Tube station on northern side, taxi rank in central reservation
B	25	66542	5.5	10.3	64.1	3.4	13.2	3.1	0.4	Several bus stops
C	25	66542	5.5	10.3	64.1	3.4	13.2	3.1	0.4	Bus Stops
D	25	66542	5.5	10.3	64.1	3.4	13.2	3.1	0.4	n/a
E	23	65658	5.4	20.8	53.9	1.1	0.5	17.8	0.5	Confusing junction
F	23	65658	5.4	20.8	53.9	1.1	0.5	17.8	0.5	Bus stop

[a] Private Hire Vehicles are excluded

Table 5: Pollution Climate – Marylebone Road

Link	Background Contribution (µg/m³)[a]	Road Transport Contribution[b] (µg/m³)[a]	Road Transport Source Apportionment[c] (%)							Proportion from Tyre & Brake Wear (%)
			Motorcycles	Taxis	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	23.1	15.6	3.7	18.3	36.5	8.8	20.0	11.0	1.8	50.2
B	23.1	15.6	3.7	18.3	36.5	8.8	20.0	11.0	1.8	50.2
C	23.1	15.6	3.7	18.3	36.5	8.8	20.0	11.0	1.8	50.2
D	23.1	15.6	3.7	18.3	36.5	8.8	20.0	11.0	1.8	50.2
E	23.1	15.6	2.3	27.1	20.5	2.0	0.5[c]	45.7[d]	1.8	39.6
F	23.1	15.6	2.3	27.1	20.5	2.0	0.5[c]	45.7[d]	1.8	39.6

[a] Contributions to annual mean PM_{10} concentrations.
[b] Refers to the average kerbside concentration along all the links. Contribution in this case is based on modelling the traffic mix on Links E and F (which is worst case).
[c] Source apportionment for combined exhaust emissions and tyre & brake wear.
[d] The source apportionment for Links E and F is based on old data – it is not certain how accurate the LGV and HGV contributions are.

5.5 Specific issues that may influence the choice and suitability of measures include:

- Traffic congestion, giving rise to stop-start driving, is exacerbated by the number of signalled junctions, and bus stops (when buses are stopped, taxis pull out into the right-hand lane);
- The road is bounded by tall buildings on both sides, forming a street canyon;
- There are low level railings along many sections of the central reservation and pavements;
- The canopy height of the mature trees is about 3 metres, and so likely to be of limited benefit in reducing PM_{10} emissions from the road;

- Emissions from road traffic on Marylebone Road account for 40% of the total annual mean PM_{10} concentration at the kerbside;
- The most significant vehicle exhaust emissions contributions are from cars, LGVs and taxis;
- Non-exhaust emissions (brake & tyre wear) account for 50% of the road transport contribution;
- Marylebone Road is the only hotspot that has a monitoring station – in 2008 there were 58 days on which PM_{10} concentrations above 50 µg/m^3 were recorded (see Figure 3).

Euston Road

5.6 The hotspot comprises a section of Euston Road, with a total length of about 570 metres, extending from the junction with Upper Woburn Place (west) to the junction with St. Pancras Road (east). The road varies between 5 and 7 lanes, including occasional bus lanes; the east and west carriageways are often separated by a central reservation. The pavement width varies between about 2.5 to 5 metres. There are a number of major junctions. Mature tree planting is principally confined to the western section of the link. The buildings along the road make it canyon-like. The traffic composition and source apportionment data are summarised below.

Table 6: Traffic Characteristics – Euston Road

Link	Traffic Speed (km/hr)	Traffic Flow (AADT)	Traffic Composition (%)							Features Causing Congestion
			Motorcycles	Taxis[a]	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	18	50794	6.6	16.5	55.0	5.4	11.5	4.2	0.8	Junctions. Bus lane.
B	18	50794	6.6	16.5	55.0	5.4	11.5	4.2	0.8	End of bus lane. Bus lane
C	18	50794	6.6	16.5	55.0	5.4	11.5	4.2	0.8	Traffic lights. Entire section of road stationary when red.
D	18	50794	6.6	16.5	55.0	5.4	11.5	4.2	0.8	Traffic lights. Entire section of road stationary when red.
E	18	50794	6.6	16.5	55.0	5.4	11.5	4.2	0.8	N/A
F	18	50794	6.6	16.5	55.0	5.4	11.5	4.2	0.8	N/A
G	18	50794	6.6	16.5	55.0	5.4	11.5	4.2	0.8	Junction

[a] Private Hire Vehicles are excluded

Table 7: Pollution Climate – Euston Road

Link	Background Contribution ($\mu g/m^3$)[a]	Road Transport Contribution[b] ($\mu g/m^3$)[a]	Road Transport Source Apportionment[c] (%)							Proportion from Tyre & Brake Wear (%)
			Motorcycles	Taxis	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	20.4	10.7	3.4	29.2	25.0	11.8	14.8	12.6	3.3	41.0
B	20.4	10.7	3.4	29.2	25.0	11.8	14.8	12.6	3.3	41.0
C	20.4	10.7	3.4	29.2	25.0	11.8	14.8	12.6	3.3	41.0
D	20.4	10.7	3.4	29.2	25.0	11.8	14.8	12.6	3.3	41.0
E	20.4	10.7	3.4	29.2	25.0	11.8	14.8	12.6	3.3	41.0
F	20.4	10.7	3.4	29.2	25.0	11.8	14.8	12.6	3.3	41.0
G	20.4	10.7	3.4	29.2	25.0	11.8	14.8	12.6	3.3	41.0

[a] Contributions to annual mean PM_{10} concentrations.
[b] Refers to the average kerbside concentration along all the links.
[c] Source apportionment for combined exhaust emissions and tyre & brake wear.

5.7 Specific issues that may influence the choice and suitability of measures include:

- Traffic congestion, which gives rise to stop-start driving, is exacerbated by the number of signalled junctions;
- The road is bounded by tall buildings on both sides, forming a street canyon;
- There are low level railings along many sections of the central reservation and pavements;
- The canopy height of the mature trees is about 3 metres, and so likely to be of limited benefit in reducing PM_{10} emissions from the road;
- Emissions from road traffic on Euston Road account for 34% of the total annual mean PM_{10} concentration;
- The most significant vehicle exhaust emissions are from taxis;
- Non-exhaust emissions (brake & tyre wear) account for 41% of the road transport contribution.

Marble Arch

5.8 The hotspot comprises the gyratory system that lies to the north of Park Lane, and west of Oxford Street. The road varies between 4 and 5 lanes, with occasional bus lanes or extended bus stop areas. The pavement width varies from about 1 to 5 metres, although there are some areas with no pavement. There are park areas and mature trees alongside the southern and western sides of the site. The traffic composition and source apportionment data are summarised below.

Table 8: Traffic Characteristics – Marble Arch

Link	Traffic Speed (km/hr)	Traffic Flow (AADT)	Traffic Composition (%)							Features Causing Congestion
			Motorcycles	Taxis[a]	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	Large number of buses, many of which were stopping.
B	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	Large number of buses
C	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	Large number of buses
D	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	Large number of buses
E	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	Large number of buses
F	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	Roadworks
G	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	-
H	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	-
I	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	-
J	31	92113	3.6	18.0	61.2	5.8	8.4	2.4	0.6	Bus stop. Buses waiting for long periods but very little traffic.

[a] Private Hire Vehicles are excluded

Table 9: Pollution Climate – Marble Arch

Link	Background Contribution (µg/m³)[a]	Road Transport Contribution[b] (µg/m³)[a]	Road Transport Source Apportionment[c] (%)							Proportion from Tyre & Brake Wear (%)
			Motorcycles	Taxis	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
B	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
C	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
D	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
E	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
F	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
G	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
H	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
I	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6
J	19.8	9.1	2.1	30.0	30.8	13.7	12.3	8.3	2.8	45.6

[a] Contributions to annual mean PM_{10} concentrations.
[b] Refers to the average kerbside concentration along all the links.
[c] Source apportionment for combined exhaust emissions and tyre & brake wear.

5.9 The identified hotspot includes a bus-only lane that bisects the gyratory system (identified as link "J" in the Detailed Profile). However, it is important to note that the model has assumed a uniform traffic composition across all links, and does not take specific account of the bus lane (where there is a substantially reduced flow). Thus, it is not considered likely that there will be exceedences across this central area, and for the purpose of developing measures, the central bus link has been assigned a lower priority.

5.10 Specific issues that may influence the choice and suitability of measures include:

- Traffic congestion, which gives rise to stop-start driving, is exacerbated by the large number of buses;
- The junction is open, with buildings set well back;
- There are low level railings along some sections of the pavements;
- The canopy height of the mature trees is about 3 metres, and so likely to be of limited benefit in reducing PM_{10} emissions from the road;
- Emissions from road traffic on Marble Arch account for 31% of the total annual mean PM_{10} concentration;
- The most significant vehicle exhaust emissions are from taxis;
- Non-exhaust emissions (brake & tyre wear) account for 46% of the road transport contribution.

Tower Hill

5.11 The hotspot comprises of two road links to the north of the Tower of London. The first link extends from the western boundary of Tower Hill Terrace to the main junction at The Minories, and is approximately 240 metres in length (identified as links "A" and "B" in the Detailed Profile). The second link includes Shorter Street. However, it is important to note that the model has assumed a uniform traffic composition across all links at Tower Hill and does not take account of the 2-lane, one-way system at Shorter Street (where there is a substantially reduced flow). It is not considered likely that there will be exceedences along Shorter Street, and for the purpose of developing measures, this link has been assigned a lower priority. Apart from Shorter Street, this hotspot has a generally open setting with two lanes of traffic in each direction.

Table 10: Traffic Characteristics – Tower Hill

Link	Traffic Speed (km/hr)	Traffic Flow (AADT)	Traffic Composition (%)							Features Causing Congestion
			Motorcycles	Taxis[a]	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	24 (ranging from 15 to 33)	52624	8.8	15.3	52.8	1.8	15.6	5.0	0.6	Signalised pedestrian crossing; on day of site visit an ice cream van was parked on south carriageway red route approx. 10m from crossing blocking nearside lane
B	24 (ranging from 15 to 33)	52624	8.8	15.3	52.8	1.8	15.6	5.0	0.6	Signalised junction on east approach to Tower Bridge. Traffic queuing back entire length of link on red light
C	24 (ranging from 15 to 33)	52624	8.8	15.3	52.8	1.8	15.6	5.0	0.6	Signalised junction at west end of Shorter Street - no obvious congestion beyond 5-10 vehicles.

[a] Private Hire Vehicles are excluded

Table 11: Pollution Climate – Tower Hill

Link	Background Contribution ($\mu g/m^3$)[a]	Road Transport Contribution[b] ($\mu g/m^3$)[a]	Road Transport Source Apportionment[c] (%)							Proportion from Tyre & Brake Wear (%)
			Motorcycles	Taxis	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	20.5	10.7	5.5	24.7	27.0	4.4	20.4	15.6	2.4	46.4
B	20.5	10.7	5.5	24.7	27.0	4.4	20.4	15.6	2.4	46.4
C	20.5	10.7	5.5	24.7	27.0	4.4	20.4	15.6	2.4	46.4

[a] Contributions to annual mean PM_{10} concentrations.
[b] Refers to the average kerbside concentration along all the links.
[c] Source apportionment for combined exhaust emissions and tyre & brake wear.

5.12 Specific issues that may influence the choice and suitability of measures include:

- Traffic congestion, which gives rise to stop-start driving, is exacerbated by the signalled junctions and pedestrian crossings. Although the road is a designated “red route” there was an ice cream van parked close to the pedestrian crossing, blocking the inside lane;
- The area is generally open, with buildings set well back;
- There are low level railings along some sections of the pavements;

- The canopy height of the mature trees is about 3 metres, and so likely to be of limited benefit in reducing PM_{10} emissions from the road
- Emissions from road traffic on Tower Hill account for 34% of the total annual mean PM_{10} concentration;
- The most significant vehicle exhaust emissions are from taxis and LGVs;
- Non-exhaust emissions (brake & tyre wear) account for 46% of the road transport contribution.
- The Tower of London is classified as a World Heritage site, and infrastructure modifications will need very careful consideration.

Victoria Embankment

5.13 The hotspot comprises of the section of the Victoria Embankment from Charing Cross Bridge to the eastern boundary of Temple Place, extending over about 920 metres. The road is four lanes wide with a central reservation. The pavement width varies from about 5 metres (north side) to over 6 metres (south side). There are four major junctions which are all signalled. There are mature trees planted along both sides, which form a canopy over the road. The southeastern aspect is open to the River Thames. Buildings are set well back from the road on the northwestern side.

Table 12: Traffic Characteristics – Victoria Embankment

Link	Traffic Speed (km/hr)	Traffic Flow (AADT)	Traffic Composition (%)							Features Causing Congestion
			Motorcycles	Taxis[a]	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	32	74023	4.9	25.4	59.8	1.2	6.9	1.5	0.1	Signalised junctions and pedestrian crossing. No significant congestion noted during site visit[b]
B	32	74023	4.9	25.4	59.8	1.2	6.9	1.5	0.1	Signalised junctions and pedestrian crossing. Main congestion at junction with Savoy St.
C	32	74023	4.9	25.4	59.8	1.2	6.9	1.5	0.1	Road works close to Charing Cross bridge caused major congestion on day of site visit - tailback of several hundred metres.

[a] Private Hire Vehicles are excluded
[b] Site visit conducted mid-afternoon

Table 13: Pollution Climate – Victoria Embankment

Link	Background Contribution (µg/m³)[a]	Road Transport Contribution[b] (µg/m³)[a]	Road Transport Source Apportionment[c] (%)							Proportion from Tyre & Brake Wear (%)
			Motorcycles	Taxis	Cars	Buses & Coaches	LGV	Rigid HGV	Artic HGV	
A	20.0	11.5	3.6	42.6	34.7	3.1	10.0	5.5	0.4	46.6
B	20.0	11.5	3.6	42.6	34.7	3.1	10.0	5.5	0.4	46.6
C	20.0	11.5	3.6	42.6	34.7	3.1	10.0	5.5	0.4	46.6

[a] Contributions to annual mean PM_{10} concentrations.
[b] Refers to the average kerbside concentration along all the links.
[c] Source apportionment for combined exhaust emissions and tyre & brake wear.

5.14 Specific issues that may influence the choice and suitability of measures include:

- Congestion, which gives rise to stop-start driving, appears to be limited to peak-hour periods, and to a section of the westbound carriageway close to Charing Cross bridge (associated with the coach parking area and current roadworks);
- The area to the north is generally open, with buildings set well back; the southern carriageway is bounded by the river;
- There are low level railings along some sections of the pavements;
- The canopy height of the mature trees is about 3 metres, and so likely to be of limited benefit in reducing PM_{10} emissions from the road;
- Emissions from road traffic on Victoria Embankment account for 37% of the total annual mean PM_{10} concentration;
- The most significant vehicle exhaust emissions are from taxis;
- Non-exhaust emissions (brake & tyre wear) account for 47% of the road transport contribution.

6 Evaluation of Local Measures

6.1 A detailed review of potential measures that could be applied to reduce PM_{10} emissions and/or concentrations has been carried out, and is set out in full in Appendix 2 of this document. This Chapter provides a summary of that review, and the main conclusions that have been drawn from it. Also included are a number of measures not identified within the literature review.

6.2 A wide range of local measures for application within the hotspots have been identified[7]. They fall into to two groups, one designed to reduce emissions of PM_{10}, the other to limit exposure to PM_{10} by reducing concentrations and/or increasing the separation distance between the source and receptor. The following is a summary of the measures:

<u>Reducing Source Strength (Emissions)</u>

- Road cleaning (sweeping and washing)
- Vehicle cleaning
- Dust suppressants
- Traffic management
    - Measures which influence vehicle operation (e.g. traffic calming, traffic signals)
    - Car clubs and car sharing
    - Cycle hire schemes
    - Shared space and level surfaces
    - Home Zones
    - Development of mixed priority routes
    - Car-free days
    - Access restrictions
    - Effective policing of red routes
    - Creation of 'indented' bus stops
    - Extension of the Congestion Charge Zone
    - Deployment of the cleanest buses on routes through the hotspots
    - Deployment of the cleanest taxis on routes through the hotspots
- Other measures to control emissions
    - Engine switch off
    - Active asphalt
    - Surfaces with reduced rolling resistance

[7] London-wide measures are not included within this review, even though they would contribute to improving air quality within the hotspots.

Limiting Exposure

- Barriers and tunnels
    - o Barriers with filtration
    - o Tunnels and lightweight canopies
    - o Pollution control in tunnels and canopies
- Vegetation
    - o Trees
    - o Green walls
    - o Green barriers
- Other measures to limit exposure
    - o Cycle lanes
    - o Electrostatic precipitators

6.3 The various measures have then been tentatively rated according to a series of factors. This follows on from the assessments provided by Boulter *et al.* (2007a) and Reeves *et al.* (2008). The evaluation of "acceptability" has been based on professional judgement of potential overall political and public reaction to the measure. The results of this evaluation are provided in Table 14.

6.4 Consideration has been given to the magnitude of the reduction in PM_{10} emissions/concentrations that the measure could be expected to achieve, and how long the reduction could last. The full list of factors which have been taken into account in the evaluation is:

- The size of the reduction in PM_{10} emissions/concentrations that the measure might achieve;
- How long the impact on PM_{10} might last;
- Technical feasibility;
- Timescale for implementation;
- Cost;
- Any other environmental impacts, either positive or negative (e.g. noise, greenhouse gas emissions);
- Road safety;
- Impact on travel times;
- Public appeal;
- Political/public acceptability.

6.5 For each measure an indication of its *general* suitability for application at hotspots in London, based on the criteria above, is provided by colour-coding in Table 14 as follows:

- Dark Green – likely to be very suitable;
- Light Green – likely to be suitable;

- Orange – potentially suitable;
- Red – likely to be unsuitable (for a variety of possible reasons).

6.6 Where possible, quantitative evidence of the effects of these measures has been provided. However, apart from a few exceptions (*e.g.* road sweeping/washing and the use of de-icing compounds), the data are rather limited. Furthermore, the reported effects are likely to be rather site-specific, and may not be directly transferable to other locations. Consequently, based on current information and understanding, this assessment is largely subjective. The findings of the review, and the scores in the evaluation, are summarised below.

Summary of Potential Measures

Road Sweeping and Wet Cleaning

6.7 The evidence currently indicates that road sweeping (without water) removes large particles efficiently but, even with modern vacuum-assisted sweepers, is not a particularly effective means of reducing PM_{10} concentrations. Studies have yielded rather variable results, and it seems that only a small decrease in PM_{10} is possible, which may in some instances become a small increase, with any effect being relatively short-lived (of the order of hours). However, road sweeping may have a beneficial effect on air quality over the long term if it can remove particles that may subsequently evolve into PM_{10} with weathering and mechanical abrasion, although there is currently little evidence to support this. Nevertheless, road sweeping should be technically undemanding, and if sweepers could be further developed and proven to be effective at reducing PM_{10} concentrations, then it ought to be possible to implement them on a fairly short timescale and at relatively modest cost. Given the absence of suitable equipment, and the amount of development and testing required, this measure is not considered worthy of further attention for this project. However, the development and certification of efficient sweepers is encouraged for future use.

6.8 The extent to which wet cleaning has an effect on combating PM_{10} is dependent on the technique used and environmental factors which determine dispersion. Some trials have indicated potential benefits of wet cleaning, but the evidence is mixed and again the duration of the effect appears to be rather short. However, wet cleaning measures are relatively inexpensive and easy to implement. Some studies have also suggested that the laying of a PCM (pervious coated macadam) surface might increase the effectiveness of wet cleaning at reducing PM_{10}.

6.9 Clearly, both sweeping and washing programmes would have to be conducted during periods when traffic flows are low, so that any disruption to the traffic is minimised.

Vehicle Washing

6.10 The regular washing of vehicle wheels, wheel arches, chassis, bodywork and brakes could also reduce the amount of material deposited on the road, and hence reduce resuspension. Vehicle washing is also fairly undemanding technically, although changes to the infrastructure would be required to allow for the routine washing of vehicles. For example, washing bays could be constructed at larger fuel retail outlets. It would nevertheless be difficult to make such a measure mandatory, other than for selected types of vehicle (e.g. buses and taxis). There is no evidence as to how effective such a measure could be, especially if it only applied to a fraction of the vehicles on the road. It should be noted that vehicle washing is usually required for construction sites, and certain other industrial activities, and measures to enforce this strictly, and with the latest equipment, for operations within 1 km of the hot-spots would potentially be beneficial, as they would limit the track-out of dust and dirt onto the public roads. Control of construction activities that might give rise to off-site impacts is the responsibility of the local authority. It would be possible for the Mayor to encourage the relevant local authorities to enforce strict controls on dust track-out for developments within 1 km of hotspots by clearly identifying the 1 km zone around the hotspots on maps to be supplied to the local authority, together with a briefing on the measures that are expected to be applied, thereby reinforcing the message within the Mayor’s best practice guidance on the control of dust and emissions from construction and demolition activities (GLA, 2006).

Dust Suppressants

6.11 There is reasonably convincing evidence from pilot studies that the use of dust suppressants could make a significant difference to roadside PM concentrations on timescales of hours to days. However, further work is required to assess the possible adverse impacts on the environment, human health and road safety. For example, one concern is that dust suppressants can reduce road surface friction. There is also the possibility that suppressants may create an impervious surface, resulting in increased run-off and hydrological impacts during periods of rainfall. Whilst evidence from European pilot studies has indicated no increase in accident rates, before dust suppressants can be used extensively on UK roads there is therefore a need for further investigation (which will be explored in the Pilot Programmes).

Traffic Management

6.12 Many different types of traffic management measure are available, and a number have the potential to reduce emissions at source; however, the effects depend largely upon the type and characteristics of the scheme (e.g. extent, intensiveness or uptake). It is likely that the most effective measures will be those which restrict access to all vehicles, or to specific vehicle types at certain times of day. Restricting access to and from certain road links may also be beneficial in easing congestion. However, it is possible that new pollution hotspots could be created if the traffic is merely displaced and the demand for travel is not addressed. The following specific traffic management measures have been considered as potential options:

- *Shared spaces:* evidence from a scheme on the Ashford Ring Road indicates that shared space schemes are applicable to roads with relatively high traffic flows. There are also plans for shared space schemes in London, including in Exhibition Road and Camden High Street. There is a lack of evidence on their ability to reduce PM_{10} concentrations, although they can be expected to do so. There are, nevertheless, other significant environmental and amenity benefits associated with them, and their application to certain types of hotpots in London should be considered.

- *Effective policing of red routes:* all of the identified hotspots are within designated red routes, but observations at Tower Hill identified a parked ice cream van which was causing significant traffic congestion. This measure should be taken forward;

- *Creation of 'indented' bus stops:* buses stopping in the inside lane cause traffic behind to have to pull out, adding to congestion. This is even the case where there is a dedicated bus lane, as there are still substantial traffic flows in these lanes (due to the high proportion of buses and taxis). This measure is considered worthy of further investigation;

- *Extension of the Congestion Charge Zone:* The congestion charge scheme in London was primarily designed to reduce traffic flows and congestion within the central London area, rather than to deliver air quality improvements. Nonetheless, congestion is believed to significantly contribute to PM_{10} emissions along some of the identified hotspots and the congestion charge scheme does incentivise the use of low emission vehicles through charge exemption. Extension of the zone to include both Marylebone Road and Euston Road would therefore be expected to be beneficial in air quality terms, but there would need to be an assessment of impacts along alternative routes for vehicles avoiding the congestion charge zone. This measure is considered worthy of further investigation;

- *Deployment of the cleanest buses:* The draft MAQS identifies the potential of deploying buses with the cleanest emissions through hotspot areas. This measure has the potential for a positive impact, although the contribution of bus emissions to the modelled exceedences is relatively small. The London Transport bus fleet is already based on Euro V buses, however new hybrid buses are being introduced into the London fleet. It would therefore be sensible to prioritise the use of these buses on routes passing through the hotspot areas. This measure should be taken forward and is already identified within the MAQS..

- *Deployment of cleaner taxis:* The draft MAQS seeks to accelerate the take-up of cleaner, new vehicles into the taxi fleet by introducing age-based limits for taxis, and a requirement for all new taxis to meet a minimum of Euro 4 standard from 2012. The MAQS also references the "Green NYC" logo that is awarded to taxis in New York that comply with cleaner standards. Emissions from taxis make a substantial contribution to the modelled exceedences at all hotspots, and (in line with the re-routing of cleaner buses identified above) it would be beneficial to prioritise the use of cleaner taxis through the hotspot areas. This could be based on a minimum emissions standard, enforced via an extension of the CCZ ANPR cameras or a "green labelling" system as used in New York.

Reducing Idling

6.13 In large cities, where traffic congestion is often widespread, engines running at idle can be a significant source of air pollution. Whenever it is safe to do so, switching off the engine should generally reduce fuel consumption and emissions. The legislation[8] to allow boroughs to enforce no-idling already exists, however, effective and consistent enforcement is difficult. The draft MAQS identifies the establishment of a "no-idling" zone throughout London with a focus on buses, coaches and taxis, and with an emphasis on problem areas, such as schools. It is noted that some new cars automatically switch off when stationary.

Active Asphalt

6.14 The development of "active asphalt" is being carried out by Shell Bitumen, and has only been subject to limited investigation so far. However, at this time it is understood that the results from these initial trials have not proved promising for PM reduction, and Shell is not currently marketing the product. It is therefore excluded from further consideration. .

Surfaces with Reduced Rolling Resistance

6.15 The use of road surface materials designed to reduce the rolling resistance of vehicles can be beneficial for fuel consumption and as such would be expected to be beneficial for reducing PM_{10} exhaust emissions. The potential disadvantage is a trade-off with surface friction and stopping distances. This measure offers an attractive option as it could be relatively easily applied to sections of London streets as part of the routine maintenance and replacement of the road surface. It is therefore considered worthy of further investigation.

[8] **Road Traffic (Vehicle Emissions) (Fixed Penalty) Regulations 2001**

Tunnels and Barriers

6.16 Road tunnels and various forms of barrier could be used to reduce exposure to vehicle emissions within the hotspots. Tunnels would not however be practical within the timescale for this project, and may have the disadvantage of potentially increasing exposure to air pollutants within the vehicles on the road, unless tunnel ventilation/filtration systems are installed. Barriers and lightweight canopies offer more practical options, but would give rise to major issues of severance, particularly if applied within canyon-like streets.

6.17 The introduction of a noise barrier can lead to reduced concentrations of PM immediately downwind of the barrier, but may be less effective away from the barrier. The combination of a noise barrier and vegetation can lead to additional benefits, but the implications for amenity and aesthetics would also need to be considered in densely populated areas of Central London. Further research is also needed to identify the effects of roadside structures under varying wind and topographic conditions, and further evaluation of numerical models may be necessary. The option of using low barriers (say of 1 m height) between the traffic and the pavement could be more acceptable than higher (and probably more effective) barriers in London, but no studies have been identified that assess the impact of low barriers in reducing PM_{10} concentrations. This measure may conflict with the desire to reduce barriers (fences) within the street environment, to make the setting more pedestrian friendly.

Vegetation

6.18 Vegetation could potentially be used to reduce roadside concentrations. However, to be most effective the vegetation would have to lie between the traffic source of PM and the exposure on the pavement. This would require the use of vegetative barriers alongside the edge of the road. The use of trees to reduce concentrations would be unlikely to be effective immediately alongside the road and there may even be an adverse effect on roadside concentrations if the trees create tunnel like conditions, reducing dispersion in the immediate road environment. Planting of vegetative traps between the road and the pavement may have a minor effect on roadside concentrations, in particular for the larger sized resuspension component of PM. However, the effects are not well known, and large-scale planting is not a realistic proposition for urban areas where exceedences of PM_{10} limit values are the most common; there are also potential safety issues associated with obscuring drivers views of pedestrians and other objects, and account will need to be taken of the potential increase in biogenic VOC emissions, which leads to increased ozone formation.

6.19 The use of green walls on the facades of roadside buildings could be a more practical way of potentially reducing PM_{10} concentrations. Whilst the vegetation does not provide a barrier between the road and the pavement, such schemes may be effective in street canyons, such as Marylebone Road, where the recirculation of polluted air has been demonstrated. Such schemes could also be beneficial in removing nitrogen dioxide from the atmosphere, depending on the species of vegetation selected.

Electrostatic Precipitators

6.20 Electrostatic precipitators (ESP) systems have been demonstrated as being effective in removing particles from the atmosphere, with varying efficiency. Whilst many of these systems are targeted at installation within tunnels, the most promising system appears to be the "fine dust reduction system" that has been developed in the Netherlands for use in both tunnels and roads. This system creates an "electrostatic roof" over the road, which charges the particles which are subsequently removed by passive screens. Further investigation into the effectiveness of these systems in canyon-like roads of London is recommended.

Cost Implications of Measures

6.21 The cost implications of measures are difficult to estimate, as they are largely dependent upon the scale of application and location-specific factors. For the use of $MgCl_2$ dust suppressant in Norway, Aldrin et al. (2007) give a cost of 130 Euro per km for each application. For road sweeping, a cost of 210 Euro per km per treatment is given, and it is stated that washing is more expensive. Another issue is that the costs of the various options will be borne by different organisations and bodies. The costs of sweeping and washing roads would generally be borne by local authorities. Vehicle washing and the use of dust suppressants may be the responsibility of both local authorities and commercial organisations. Similarly, the effects of measures on road safety, travel times, public appeal and general acceptability will be very much depend on the type of measure used and its extent.

Recommendations for Pilot Programmes

6.22 Based on the review and evaluation presented here, measures are proposed for general consideration in the Pilot Programmes. Whether individual measures are suitable for specific hotspots is an issue that is considered in Chapter 7 related to the Pilot Programmes, where the Detailed Profiles for each location are also taken into account. The measures are:

- *Washing the road surface* (*e.g.* using high-pressure jets). This is a measure which can be applied relatively easily and frequently, and appears to have some small benefits in terms of PM_{10}-reduction. The most cost-effective approach might be to use this measure to reduce the possibility of exceedence of the daily mean PM_{10} standard, by washing roads immediately before periods when high PM_{10} concentrations are forecast. The main drawbacks of this approach would be possible disruption to traffic (it is assumed that the whole carriageway would be washed), and the difficulty of applying the approach in cold weather (risk of ice formation).

- *Application of dust suppressants*. This is a measure which is not technically demanding. Nor are the costs likely to be prohibitive. It is a measure which would be well suited to addressing short-term concentration peaks, and consideration would need to be given to the timing of application (both in terms of the day, and the time of day). Again, there would probably be some disruption to traffic.

- *Low barriers with filters*. Noise barriers can lead to reductions in pollutant concentrations, but both the design and the deployment (location) affect the results. The implications for, amenity and aesthetics would also need to be considered. At present, it is unclear whether sufficient research is available to enable such decisions to be made in relation to the hotspots in London. On the other hand, the data from the EU SPAS project has shown that the use of filter elements reduced PM_{10} caused by resuspension. Further testing of low barriers – which would be more acceptable in London – combined with filter elements would be beneficial.

- *Adjustment or removal of traffic lights.* Simple cost-effective measures that can effectively smooth the traffic flow and reduce congestion including average speed enforcement cameras or the programming of responsive traffic light systems such as SCOOT to smooth flow along the hotspot roads, or even the removal of traffic lights in some situations, would be suitable for a number of the hotspot locations in central London. This would be consistent with the commitment in the draft MAQS to smooth traffic flows through better traffic management.

- *Effective policing of red routes:* All of the identified hotspots are within designated red routes, but observations at Tower Hill identified a parked ice cream van which was causing significant traffic congestion;

- *Creation of "indented" bus stops:* Buses stopping in the inside lane causes traffic behind to have to pull out, thereby introducing unnecessary decelerations and accelerations of traffic, i.e. reducing the smooth flow of traffic. This is even the case where there is a dedicated bus lane, as there are still substantial traffic flows in these lanes (due to the high proportion of buses and taxis).

- *Extension of Congestion Charge zone:* Congestion is believed to significantly contribute to PM_{10} emissions along some of the identified hotspots, and extension of the zone to include both Marylebone Road and Euston Road would be expected to be beneficial in air quality terms, although this could give rise to problems with diversion of traffic.

- *Deployment of cleaner buses:* Although buses make a relatively small contribution to PM emissions, deployment of new hybrid buses along these hotspots would be beneficial. This measure has been identified within the draft MAQS.
- *Deployment of cleaner taxis:* Taxis make a substantial contribution to PM emissions, and deployment of newer, cleaner taxis along these hotspots would be very beneficial. The potential for introducing this measure should be considered.
- *Shared spaces.* This is a measure which is potentially attractive for hotspot areas which are sensitive to infrastructure changes e.g. due to conservation restrictions. Whilst unproven in terms of PM_{10} reduction, shared space schemes potentially offer other environmental and amenity benefits.
- *Access restrictions.* Measures to control and/or limit access to and from sections of main road (e.g. by closure of side roads) could also be effective in relieving congestion, although care would need to be taken to ensure that congestion was not increased in other areas.
- *Cycling/walking days.* These are aimed at promoting the use of cycling and walking in London. By restricting access to vehicular traffic on certain days, usually weekends, this provides an improved and safer environment for both pedestrians and cyclists. Whilst unproven in terms of PM_{10} reduction, such restrictions could potentially offer other environmental and amenity benefits, and are considered suitable for targeting specific hotspots.
- *Reducing idling.* The assignment of these hotspot areas as priority locations for the enforcement of existing powers to enforce no idling, and to be taken forwards in new measures established by the Mayor would be beneficial.
- *Modified Road Surfaces (Reduced Rolling Resistance).* The use of road surface materials designed to reduce the rolling resistance of vehicles is expected to be beneficial for reducing PM_{10} exhaust emissions, and could be relatively easily incorporated into maintenance and resurfacing programmes. It is a measure which should be considered.
- *Vegetation.* The installation of major vegetative barriers between the carriageway and the pavement would appear to be very restricted for the hotspots under consideration, but the installation of low level vegetation planting ("Green Screens") could be feasible, but may contrary to existing policies in Streetscape Guidance. The use of green ("living") walls may also be effective in street canyons by reducing PM_{10} concentrations in recirculated air.

- *Electrostatic treatment.* The electrostatic concept developed in the Netherlands has been shown to reduce the PM_{10} concentration in a tunnel environment. The concept is also applicable in the open air, but more research into its effectiveness in such an environment (and any associated concerns) is required. It should be noted that systems, such as large air scrubbers that include electrostatic treatment, are not included within this category.

Table 14: Assessment of Potential Measures to Reduce PM_{10} Concentrations in Hotspots.

Measure	PM_{10}		Technical feasibility	Timescale to implement measure	Cost	Other environmental impacts	Road safety impacts	Impact on travel times	Public appeal	Acceptability
	Impact	Duration of impact								
Road and vehicle cleaning										
Vacuuming or sweeping road surface	ü/x	Hours	üüü	*T*	Low-medium	Limited	Potential improvements in friction	Limited	Good public visibility	Low if traffic is disrupted and speeds are reduced. May also lead to increased soiling of vehicles
Power washing road surface	ü/x	Hours	üüü	*T*	Low-medium	Unlikely to be different from the effects of rainfall	The removal of loose debris will improve friction, but wet surfaces would reduce traction.	Limited	Important to link with water conservation strategies	Low if traffic is disrupted and speeds are reduced. May also lead to increased soiling of vehicles
Vehicle cleaning	ü	Days	üü	*TT*	Medium (would require new infra-structure)	Limited. Run-off needs to be controlled	Potential issues of road surface becoming wet	Medium	Good public visibility, with costs charged to vehicle operator	Depends on the scale of application. Probably high if only commercial vehicles are targeted. Probably low if private vehicles are included
Enforcement of vehicle cleaning on construction sites	ü	Duration of construction works	üüü	*T*	Low	Will reduce nuisance effects of soiling	Potential to improve friction	N/A	Should be welcomed by the public, especially near to the construction sites	High
Dust suppressants										
Use of dust suppressants	üü	Hours-days	üüü	*T*	Low	Possibly increased hydrological impacts	Could reduce skid resistance	Low	Good public visibility, but re-assurance required to demonstrate benign health & environmental effect.	Low-medium. There may be some disruption to traffic and increased vehicle corrosion, and concerns about the environmental impacts of suppressants
Traffic management										
Adjusting or removing traffic lights	ü	Years	Depends on scheme	*T*	Low	Smoothing of traffic should reduce fuel consumption and noise	Ought to be beneficial, but may not be significant.	Probably small.	Should be positive if reduces stop-start driving	High, if reduces congestion and/or stop-start driving
Car clubs/sharing	n/s	Depends on scheme	üüü	*T*	Low	Reduced fuel consumption and noise.	Limited	Could be reduced if there are fewer vehicles on the road	Should be positive	Medium
Cycle hire	n/s	Depends on scheme	üüü	*T*	Low-medium	Reduced fuel consumption and noise.	Limited	Limited	Should be positive	Medium
Shared space	ü	Years	üü	*T*	Medium-high	Smoothing of traffic should reduce fuel consumption and noise	Should be beneficial	Potential increase if speeds are low and diversions are common	Good public visibility. Should create a more pleasant environment for pedestrians and cyclists	Medium, although potential objections form visually impaired groups

Measure	PM_{10}		Technical feasibility	Timescale to implement measure	Cost	Other environmental impacts	Road safety impacts	Impact on travel times	Public appeal	Acceptability
	Impact	Duration of impact								
Home Zones	n/s	Years	ü ü	T	Medium-high	Limited	Should be beneficial	Potential increase if speeds are low and diversions are common	Good public visibility	Medium
Development of mixed priority routes	ü	Years	ü ü	T	Medium	Reduced fuel consumption and noise	Beneficial	Limited	Low	Only suited to mixed-use environments
Cycling / walking days	ü	Depends on policy	ü ü ü	T	Medium	Reduced fuel consumption and noise	Slight benefit	Depends on uptake	Should be positive	Medium
Access restrictions	ü ü/x	As and when required	ü ü	T	Medium	Generally positive inside zone. May lead to increased emissions outside the restricted zone	Should be beneficial	Depend on scheme	Good public visibility, but unlikely to be popular with motorists and some businesses	Medium
Effective policing of red routes	ü	Years	ü ü ü	T	Low	Limited	Should be beneficial	Should be beneficial	Good public visibility,	High
Creation of indented bus stops	ü	Years	ü	TT	Medium	Limited	Should be beneficial	Should be beneficial	Good public visibility, Beneficial for cyclists	High
Extension of Congestion Charge Zone	ü ü/x	Years	ü	TT	Medium	Generally positive inside zone. May lead to increased emissions outside the restricted zone	Should be beneficial	May increase journey times outside of zone	Unlikely to be popular with motorists and some businesses	Low/Medium
Deployment of cleaner buses	ü	Years	ü ü	T	Low	Limited	N/A	N/A	No specific issues	High
Deployment of cleaner taxis	ü ü	Years	ü ü	T	Low	Limited	N/A	N/A	No specific issues	Low/Medium
Other measures to control emissions										
Reducing idling	ü	Years	ü ü ü	T	Low-medium	Noise reduction	Limited	Limited	Has promotional value, but can be difficult to enforce	Medium
Modified road surface	ü	Years	ü ü ü	T	Medium	May reduce road noise	May reduce road surface friction	Disruption to traffic during resurfacing.	Has promotional value	Medium
Active asphalt	n/s	N/A	0	T	Medium	N/A	N/A	Disruption to traffic during resurfacing.	Has promotional value	Medium
Barriers and tunnels										
Barriers[a]	ü/x	Years	ü ü	T	Low-medium	Reduce noise. May increase exposure of vehicle occupants. Increased severance	No effect	No effect	High barriers unlikely to be popular. Lower barriers may be acceptable	Use of vegetation may help acceptability.

Measure	PM_{10}		Technical feasibility	Timescale to implement measure	Cost	Other environmental impacts	Road safety impacts	Impact on travel times	Public appeal	Acceptability
	Impact	Duration of impact								
Tunnels	ü ü/x	Years	ü	*TTT*	High	Reduce noise and severance. May increase exposure of vehicle occupants	No effect	Possible beneficial	High	Probably low. Tunnelling operations at hotspots would cause major disruption
Lightweight canopies	ü ü/x	Years	ü	*TT*	Medium-high	Reduce noise. Will increase severance and likely to increase exposure of vehicle occupants. Visual impact.	No effect	No effect	Low – depending upon design	Probably low – depending on design
Vegetation										
Trees	ü/x	Years	ü	*TT*	Low-medium	Absorb CO_2 while growing. May increase exposure of vehicle occupants	Trees planted at roadside could lead to increased severity of RTAs. Visual impairment possible at junctions and bends	No effect	High	Medium-high. Highly visual. Improved street environment
Green walls	ü/x	Years	ü	*TT*	Low-medium	Absorb CO_2 while growing	None	No effect	High	Medium-high. Highly visual. Improved street environment
Green barriers	ü/x	Years	ü	*TT*	Low-medium	Absorb CO_2 while growing	Visual impairment possible at junctions and bends	No effect	Medium	Medium-high. Highly visual. Improved street environment
Other Measures to Limit Exposure										
Cycle lanes	ü	Years	ü ü ü	*T*	Medium	None	None	Could increase congestion	Medium	High
Electrostatic precipitators	ü ü	Years	ü ü	*T*	Medium	Visual impact	None	No effect	High	Medium

[a] Effectiveness could be improved by use of filter elements.

Key

Impact on PM_{10}

x	slight increase in PM_{10} possible
xx	substantial increase in PM_{10} possible
ü	slight reduction in PM_{10} possible
ü ü	substantial reduction in PM_{10} possible
n/s	effect probably not significant

Technical feasibility

0	Unlikely to be feasible
ü	Feasible but difficult
ü ü	Intermediate
ü ü ü	Straightforward

Timescale

T	Short-term
TT	Medium-term
TTT	Long-term

Likely to be very suitable

Likely to be suitable

Potentially suitable

Unlikely to be suitable

Notes

The evaluation of Cost is based on a relative assessment between the various measures.

The evaluation of Acceptability is based on professional judgement of the potential overall political and public reaction to each measure; no opinion surveys were carried out

7 Pilot Programmes

7.1 This section sets out the recommended Pilot Programmes for each of the five hotspots. These Programmes take into account the Detailed Profiles set out in Chapter 4, the suitability of various measures set out in Chapter 6, and the magnitude of PM_{10} reduction required. The forecast reductions in traffic emissions in 2011 for each hotspot have been derived from modelling carried out by King's College ERG. These are summarised in Table 15. The values represent the mean reduction required within each of the hotspots. Also shown are the reductions based on the lower and upper bounds of the uncertainty assumed in the modelling. In some hotspots the predicted mean concentration is not above the limit value, however taking account of the model uncertainty, then reductions would be required to ensure that the limit value is met.

Table 15: Required Reduction in PM Traffic Emissions at Each Hotspot

Hotspot	Average Reduction in PM Traffic Emissions (%)[a]		
	Mean	Lower	Upper
Marylebone Road	33.3	19.0	47.6
Euston Road	0	0	19.5
Marble Arch	20.1	3.1	37.1
Tower Hill	0	0	19.3
Victoria Embankment	0	0	21.1

[a] The reductions are for the traffic passing through the hotspots. They include emissions of exhaust and non-exhaust PM.

7.2 The required reduction in PM_{10} concentrations is greatest at the Marylebone Road hotspot. The assessment of recent measured concentrations (see Chapter 3) shows that it is likely to be necessary to reduce daily mean concentrations by around 5 $\mu g/m^3$ on exceedence days. Modelling shows local road traffic contributes ~15 $\mu g/m^3$ to annual mean, of which approximately 50% is estimated to be brake & tyre wear (the modelling does not include any resuspension component, thus it is not possible to model the benefits of measures to control this source). The traffic component on exceedence days is likely to be higher than this, except on days when exceedences are dominated by long-distance transport. It may be assumed to range from 15 $\mu g/m^3$ to 30 $\mu g/m^{3.}$ The reduction in emissions required on exceedence days at Marylebone Road is therefore likely to be around 17-33%. Similar reductions in PM_{10} concentrations on exceedence days are expected to be required at the other hotspots, although the frequency of such exceedence days is expected to be lower.

Quantification of Emissions Reduction

7.3 It is extremely difficult to accurately quantify the reduction in PM_{10} concentrations that would be achieved by individual, or a combined "package" of measures. Where the measure specifically addresses traffic flows, compositions or speeds, then these can be quantified in a traffic model and used to revise the air quality predictions. However, this is a complex exercise that could not be completed within the timeframe of this report.

7.4 Other measures cannot be quantified within the air quality model, as the sources they are intending to address are not specifically included e.g. the application of road surface washing and the use of dust suppressants are aimed at reducing the resuspension component that is not included within the model. A further consideration is whether these measures can be effectively targeted on "exceedence days" and is, in part, related to the accuracy of forecasting such events.

7.5 It is considered highly unlikely that any individual measure could deliver the reduction in emissions/concentrations that is required, and so a package of measures is recommended for each hotspot, taking into account the Detailed Profiles. Professional judgement would suggest that individual measures might contribute reductions of between 1 and 10% to total PM_{10} on exceedence days, while a package might contribute some 10 to 20%.

Summary of General Issues

7.6 The information and analyses set out in the previous six chapters have highlighted some generic issues;

- Sources outside of the hotspots dominate the kerbside concentrations of PM_{10}, with local road traffic accounting for about 30 to 40%;
- Taxis and LGVs are a significant source of PM_{10} emissions;
- Non-exhaust (brake and tyre wear) emissions are very important, and account for about half of the total road transport contribution;
- Resuspension of road dust is likely to be an important source, but this is not included in the modelling studies as the source strength cannot be quantified;
- Traffic congestion increases emissions (by causing stop-start driving), and is thought to be exacerbated by junctions, but it is difficult to quantify by how much;
- The majority of PM_{10} exceedence days occur during the winter months;
- The daily limit value is more stringent than the annual mean limit value, thus the focus should be on reducing daily exceedences; and
- Emissions of PM_{10} from local traffic need to be reduced by around one-third on exceedence days to meet the daily limit value;

7.7 These generic issues, and more site-specific issues, have been considered in the light of the preferred options described in Chapter 6, and used to prepare a list of the measures recommended within each Pilot Programme. These are summarised as a matrix in Table 16, and described in more detail in subsequent sections.

Table 16: Summary of Recommended Measures at Each Hotspot

Measure	Marylebone Road	Euston Road	Marble Arch	Tower Hill	Victoria Embankment
Power washing road surface	√	√	√		√
Construction site vehicle cleaning	√	√	√	√	√
Dust suppressants	√	√	√		√
Adjusting or removing traffic lights	√	√	√	√	√
Access restrictions	√	√			
Indents for bus stops	√	√			
Cycling/walking days					√
Effective policing of red routes	√	√	√	√	√
Extension of Congestion Charging	√	√			
Deployment of cleanest buses	√	√	√	√	√
Deployment of cleanest taxis	√	√	√		
Shared space				√	
No-idling enforcement	√	√	√	√	√
Modified Road Surfaces	√				
Low barriers with filtration	√				
Green Screens	√	√	√		√
Green walls	√	√	√	√	√
Electrostatic precipitators	√				

Power Washing of Road Surfaces

7.8 This measure is designed to reduce PM_{10} emissions arising from resuspended road dust. It would be targeted at days when exceedences are forecast, and could probably be focused on the winter months (when the frequency of exceedence days is much higher). It is anticipated that road washing with high pressure jets would take place in the early hours of the morning, say between 3am to 6am, when traffic is light, although consideration would need to be given to potential noise issues if it takes place near to residential properties or hotels. The washing would take place on the nights before a potential exceedence day is forecast, i.e. it would be carried out prior to all those days forecast to experience concentrations above the limit value (50 µg/m^3);_experience would indicate whether it would be necessary to repeat this measure every night during a PM_{10} episode of several days. Specific air quality forecasts would need to be commissioned from one of the current providers. It is expected that the measure would apply to the whole of the hotspot.

7.9 Issues that will need to be considered in detail include:

- Development of specific PM_{10} exceedence day forecasts from one of the current providers (e.g. specifically related to days on which PM_{10} concentrations greater than 50 µg/m^3 are forecast for central London roadside sites);
- Identification of suitable power washing equipment and resources that would allow the hotspot areas to be washed within the available period of notification and time window;
- Identification of responsibilities for undertaking the washing (e.g. TfL, London borough, or another organisation);
- Potential issues during periods of cold weather (e.g. freezing on road surface, or washing off of de-icing salt) and the potential impact on the quality of the drainage water and cleaning of gulley pots.

7.10 It is recommended that this measure be applied to Marylebone Road, Euston Road, Marble Arch and Victoria Embankment. It is a relatively low cost measure that could be implemented in the short term. It is not recommended for Tower Hill, as this location is recommended for the development of a “shared space” area, and it is not considered that power washing would be appropriate.

Construction Site Vehicle Cleaning

7.11 This measure is designed to reduce PM_{10} concentrations arising from resuspended road dust. It is aimed at reducing the amount of dust on the road arising from track-out of construction dust and dirt on the bodies and wheels of construction vehicles departing from construction sites within 1 km of the hotspot. The measure would involve encouraging the relevant London boroughs to strictly apply and enforce measures to clean vehicles leaving construction sites. It could be achieved by preparing maps clearly identifying the area within 1 km of the hotspot, within which extra vigilance would be encouraged. It would also involve providing briefings for the London boroughs on the most appropriate cleaning facilities to expect to be applied and how to ensure enforcement of their proper use.

7.12 It is recommended that this measure be applied to all of the hotspots. It is a relatively low cost measure that could be implemented immediately, and is consistent with the commitment in the draft MAQS to seek full implementation of the Best Practice Guidance on Construction and Demolition.(GLA, 2006).

Dust Suppressants

7.13 This measure is designed to reduce PM_{10} concentrations arising from resuspended road dust. As with power washing, it would be targeted at days on which exceedences are forecast, and could probably be focused on the winter months (when the frequency of exceedence days is much higher). It is anticipated that the dust suppressant would be sprayed onto the road surface after it had been power washed. However, as these types of suppressants have not previously been used in the UK, it would be necessary to identify the most appropriate suppressant, and to then carry out a review of any toxicity or other environmental issues that may arise, including potential impacts on water quality. It would also be necessary to evaluate the potential impact of the suppressant on surface friction, possibly through a series of trials. Other aspects of the use of suppressants would be as for road washing above.

7.14 Issues that will need to be considered in detail include:

- Co-ordination with any road washing to ensure suppressants are only applied after washing;
- Development of specific PM_{10} exceedence-day forecasts from one of the current suppliers;
- Identification of suitable equipment for spraying the suppressant, determining the concentrations to be used and surface loading issues, and resources that would allow the hotspot areas to be treated within the available period of notification and time window allowed;
- Identification of responsibility for undertaking the treatment (e.g. TfL, London borough, or another organisation);
- Review of potential issues related to toxicity and other environmental issues (potentially in discussion with European practitioners and the UK Health Protection Agency);
- Investigations into the potential effects on surface friction through a number of trials on test tracks.

7.15 It is recommended that this measure be applied to Marylebone Road, Euston Road, Marble Arch and Victoria Embankment. It is a relatively low cost measure that could be implemented in the short term, provided issues regarding toxicity and surface friction can be quickly resolved. It is not recommended for Tower Hill, as this location is recommended for the development of a “shared space” area, and it is not considered that treatment using dust suppressants would be appropriate.

Adjusting or Removing Traffic Lights

7.16 This measure is designed to smooth traffic flows and thereby reduce both exhaust and brake & tyre wear PM emissions. Observations at the hotspots has identified congestion being exacerbated by signalled junctions and crossings. This would require an investigation of the potential for traffic light optimisation to allow a smoother traffic flows, but consideration would need to be given to the potential effects on side roads. There may also be opportunities to remove traffic lights at some junctions to smooth traffic flow. Whilst smoothing flows via traffic management systems has been previously investigated by TfL, this has focused on wider areas, and was not intended to influence flows across specific road links (i.e. the hotspot areas).

7.17 It is assumed that this measure would apply at all times, though it could be worth exploring whether it could be applied only during periods of heavy traffic, or on days when exceedences are forecast. As an example, the signals could be used to prioritise the main road during peak hours, thereby discouraging use of the side roads.

7.18 Detailed investigations will be required, covering:

- Traffic management options to smooth flows along specific hotspot links;
- Options for removal of signalled junctions or crossing to ease congestion.

7.19 It is recommended that this measure be investigated for all of the identified hotspots. It is a relatively low cost measure that could be implemented in the short term.

Access Restrictions

7.20 The implementation of access restrictions is coupled with the traffic management measures discussed above, and is designed to smooth the traffic flow and thereby reduce both exhaust and brake & tyre wear emissions. It would involve the closure or restriction of access from one or more side roads onto the hotspot link, either during peak hours or on a permanent basis. Consideration would need to be given to the potential effects of diverting traffic elsewhere.

7.21 Detailed investigations will be required to:

- Identify those side roads that could be closed on a limited or permanent basis, and the traffic flow implications for the wider road network;

7.22 It is recognised that this will be a difficult measure to implement, and it is recommended that it be investigated for Marylebone Road only, where the most substantial reductions in PM_{10} emissions/concentrations are required. It is a relatively low cost measure that could be implemented in the short term.

Indents for Bus Stops

7.23 This measure is designed to minimise congestion and thereby reduce exhaust and brake & tyre wear emissions. It could only be applied to sections of road where the pavement is wide enough to accommodate a bay.

7.24 Detailed investigations will be required to:

- Identify sections of roads where indented bus bays could be established.

7.25 Potential exacerbation of congestion by buses stopping was only identified along Marylebone Road and Euston Road. It is recommended that this measure be investigated for these two hotspots only.

Cycling/walking Days

7.26 TfL has previously funded boroughs via their Local Implementation Plans (LIPs) to stage "car free days". This measure is primarily aimed at generating publicity for other modes of sustainable transport, such as walking or cycling, but would also reduce emissions on the day.

7.27 The measure is only feasible for implementation at hotspots where the roads could feasibly be closed for one or more days, and is best suited to locations that have an appeal to cyclists and pedestrians. It is recommended that this measure be investigated for Victoria Embankment and Tower Hill on one or both weekend days, on a regular, or permanent basis. It would provide enhanced pedestrian and cyclist access to a route directly adjacent to the River Thames, and would encourage tourists.

7.28 It is suggested that closure to traffic be implemented along:

- A section of the Embankment extending from Hungerford Bridge to Temple Place. Such a closure could be linked to other events along the Embankment, such as street markets, entertainment etc. to attract pedestrians;
- A section of Tower Hill extending from Trinity Square to the Minories.

7.29 It is a relatively low cost measure that could be implemented in the short term.

Effective Policing of Red Routes

7.30 All of the hotspots links are designated red routes, established to reduce congestion. However, observations during collation of the Detailed Profiles identified vehicles parked on a red route, causing substantial congestion.

7.31 It is recommended that strict enforcement of the red route restrictions be applied to all of the hotspot areas.

Extension of Congestion Charging Zone

7.32 The current Congestion Charging Zone terminates at the southern boundary of Marylebone Road/Euston Road. It is a measure that was primarily introduced to reduce traffic volumes on London roads and thereby ease congestion. Congested traffic has been identified as a potentially significant contributor to PM_{10} emissions along both Marylebone Road and Euston Road.

7.33 Detailed investigations will be required, covering::

- An assessment of the implications of extending the congestion charge zone to include Marylebone Road and Euston Road, specifically with regard to traffic flows and speeds, and taking account of the fact that Euston Road is a major arterial route providing access to several major railway stations.
- The implications of re-routed traffic avoiding the proposed extension to the congestion charge zone.

7.34 It is a relatively low cost measure that could be implemented in a short timescale.

Deployment of the Cleanest Buses to the Hotspots

7.35 This measure is aimed at reducing PM_{10} emissions. Although buses make a relatively small contribution to PM emissions, rerouting of new hybrid buses through the hotspots would be beneficial, and has been proposed within the draft MAQS. It is recommended that priority is given to deploying the new diesel-electric hybrid buses onto routes along Marylebone Road and through Marble Arch (where the required reduction in PM_{10} concentrations is the greatest), and to the other hotspots as appropriate.

Deployment of the Cleanest Taxis to the Hotspots

7.36 This measure is aimed at reducing PM_{10} emissions. Taxis make a substantial contribution to PM emissions, and rerouting of newer, cleaner taxis along these hotspots would be very beneficial.

7.37 The 2008/09 taxi fleet comprises of approximately 20% Euro 4, 30% Euro 3, and 22% Euro 2 and 27% Euro 1 vehicles. Those taxis older than Euro 3 have been retrofitted with Diesel Particulate Filters (DPF) in compliance with the Mayors Taxi Emission Strategy, to make them compliant with the Public Carriage Office (PCO) Euro 3 standard. Although compliant with the Euro 3 standard, retrofitted vehicles never perform as well as the Original Equipment Manufacturer (OEM) vehicles.

7.38 Issues that will need to be considered in detail include:

- Investigation as to what minimum Euro standard could be introduced from 2011, and quantification of the emission benefits associated with each. If the measure were restricted to Marylebone Road (where the greatest reduction in PM_{10} concentrations is required) it is recommended this should restrict taxis to Euro 4 and above from 2011;
- Investigate potential enforcement measures that could be applied, including the use of traffic cameras and/or a "Green Certification" scheme.

Shared Space

7.39 This measure is intended to reduce traffic flows and ease congestion. Although unproven in terms of PM_{10} reduction, it offers other environmental benefits including improved amenity space. It is considered that the introduction of a shared space at Tower Hill would be appropriate, and whilst some diversion of traffic may be required, shared space schemes have been implemented in high-trafficked areas elsewhere. The specific benefits for Tower Hill are:

- It is located adjacent to a World Heritage site, and other types of infrastructure developments could be very difficult to implement at this location, particularly if they obscured views of the Tower;
- It is a popular tourist location that would benefit from reduced traffic flows and speeds.

7.40 Issues that will need to be considered in detail include:

- Identifying the feasibility of establishing a shared space at Tower Hill, based on existing traffic flows and routes;
- Reviewing issues raised with other proposed shared spaces e.g. at Exhibition Road, with regard to design details to meet the needs of visually-impaired pedestrians.

No-idling Zones

7.41 Both taxis and buses/coaches contribute to PM_{10} emissions whilst waiting with their engines running at taxi ranks or at bus/coach holding areas. The London boroughs have existing powers to require drivers to switch off engines, and can issue fixed penalty notices. In addition, TfL discourages the practice of bus and coach drivers from running engines while stationary, via the Coach Parking Map and the TfL website.

7.42 The draft MAQS commits to the establishment of a no-idling zone in London, focused on buses, coaches and taxis, and for cars in problem areas (such as schools). However, professional judgment needs to applied in the enforcement of this measure to prevent continual stopping and starting of engines which may cause higher pollution (for example at taxi ranks where the vehicles are slowly moving).

7.43 Issues that will need to be considered in detail include:

- Encouraging relevant London boroughs to apply no-idling enforcement within the hotspot areas. This could be accompanied by guidance on when it is (and is not) appropriate to require engines to be turned off;
- Investigating the use of signage in the hotspot areas to raise awareness of engine idling;

7.44 It is a relatively low cost measure that could be implemented in the short term. It is recommended that this measure be investigated for all of the hotspots.

Modified Road Surfaces

7.45 The use of modified road surface materials designed to reduce the rolling resistance of vehicles can be beneficial for fuel consumption (thereby reducing CO_2 emissions and noise) and as such would be expected to be beneficial for reducing PM_{10} exhaust emissions. This measure offers an attractive option as it could be relatively easily applied to sections of London streets as part of the routine maintenance and replacement of road surfaces. It is therefore considered worthy of further investigation.

7.46 There are no sections of Marylebone Road scheduled to be resurfaced before 2011. It is nevertheless recommended that consideration be given using a modified road surface along one or more sections of Marylebone Road during 2010.

7.47 Issues that will need to be considered in detail include:

- Discussions with manufacturers and possible trials to determine implications of the material for surface friction and stopping distances;
- Opportunities to bringing forward the resurfacing of sections of Marylebone road to an earlier data.

Low Barriers with Filtration

7.48 This measure is designed to remove PM_{10} from the atmosphere, and directly reduce concentrations. The use of barriers with filtration has been shown to be effective, but the installation of tall barriers (2 to 3 m high) would not be practicable along any of the London hotspots. The option of installing low barriers (of about 1 m height) between the traffic and the pavement is potentially feasible, but no studies are available on which to estimate the efficiency of such barriers in reducing PM_{10} concentrations. It is however considered a measure worthy of further investigation.

7.49 Issues that will need to be considered in detail include:

- Initial discussions with barrier manufacturers to determine if suitable low-level barriers could be provided;

- Identification of suitable areas where installation of barriers would not cause problems with regards to public access and safety.

7.50 This measure is only experimental, and it is recommended that it be installed at a short section (about 100-200 metres) of Marylebone Road, where the required reduction in PM_{10} concentrations is the greatest.

Green Screens

7.51 This measure is designed to remove PM_{10} from the atmosphere. Plants would be grown up existing safety railings from boxes at the top or bottom of the railing. Commercially available “green screens” could also be used instead of railings, or where railings do not exist. It would be necessary to identify species that would provide dense foliage and be long lasting. There may also the opportunity to select plants that absorb nitrogen dioxide, which would be an added benefit. It would be necessary to provide maintenance, including watering during dry periods.

7.52 Issues that will need to be considered in detail include:

- Identification of sections of road suitable for establishment of green screens. Issues related to traffic and pedestrian safety will need to be considered, particularly with regard to pedestrian crossings.
- Determining who will be responsible for installation and maintenance;
- Identification of most suitable species for planting, bearing in mind durability, resistance to pollution, efficiency of PM removal etc.

7.53 This measure is recommended for all hotspot areas with the exception of Tower Hill (due to issues associated with the World Heritage status of this area).

Green Walls

7.54 This measure is designed to remove PM_{10} from the air that is recirculating within the canyon. Plants would be grown up the walls of suitable buildings near to the road. This measure would require the permission of the building owner. It would be necessary to identify species that would provide dense foliage and be long lasting. There is also the opportunity to select plants that absorb nitrogen dioxide, which would be an added benefit. It would be necessary to provide maintenance, including watering during dry periods.

7.55 Issues that will need to be considered in detail include:

- Identification of buildings suitable for establishment of green walls. It is envisaged that public and/or academic buildings might be considered for this purpose. This will need to include responsibilities and funding for installation and maintenance;

- Identification of most suitable species for planting, bearing in mind durability, resistance to pollution, efficiency of PM removal etc.

7.56 This measure is best suited to street canyons where there is recirculation of air, and is recommended for suitable sections of road in Marylebone Road and Euston Road. However, the measure could also be implemented at other hotspot locations where suitable buildings are available.

Electrostatic Precipitators

7.57 This measure is designed to remove PM_{10} from the air that is recirculating within the canyon. The electrostatic concept developed in the Netherlands (patent held by BAM and TU-Delft) has been shown to reduce the PM_{10} concentration in a tunnel environment, and whilst it is understood to be applicable to open environments, the performance of the system is unknown. It is, however, considered a measure worthy of further investigation.

7.58 Issues that will need to be considered in detail include:

- Initial discussions with manufacturers to determine if suitable systems could be designed for London hotspots, and whether additional details on system performance are available;
- Identification of design, engineering and safety issues.

7.59 This measure is only experimental, and it is recommended that, if practicable, it be installed along a short section (about 100-200 metres) of Marylebone Road, where the required reduction in PM_{10} concentrations is the greatest.

Other Environmental Considerations

7.60 A brief summary of the other potential environmental effects of the proposed measures has been set out in Table 14. These are considered in greater detail within this section, with specific focus on nitrogen dioxide, carbon dioxide and noise. The principal aim of this study has been to identify local measures that will reduce PM_{10} emissions/concentrations within a relatively short timescale; however if the measures also provide benefits for other important environmental considerations, then this would be an obvious benefit.

7.61 The assessment is summarised in Table 17 below.

Table 17: Summary of Potential Environmental Benefits/Disbenefits Associated with Each Proposed Measure

Measure	Nitrogen Dioxide	Carbon Dioxide	Noise
Power washing road surface	Negligible	Very minor (associated with use of power washers) but probably insignificant	Potential issues if carried out close to residential properties
Construction site vehicle cleaning	Negligible	Negligible	Negligible
Dust suppressants	Negligible	Very minor (associated with use of power washers) but insignificant	Potential issues if carried out close to residential properties
Adjusting or removing traffic lights	Beneficial if reduces congestion	Beneficial if reduces congestion	Beneficial in reducing stop/start movements of vehicles
Access restrictions	Beneficial within zone of restriction. May increase emissions elsewhere if traffic diverted	Beneficial within zone of restriction. May increase emissions elsewhere if traffic diverted	Beneficial within zone of restriction. May increase noise elsewhere if traffic diverted
Indents for bus stops	Negligible	Negligible	Negligible
Cycling/walking days	Beneficial if reduces traffic	Beneficial if reduces traffic	Beneficial if reduces traffic
Effective policing of red routes	Negligible	Negligible	Negligible
Extension of Congestion Charging	Beneficial within zone of restriction. May increase emissions elsewhere if traffic diverted	Beneficial within zone of restriction. May increase emissions elsewhere if traffic diverted	Beneficial within zone of restriction. May increase noise elsewhere if traffic diverted
Deployment of cleanest buses	Beneficial within zone (reduces engine running)	Beneficial within zone (reduces fuel consumption)	Negligible
Deployment of cleanest taxis	Beneficial	Beneficial	Negligible
Shared space	Beneficial (if traffic volumes reduced, and congestion relieved)	Beneficial (if traffic volumes reduced, and congestion relieved)	Beneficial (if traffic volumes reduced, and congestion relieved)
No-idling enforcement	Beneficial if reduces engine running	Beneficial if reduces fuel consumption	Beneficial if reduces engine running
Modified road surfaces	Beneficial if reduces fuel consumption	Beneficial if reduces fuel consumption	Beneficial in reducing tyre noise
Low barriers with filtration	Negligible	Very minor (associated with use of powered filtration) but probably insignificant	Reduction in noise levels depending upon barrier design

Table 17 (contd): Summary of Potential Environmental Benefits/Disbenefits Associated with Each Proposed Measure

Measure	Nitrogen Dioxide	Carbon Dioxide	Noise
Green Screens	Could be beneficial in NO_2-phillic species are incorporated	Beneficial, but minor	Negligible
Green walls	Could be beneficial in NO_2-phillic species are incorporated	Beneficial, but minor	Negligible
Electrostatic precipitators	Negligible	Very minor (associated with use of powered system) but probably insignificant	Negligible

Applicability of Measures to Other Hotspot Areas

7.62 Whilst the focus of this report is upon the five priority hotspots identified within the draft MAQS, the Strategy also recognises that there are potentially other locations in London where air quality is poor, including those areas identified by the boroughs' own monitoring and modelling assessments. As previously described in Chapter 1, it is intended that the "tailored measures" identified within this report could be adapted for these other locations, as appropriate.

7.63 As the measures proposed above are investigated further by TfL, it is recommended that the outcomes of these studies be published, so that the practicalities and applicability of individual measures can be taken on board by other organisations.

7.64 As an example, brief consideration in this study was given to Upper Thames Street. Whilst this has not been identified as a hotspot within the draft MAQS, it effectively forms the major traffic link between Tower Hill and Victoria Embankment, and measures to reduce PM_{10} emissions/concentrations on this road could have potential benefits on adjacent roads.

7.65 Many features of Upper Thames Street are similar to Marylebone Road and Euston Road:

- It largely consists of a dual carriageway road, separated by a central reservation;
- It has tall buildings on either side forming a street canyon;
- There is a high proportion of taxis and LGVs (from visual observation); and
- The traffic is congested in the vicinity of signalled junctions.

7.66 One distinguishing feature of this road is the underpass that runs from the Mermaid Centre to the junction with Lamb Hill. There is no pedestrian access to the underpass and the limit values would not apply at this location, however emissions arising from vehicles in the tunnel could potentially generate hotspots in open areas close to the portals. Measures could potentially be installed to reduce PM_{10} concentrations within the underpass (e.g. the Electrostatic Precipitators have been shown to work very effectively in tunnels) and this could prove beneficial to areas close to the tunnel portals.

7.67 Pending the outcome of further studies, it is suggested that the proposed measures for Marylebone Road and Euston Road could be applied to Upper Thames Street.

8 Monitoring Programme

8.1 The objective of the Monitoring Programme is to determine the effectiveness of the measures that have been implemented, and to justify continuing operation. Ideally, this programme would record changes in PM_{10} concentrations brought about by the individual measures, but in practice this will be difficult to achieve for a number of reasons:

- Given the timescale for the requirement to implement the measures (if the limit value is to be achieved by the end of 2011) it will not be practicable to establish a robust baseline monitoring programme to establish “before and after” concentrations;
- It will be necessary to implement the proposed measures concurrently (so as to achieve the maximum reduction in PM_{10} concentrations) - it will be therefore be difficult to assess the effectiveness of individual measures;
- The number of exceedence days recorded in each year is highly dependent upon the meteorological conditions. It will therefore be difficult to directly link any change in the number of measured exceedence days with any implemented measure(s).
- The only reliable means of measuring PM_{10} concentrations for compliance with the limit value involves the use of sophisticated and expensive equipment (such as the FDMS analyser described in Chapter 4). It would not be practicable to install such equipment at a large number of kerbside locations, for reasons of both access and cost.

8.2 Notwithstanding the above comments, whilst the effectiveness of some measures can be judged from surrogate information, e.g. relating to changes to traffic flows, speeds, vehicle composition etc, as appropriate, for other types of measures the only means of quantification is through measurements of PM_{10} concentrations. On this basis, recommendations for the Monitoring Programme are set out below.

Monitoring Traffic

8.3 Measures that are directly focused upon changing traffic flows, speeds or vehicle composition can be usefully assessed by monitoring these changes over time. Such monitoring can be applied to:

- Adjusting or removing traffic lights;
- Access restrictions;
- Indents for bus stops
- Cycling/walking days
- Effective policing of red routes;
- Extension of congestion charging;
- Rerouting of cleaner buses;

- Rerouting of cleaner taxis; and
- Shared spaces

8.4 Detailed information would be required both before and during implementation of the measures covering the composition and speed of the traffic, as well as locations, lengths of queues, and this should cover all hours of the day and days of the week. In some cases, this information may need to be provided for individual lanes so as to take account of features such as bus lanes, as the separation distance from the traffic is an important consideration for some proposed measures. This information can then be used to quantify the emissions benefits associated with each measure, and also be used to model the expected reduction in PM_{10} concentrations.

Monitoring PM_{10} Concentrations

8.5 For those measures that are aimed at reducing the resuspension of road dust, or are aimed at reducing airborne PM_{10} concentrations directly (by filtration etc), it will not be feasible to quantify the benefits by use of surrogate information. It is therefore recommended that a programme of PM_{10} monitoring be carried out.

8.6 It is appreciated that this is not a straightforward task, and it cannot be achieved simply. For this reason, a comprehensive programme is recommended, but limited to the Marylebone Road hotspot; it is assumed that if measures are proving effective at Marylebone Road then they will also be working elsewhere.

8.7 Due to limitations of access, it is not considered feasible to install equipment that will measure PM_{10} concentrations to the same standard as the Marylebone Road monitoring site (i.e. equivalent to the European reference method). However, the proposed monitoring programme is not intended to demonstrate compliance with the limit value, but to provide evidence that the implemented measures have been successful in reducing PM_{10} emissions and/or concentrations.

8.8 It is therefore proposed that the monitoring is based on the use of either Osiris analysers or MiniVol samplers. These are both small instruments that can be fitted to lampposts. The Osiris system is based on using a nephalometer to measure the particles as they pass through a laser beam, and has the advantage of providing continuous measurements, nominally separated into different size fractions, typically PM_1, $PM_{2.5}$, PM_{10} and total PM, which may be advantageous in data analysis. The MiniVol collects PM_{10} particles onto filters for subsequent determination by weighing, and can only provide 24-hour concentrations.

8.9 It is recommended that four samplers[9] be installed at kerbside locations along Marylebone Road. The precise location of these monitoring sites is difficult to determine at this stage, but they should

[9] The instruments selected would have to be uniform throughout – i.e. all Osiris or MiniVol.

coincide with locations where specific measures are being implemented e.g. close to where vegetation barriers, electrostatic precipitators etc. have been installed.

8.10 A difficulty in evaluating the monitoring data will be determining whether the changes in average and/or daily mean PM_{10} concentrations are associated with the measures themselves, or other factors, in particular changing meteorological conditions. The optimum way to allow for meteorological factors will be to analyse daily (or shorter-term) data within the hotspots against data collected at control sites. The control sites should also be at kerbside locations with similar characteristics to Marylebone Road, i.e. busy canyon street running broadly east-west. They could be sections of Marylebone or Euston Road where measures are not being applied, although in this case it would also be necessary to monitor traffic conditions, as they may change following implementation of some of the measures in the hotspots.

8.11 An optional (or additional) approach to fixed monitoring could be the use of personal monitors, based on the approach used in the DAPPLE project[10]. This would involve people walking along identified sections of road links before and after measures were implemented, and potentially along sections where different measures were implemented.

Recommendations for Detailed Modelling

8.12 As set out in Chapter 3, there are a number of limitations with the modelling approach used to identify the five hotspot areas. With the exception of Marylebone Road, where there is a PM_{10} monitoring site, all of the other hotspot areas have been identified on the basis of modelling predictions alone.

8.13 It is recommended that consideration be given to a more detailed modelling study at these hotspots, which would specifically take into account:

- Shorter link lengths, with updated traffic data provided by TfL;
- Specific consideration of speeds close to junctions;
- Precise carriageway widths along each link;
- Recognition of bus lanes and restricted access routes; and
- Presence of street canyons.

8.14 The assessment could be undertaken using any appropriate model, e.g. ADMS-Roads, which has been used extensively in London. The modelling could be further enhanced using the more detailed traffic data held by TfL, and by the collection of driving characteristics along each link; such information could then be fed into an instantaneous emissions model. Model verification would be an important element of the study, whereby modelled concentrations are compared with measured concentrations and adjustments made as necessary. The verification should include the

[10] www.dapple.org.uk

monitoring carried out at the Marylebone Road site, and a number of other roadside/kerbside PM_{10} monitoring sites in close proximity to the identified hotspot areas.

9 Special Measures

9.1 This Chapter deals specifically with Special Measures which could be implemented as a short-term response to high-pollution days, as well as seeking to promote more lasting behavioural changes. A review of the different short-term or emergency measures that have been employed in other UK or European cities has been carried out, and these are presented as series of Case Studies. The feasibility of employing these measures in London is then discussed.

9.2 The following types of measure have been considered:

- **Public information**
  - Road traffic signage (e.g. Variable Message Signs)
  - Messages disseminated via the media to discourage travel (television, radio, mobile phone, internet, email)
  - Real-time information on traffic conditions (congestion, accidents, etc.)
  - Information on parking (e.g. availability of spaces)
- **Controlling vehicle access**
  - Banning vehicles on a certain day (e.g. at peak times of day, odd/even number plates, cordons).
  - Road pricing.
  - Altering traffic signals and changing signal priorities.
  - Diverting traffic to alternative routes.
- **Enhancement of public transport**
  - Incentives for people to avoid using cars, such as free use of public transport, including park-and-ride.
  - Changes to the operation of public transport (e.g. increased numbers of buses or trains).

9.3 Because different types of measure have been used in combination, the potential effects on air quality conditions are addressed via reference to a number of case studies. Although some of these measures are not currently focussed on high-pollution days, such as the London Congestion Charging Scheme, they could be modified to do so, and are therefore considered relevant. A number of the case studies are taken from a previous TRL report in which they were described in some detail (McCrae et al., 2000). Where possible, the information provided in the earlier TRL report has been updated.

Case Studies

Athens

9.4 In Athens restrictive measures have been in place since 1983, with odd- and even-registration plate cars being banned from the city centre on alternate days, and a total ban enforced when emergency levels of pollution are reached. Although the scheme was reported to have been beneficial at the start, the increase in the overall number of cars offset any positive effects of the strategy (Kontaratos,1993). Consequently, more permanent measures were introduced, including the exclusion of older cars from the central area and free minibuses to the restricted zone. These later measures were not pollution-responsive, but permanent, in order to try and reduce pollution levels on a long-term basis (Abbott et al., 1995).

9.5 Researchers in Athens also modelled a re-routing strategy in the EU PREDICT project (Pollution Reduction by Information and Control Techniques) (PREDICT, 1991). The re-routing strategy consisted of Variable Message Signs which, during pollution episodes, would display messages concerning avoidance or restriction of access to vehicles to the central urban area. It was assumed that enforcement would be achieved using automatic cameras or registration plate recognition technology, and that 30% of vehicles would heed the advice of the signs and change route. Although the emissions in the protected area decreased, the levels on the alternative routes increased. This may be acceptable if the aim is to remove pollution away from sensitive areas, but for the area-wide reduction of a pollution episode this would not be an acceptable approach.

Beijing

9.6 The air quality in Beijing during the 2008 Olympic Games attracted wide attention from the public. Over the past five years, PM_{10} concentrations in Beijing have often breached China's Grade II air quality standards of a daily mean of 150 µg/m^3. For example, average summertime daily PM_{10} concentrations have ranged from 94 to 251 µg/m^3 with a maximum value of 368 µg/m^3 recorded in August 2003 (Streets et al., 2007).

9.7 In the run up to the opening of the Games, the authorities closed polluting industries in the surrounding regions and replaced the use of coal with gas (where possible). In addition the Beijing government applied various measures leading up to the Olympics to control pollution from road vehicles (e.g. stricter emission standards, controls on heavy-duty vehicle emissions, alternate day bans on private vehicles and the development of public transport). Furthermore, between 1 July and 20 September 20 2008 Beijing conducted a phased reduction of its car fleet, primarily by restricting the vehicles of government offices, public institutions, the army, the police, and enterprises in the Beijing municipal regions, and by introducing strict traffic demand management (TDM) based on odd and even licence-plate days (Wang and Xie, 2009). In the event of high pollution events during the period of the Games, emergency measures were also developed to not only close down additional manufacturing units and coal fired power stations, but also to remove an additional 10% of the vehicles from the roads.

9.8 As a result of the TDM measures, car traffic reduced substantially during the Olympic Games. Wang and Xie (2009) evaluated the reduction effect of these traffic management measures in urban street canyons using the Operational Street Pollution Model (OSPM) (Berkowicz, 2000). OSPM was used to calculate the on-road concentrations of PM_{10}, CO, NO_2 and O_3 before and during the days on which the traffic was controlled. During the traffic management period the traffic flow decreased by, on average, 32.3%. However, the effects were different for the four pollutants. The average PM_{10} concentration decreased from 143 $\mu g/m^3$ to 102 $\mu g/m^3$; the average CO concentration decreased from 3 mg/m^3 to 2.4 mg/m^3, and that of NO_2 decreased from 119 $\mu g/m^3$ to 104 $\mu g/m^3$. The ozone concentration, on the other hand, increased from 5.5 ppb to 6.8 ppb. The changes in air quality also showed regional differences for streets in the east, west, south and north, which was probably induced by the diverse background pollution on the different directions around Beijing, along with the impact of wind force. It was concluded that in order to achieve air quality improvements the pollution control in the surrounding regions and the pollutant transport should also be taken into consideration (Wang and Xie, 2009).

9.9 Wentao et al 2009, concluded that meteorological factors accounted for 40% of the variation in PM_{10} concentrations and control measures 16%. This once again suggests that the weather was more important than the reduction in emissions in improving air quality.

Berlin

9.10 In Berlin, when the limit values for particulate matter and NO_2 were first exceeded in 2002, a Clean Air Plan was created. The Plan described the sources of pollution and the measures to reduce emissions from them. Different sectors were addressed separately, and road traffic was covered in some detail. However, it was concluded that no measures existed that were simultaneously effective and proportionate in the short term, and which would strike a reasonable balance between intervention and air pollution abatement. Individual actions taken by the road authorities, such as road closures, were judged unsuitable as they only result in a spatial displacement of the problem. The Plan concluded that the objective of reducing atmospheric pollution could only be achieved by a combination and strategic orientation of all appropriate measures in the short, medium and long term (Senate Department of Urban Development, 2005).

London

9.11 In February 2003, a congestion charging scheme (CCS) was introduced in London with the aim of reducing traffic congestion in the centre of the city – an area covering approximately 22 km2. The scheme operates via a charge on four-wheeled vehicles entering the charging zone during the period Monday–Friday, 07:00–18:00, with exclusions for certain categories of vehicle, including those with lower emissions.

9.12 Beevers and Carslaw (2005) analysed the air pollution impacts of the London CCS. Road traffic data, combined with a traffic emission model, indicated that NOx and PM_{10} emissions had decreased by about 12% in the charging zone, but also that emissions had increased on the inner ring road, which included the Marylebone Road and Euston Road hotspots. The overall impacts on air quality were not assessed.

9.13 Tonne et al. (2008) used a combination of dispersion modelling and regression calculations to analyse the air pollution and health benefits of the CCS. They concluded that the CCS led to reductions in concentrations, although these were modest across Greater London, but greater in the charging zone. The predicted health benefits in the charging zone wards were 183 years of life per 100,000 people, assuming conditions would persist over 10 years.

9.14 The potential impacts of the CCS on pollutant concentrations (NOx, NO, NO_2, PM_{10}, CO and O_3) at roadside and background monitoring sites across Greater London were also reported by Atkinson et al. (2009). Temporal changes in pollution concentrations within the charging zone were compared with changes at pollution monitoring stations unlikely to have been affected by the CCS. Similar analyses were conducted for weekends (when the CCS was not operating). Based on data for a single roadside monitor within the CCS zone, it was not possible to identify any relative changes in pollution concentrations associated with the introduction of the scheme. However, there was good evidence from background monitors for a decrease in NO and increases in NO_2 and O_3 relative to the CCS zone. There was little change in background concentrations of NOx. There was also evidence of relative reductions in PM_{10} and CO. Similar changes were observed during the same hours on weekends when the scheme was not operating. The causal attribution of these changes to the CCS was not considered to be appropriate since the scheme was introduced concurrently with other traffic and emission interventions which might have had a more concentrated effect in central London.

9.15 This type of road pricing scheme has the potential for modification to operate as a responsive measure to address high pollution days. For example, this could be achieved by increasing the daily charge on high pollution days or by extending the charging zone. As central London already has the basis of a successful operating scheme then, in principle, these sorts of modifications would be possible.

Netherlands

9.16 Dynamic traffic management (DTM) is widely employed in the Netherlands as a strategy for tackling congestion. Pollution-responsive traffic management was investigated in the Dutch Air Quality Innovation Programme (Innovatie Programma Luchtkwaliteit - IPL). The aim was to determine the additional environmental benefits that could be achieved through the encouragement of smoother driving and more even traffic flows.

9.17 Seven measures were evaluated: 3 dynamic routing variants (local route advice, regional route advice, motorway exit closure), 3 regulated access variants (regulated access to motorways, regulated access to main roads, lane closure), and 'clean freight' on bus lanes. The effectiveness of these measures was initially assessed through the modelling of roads around Rotterdam. The results from this study were developed into a decision matrix (Ludeking et al. 2008).

9.18 The impacts achieved depended very much on the traffic volume and the amount of congestion at the location concerned. However, in terms of scale and duration the impact on traffic was judged to be so limited that over a 24-hour period there would be no marked reduction in the daily average PM_{10} concentration. In fact, relatively little congestion occurred during the study; larger reductions might be achievable where the traffic is more congested.

9.19 In addition, the traffic and air quality models were not particularly detailed. To gain a better idea of the decrease in intensity and improvement of traffic flow achievable, the effects of the DTM measures would have to be modelled for a variety of traffic situations, and the effect of traffic flow smoothing would have to be based on models which allow changes in driving dynamics to be addressed.

9.20 One aim of this work was to define how far in advance PM_{10} forecasts need to be available, and what accuracy is required with respect to concentration, place and time. A PM_{10} predictor had already been developed within the framework of road speed policy (Manders et al. 2008). However, it can only predict the PM_{10} concentrations one day in advance, and its reliability is questionable. It was therefore not considered suitable in the context of IPL.

9.21 Forecasts from KNMI (Royal Dutch Meteorological Institute) are currently being used to introduce lower speed limits whenever high PM_{10} levels are predicted, with the goal of reducing the number of exceedence days. This approach is currently only being applied at a test location, but it may be introduced at more locations if shown to be successful. The forecasts only cover one day into the future. During an early phase of the project a three-day forecast was used. This was changed, however, to prevent low speed limits being enforced on days with lower levels of pollution that occurred before the actual forecast day. In addition, during periods of intermittent high pollution events, the use of the 3-day forecast led to a almost continuous lowering of speed limits, and this was considered to have led to an adverse public reaction (personal communication, de Wildt)[11].

Paris and Ile-de-France

9.22 The response to high-pollution episodes (based on NOx and NO_2 concentrations only) in Paris and the Ile-de-France region were described in some detail in an earlier TRL review (McCrae et al., 2000).

9.23 In Paris towards the end of September 1997, weather conditions (temperature inversion and low wind speed) were such that pollutant dispersion was restricted and ground-level pollutant concentrations reached high levels. The information and alert threshold of 400 µg /m^3 for NO_2 was breached on 30 September and the weather services forecast a continuation of low-wind-speed conditions. Traffic bans were therefore introduced on an experimental basis and enforced from 05:30 on 1 October. During this period only vehicles with odd-numbered registration plates were allowed entry to the city. However, there were exceptions to this, including carpooling with a minimum of three passengers, clean vehicles (defined as those with LPG, NGV or electric engines), taxis, emergency and public service vehicles, fresh goods transportation vehicles and vehicles for the handicapped.

9.24 Complementary measures were introduced throughout the period of the traffic ban. Public transport was allowed to cross the cordon, with the fares being waived. This free public transport was extended to the whole of the Ile-de-France region. In addition, the scheme was linked with free residential parking within Paris, a reduction in speed limits of 20 km/h on the primary roads inside Paris, and the use of VMS to direct road users to park-and-ride facilities. The traffic restrictions were enforced through the deployment of an additional 1,000 police officers. The public were informed of the traffic ban the previous evening via press releases via the radio, papers and television. In addition, this was supported with announcements at public transport stations and on VMS on primary routes (Barbier, 1998).

9.25 It has been estimated that the traffic ban forced an estimated half a million cars to remain outside the city centre, resulting in a reported 14% decrease in the level of traffic within the cordon. Over the entire region an approximate 10% decrease in road traffic was recorded. An 11% increase in bus passengers was recorded by RATP, with an increase of 10% in rail trips into Paris recorded by SNCF. Rail trips between suburban areas increased by between 15 and 20% (Barbier, 1998).

9.26 Modelling exercises, taking into account the decreased traffic volumes and the altered traffic composition, indicated a reduction in the emissions of NOx. The contribution of this emission

[11] Martijn de Ruyter de Wildt, KNMI.

reduction to pollutant concentrations was uncertain. The air pollution monitoring sites around the city indicated that the levels of NO_2 did indeed fall after the morning of 1 October, but that these concentrations had already dropped well below the alert threshold by the afternoon of 30 September. The temperature inversion, which was the main cause of the episode, was considerably weaker on the morning of 1 October compared with the previous three days. Subsequently, this inversion dissipated and the wind speed increased to above 10 m/s at around midday. By midnight on the 1 October the temperature profile was almost back to normal. Estimates of the additional costs of this traffic ban were of the order of approximately 2.7 Million Euros (18 million Francs). This was composed of some 150,000 Euros for the provision of additional services, and up to 2.6 Million Euros for the loss of ticket sales. The public responses to this traffic ban indicated that 83% of respondents were in favour of the restrictions, with 29% making changes to their travel plans.

9.27 It should be noted that this procedure has only been used once, and this was only within the region of Ile-de-France. Since then, several new air quality regulations have been adopted, combined with the introduction of new traffic legislation, decision and control networks. In consequence, the current procedures for the use of a pollution-responsive traffic ban are different to those applied in 1997.

Leicester

9.28 The aim of the European project, Environmental Forecasting for the Effective Control of Traffic (EFFECT) was to improve air quality through a more efficient traffic management system. As part of this project, the City of Leicester enhanced their AIRVIRO model by incorporating real-time traffic, air quality and weather data to allow the ability to forecast pollution episodes up to 48 hours in advance. The Council tested a range of pollution responsive measures including advanced public campaigns to discourage people to drive in peak hours, Variable Message Signs and increasing road tolling charges (McCrae et al., 2000). Follow up surveys found that the public messages reached over a third of respondents, with around 10% changing their travel behaviour (e.g. travelling outside peak hours or car sharing).

9.29 Leicester was also involved in the European project HEAVEN (Healthier Environment through the Abatement of Vehicle Emissions and Noise), along with Paris, Rotterdam and Berlin. The project ran from 2000-2003. One of the aims was to manage the impact of traffic on noise and air quality by developing tools such as Decision Support System (DSS) and improving air quality modelling. For example, Leicester tested the use of a DSS to provide short-term forecasts at two sites where air quality and traffic monitoring data were available. The Leicester DSS was linked to various traffic management systems such as SCOOT (Taranto et al., 2002).

Stockholm

9.30 Johansson et al. (2009) described the effects of a trial road charging system in Stockholm on emissions and levels of air pollutants between January and July 2006. The system was designed to improve air quality and reduce traffic congestion, and consisted of three parts: extended public transport (16 new bus lines), a congestion tax, and more park-and-ride sites in the city and the county. Vehicles travelling into and out of the charging zone were charged for every passage during weekdays. The amount due varied during the day and was highest during rush hours (approximately 2 Euros with a maximum of 5.7 Euros per day). Based on measured and modelled changes in road traffic it was estimated that the system resulted in a 15% reduction in total road use within the charged cordon. Total traffic emissions in the area of NOx and PM_{10} fell by 8.5% and 13%, respectively. The reductions were mainly due to decreased traffic flow; reduced congestion had little effect. For NOx, emission reductions would have been larger without the extended bus traffic during the trial.

9.31 Air quality dispersion modelling was applied to assess the effects of the emission reductions on ambient concentrations and population exposure. For the situations with and without the trial, meteorological conditions and emissions from non-road sources were kept the same. It was found that the annual average NOx concentrations would be lower by up to 12% along the most densely trafficked streets. PM_{10} concentrations would be up to 7% lower. Figure 6 shows the geographic variation of the annual mean reduction in NOx and PM_{10} concentrations due to the reduced traffic. It was noted that the limit values for both PM_{10} and NO_2 would still be exceeded along the most densely trafficked streets. The authors emphasised the importance of not only assessing the effects relative to air quality limit values, but also to make quantitative estimates of health impacts in order to justify actions to reduce air pollution.

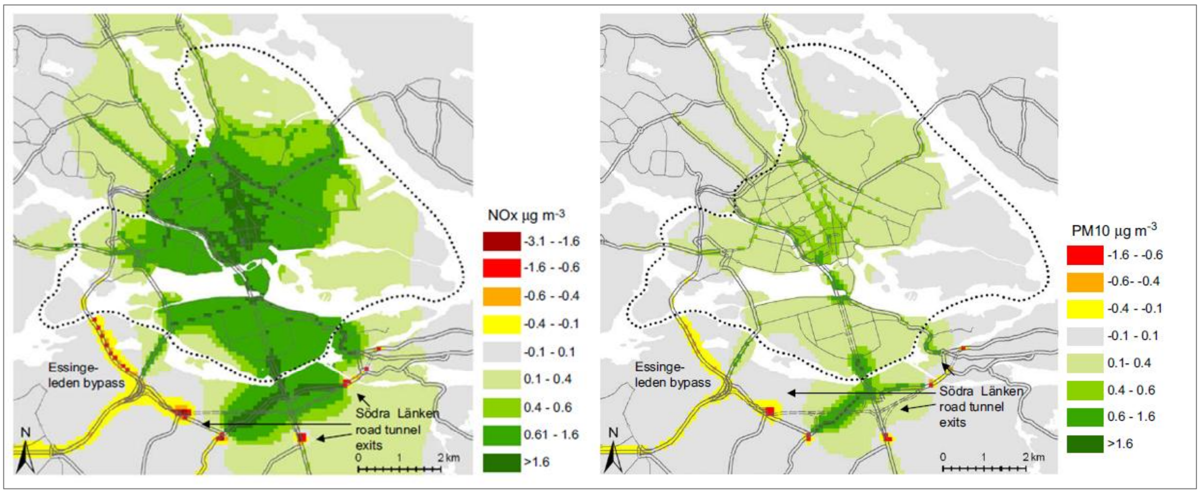

Figure 6: Differences in annual mean concentrations of NOx and PM_{10} with the Stockholm trial compared to a situation without the trial. Within the green areas the levels have fallen, within yellow to red areas there is an increase in levels (Johansson et al., 2009).

York

9.32 York's Traffic Congestion Management System (TCMS) offers real-time management and control of traffic in the city. TCMS identifies where there is spare capacity on the road network and, through links with a network of real-time air quality monitors, discerns where air quality is at an unacceptable level. Then, using an air quality prediction model and a traffic model the system calculates the most appropriate routing for traffic to avoid congested and/or polluted areas. These routes are then put into operation via a network of variable message signs (VMS). At the time of implementation it was hoped that the TCMS would be developed at a later date to incorporate physical barriers to traffic and number-plate recognition systems to identify vehicles which are present in areas where they are not permitted (Evely, 2003). Currently, York TCMS incorporates some of the following features: integrated bus systems to monitor traffic and provide information to passengers, real-time traffic web information, access control management using bollards and expansion of VMS throughout the city[12].

Discussion

9.33 The information summarised above has been collated from various cities to demonstrate a range of transport demand measures that have the potential to operate in the short term in response to forecasts of high pollution. Many of these measures have been trialled as part of demonstration projects for European collaborations, including HEAVEN and EFFECT and as such will no longer be operating. However, much of the information on the use of emergency measures for pollution control is relatively old, and little research has been undertaken in this area over the last 10 years. Therefore the conclusions and recommendations from these various investigations may be even

[12] http://www.envitia.com/casestudies/casestudydetails.aspx?id=54,0,0

less robust today, as current procedures may now be quite different to those illustrated in the case studies.

9.34 The following general conclusions can be drawn out from the Case Studies:

- Short-term measures to restrict traffic in certain zones during high pollution events can be successful, but they tend to lead to a spatial displacement of the problem and may cause exceedences in new areas.
- For such schemes to work effectively, they must be based on accurate forecasting of high pollution events, at least one day in advance; this has proven to be problematic.
- Many of these measures have built in delays so their impact on air quality may occur after the episode has passed, which means they will have limited impact in preventing an exceedence.

9.35 In addition, the following considerations are important when planning Special Measures to address exceedences of the daily threshold of 50 µg/m³ of particulate matter:

(i) *The share of imported PM pollution tends to be above the statistical mean on days with high peak levels. Such non-compliance situations usually occur in autumn and winter. Inevitably, short-term measures such as smog alerts have built-in delays, occur after the fact, have very little impact and are of limited use for preventing the exceedence of limit values.*

(ii) *Longer-term traffic-related measures are more effective at reducing PM levels and achieving compliance with the 24-hour limit value of 50 µg/m³ in locations in which the 24-hour mean values are only slightly above the threshold. In unfavourable years with high pollution, such as 2003, this applies to residential areas, but even to traffic-exposed measuring stations in favourable years such as 2004 (and 2001).*

9.36 The preference for medium and long-term measures to reduce PM pollution is also supported by the assessment of the latest research into the effects of particulate matter conducted by the World Health Organisation (WHO) on behalf of the European Commission. It found that a lasting decline in PM pollution is of much greater benefit than a strategy comprised of measures directed at combating short-term concentration peaks, whose effectiveness is necessarily limited

9.37 Table 18 considers whether any of the measures tested in other cities would be feasible for application in central London. It is likely that the simplest tool for London would be to provide up-to-date and accurate information to the public in advance of a forecast pollution episode. These types of systems could readily be implemented in London and be made widely accessible by incorporation with existing messaging services. e.g. through mobile phones (airTEXT), the internet, twitter and local news. The advantage of a public information system is that it can also be used to promote behavioural change, making members of the public more aware of pollution causes and effects, and encouraging more widespread use of public transport, cycling and walking.

9.38 The majority of the other types of transport demand measures demonstrated in the Case Studies (such as access controls using physical barriers, banning certain vehicle types on certain days, or increasing provision of public transport) would be much more costly to implement. These systems would, in some cases, require new infrastructure to be installed and would need to be enforced.

9.39 There is evidence from these Case Studies that the short-term operation of such schemes can reduce pollution emissions (such as in Beijing and Paris), although more recently preference has been given to favouring medium- or long-term measures to reduce PM. It is also not clear how the public would respond to these types of measure. For the public to have any confidence in their effectiveness to improve pollution, then the measure needs to be linked to accurate forecasting capabilities. The performance of forecasting systems has previously been discussed in Chapter 4 of this report.

Table 18: Feasibility of Special Measures for London

Type of measure	Measure	Feasibility for Implementation in London
Public information	Road traffic signage (*e.g.* variable message signs)	The use of Variable Message Signs may be more applicable to motorways as these types of signage are limited in central London, Introduction of additional signage would conflict with other policies to reduce street furniture and infrastructure..
	Messages discouraging travel	This would be possible using existing services in London such as airTEXT which currently provides a forecasting and alerting service to mobile phones. This could be enhanced and extended by providing information to the wider public, advising on areas to avoid and discouraging car travel.
	Real-time information on traffic conditions	Real-time traffic information is already available for London through local news and the internet. These existing services have the potential to be linked to air quality and/or meteorological forecasts
	Information on parking	This could include providing information on car parking spaces in the outskirts of London close to stations and encouraging passengers to travel to central London by public transport. This would require an expansion of public transport provision.
Controlling vehicle access	Vehicle bans	ANPR system of CCS could possibly be adapted to further differentiate between vehicle types, but this could be confusing to the public if the rules are not explained clearly and/or insufficient information is provided prior to their introduction. May prove to be difficult in practice. Could be combined with VMS. There is the potential to worsen air quality conditions outside of the charging zone.
	Road pricing	Already in place with CCS, but could be modified to allow higher charges on high pollution days. To work successfully, it would be necessary to accurately forecast high pollution days, and to provide advanced notice to the public so that informed choices on alternative travel can be made.. There is the potential to worsen air quality conditions outside of the charging zone.
	Altering traffic signals and changing signal priorities	High-pollution episodes tend to be regional in nature and highly dependent upon meteorology. It is therefore unlikely that the spatial distribution of traffic alone within London would be effective.

Table 28 (contd): Feasibility of Special Measures for London

Type of measure	Measure	Feasibility for Implementation in London
	Diverting traffic to alternative routes	As above.
Enhancement of public transport	Incentives for people to avoid using cars, such as free use of public transport	Free public transport has been offered in London on New Years' eve for many years. As with road pricing, to work successfully, it would be necessary to accurately forecast high pollution days, and to provide advanced notice to the public so that informed choices on the use of public transport could be made.
	Changes to the operation of public transport (*e.g.* increased numbers of buses or trains)	If cars are banned from a certain area there is the potential for more road space for buses. However, the feasibility of this measure would depend on the availability of buses 'on standby' to occupy this space.

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11 Glossary

Accumulation mode	Particles formed via the coagulation of nucleation mode particles, primary emission sources, and gas-to-particle transformations. Particles range between 0.05 and 1.0 µm have a residence time of tens of days.
AQC	Air Quality Consultants.
AQMA	Air Quality Management Area.
$CaCl_2$	Calcium chloride.
CAC	Closed asphaltic concrete.
CMA	Calcium magnesium acetate.
CO_2	Carbon dioxide.
EU	European Union.
ESP	Electrostatic precipitator.
Exceedence	A period of time or event when the concentration of a pollutant is greater than the appropriate air quality objective. This applies to specified locations.
FDMS	Filter Dynamic Measuring System
GVW	Gross vehicle weight.
HDV	Heavy-duty vehicle (heavy goods vehicles and buses) >3.5 tonnes GVW.
HGV	Heavy goods vehicle >7.5 tonnes GVW.
IPL	*Innovatieprogramma Luchtkwaliteit* (Dutch air quality innovation programme).
LDV	Light-duty vehicle (cars and light goods vehicles) <3.5 tonnes GVW.
LEZ	Low-emission zone.
LGV	Light goods vehicle <3.5 tonnes GVW.
$MgCl_2$	Magnesium chloride.
MOVA	Microprocesser controlled vehicle actuation.
$\mu g/m^3$	Microgrammes per cubic metre.

NaCl	Sodium chloride.
NO_2	Nitrogen dioxide.
NO	Nitric oxide.
NO_x	Nitrogen oxides (taken to be NO_2 + NO).
Nucleation mode	Particles emitted directly from combustion sources, having a diameter of less than around 0.05 µm and a residence time of a few hours. They are transformed by coalescence and condensation into larger accumulation mode particles.
PCM	Pervious coated macadam.
PM_{10}	Particulate matter less than 10 micrometers in aerodynamic diameter.
$PM_{2.5}$	Particulate matter less than 2.5 micrometers in aerodynamic diameter.
PM_{Coarse}	Particulate matter between 2.5 and 10 micrometers in aerodynamic diameter.
Primary particles	Particles emitted directly into the atmosphere
SCOOT	Split-cycle-optimisation-offset technique.
Secondary particles	Particles formed within the atmosphere from gas-phase precursors.
TEOM	Tapered-element oscillating microbalance.
TfL	Transport for London.
TRACKER	Testing re-entrained aerosols kinetic emissions from roads.
TRAMAQ	Traffic management and air quality research programme.
TRL	Transport Research Laboratory.

12 Appendix 1: Detailed Profiles

Introduction

12.1 This Appendix provides detailed profiles of the 5 hotspots. This includes descriptions based on visits to each of the sites, including photos, and basic information on the roads. Each hotspot has been broken up into a series of links of broadly similar character. These are shown on a map of each hotspot, then referenced to the observations set out in Tables. The traffic characteristics are set out in the main text.

Physical Attributes Marylebone Road

Link	Length (m)	Typical Road Width (m)	Orientation	Number of Lanes	Bus Lanes	Cycle Lanes	Width of Central Reservation (m)	No. Major Junctions	Pedestrian Crossings	Average Width of Pavement (m)	Red Route
A	67	24.5	WSW-ENE	4 + Taxi rank lane in central embankment + additional bus lane adjacent to Tube Stn	2	0	4.56 (inc Taxi rank)	Major Jcn at west end; minor at east	At west end Jcn	3 (N); 9 (S)	Y
B	285	25	WSW-ENE	4	2	0	1.3	Jcn at either end with several side Jcns	2, both signalled and traverse both directions	3 (N); 6-8 (S)	Y
C	211	20.6	W-E	4	2	0	1.3	One at either end.	3, all signalled	5 (N); 2 (S)	Y
D	206	20.6	E-W	4	2	0	2	One at either end.	One at either end	3 (N); 3 (S)	Y
E	64	23.4	W-E	5	2	0	1.5	One at either end.	0	2.7 (N); 2.5 (S)	Y
F	56	20.5	WNW-ESE	4	2	0	1.1	One at either end.	2	2.6 (N); 2.5 (S)	Y

Link	Sources of Dust	Description of Vegetation	Street Canyon	Description of Buildings	Typical Building Height	Road Surface
A	Dust on road	Small garden area on residential property	Y	7/8storey Tube station building on northern side; newer 4/5 storey commercial and residential properties on southern side	20m on northern side; 11/12m on southern side	Metalled in fair condition
B		Mature trees along footpath on both sides of the road	Y	Commercial and occasional residential properties	15-20m on both sides	Metalled in fair condition
C	Construction works. Dirty pavements. Soil around trees.	Mature Trees along northern side	Y	building set back from the road on the north; Tall building on south	15m	Metalled in fair condition
D	n/a	Park at either side of road	Y	n/a	n/a	Metalled in fair condition
E	n/a	Occasional trees on both sides of road	Y	Old tall buildings on both sides;	15-20m	Metalled in fair condition
F	Road works. Some dust in gutter. Overflowing bins outside underground station.	Several mature trees	Y	Old buildings set back from pavement slightly	15-20m	Metalled in fair condition

Marylebone Road

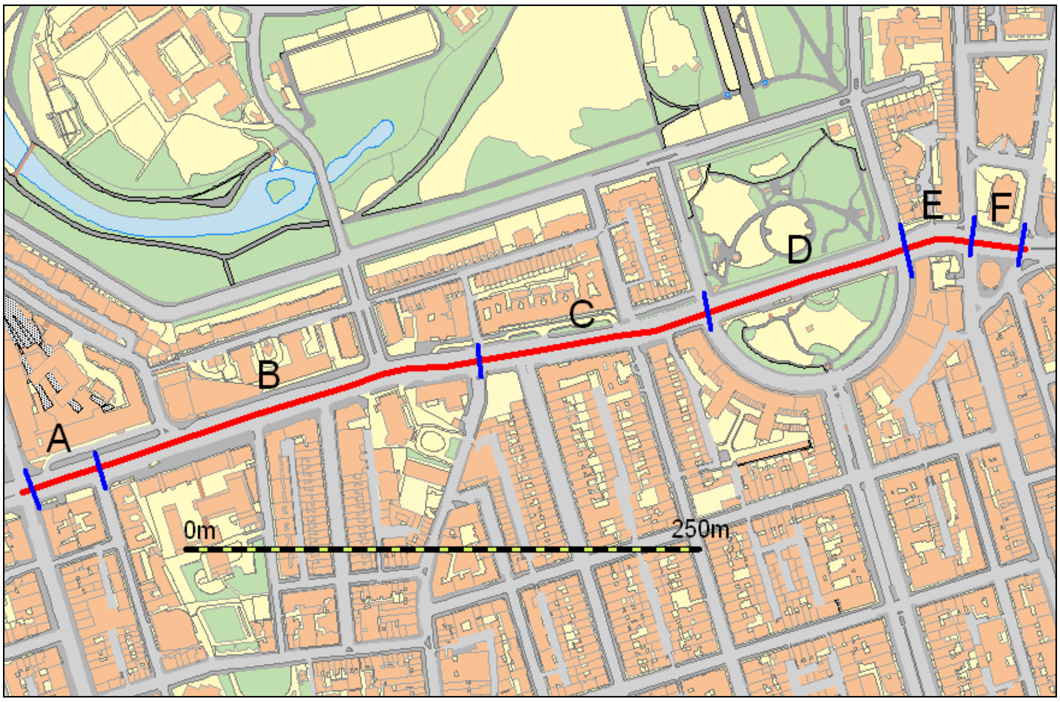

Figure 1: Marylebone Road

Figure 2: Link A – west to east view

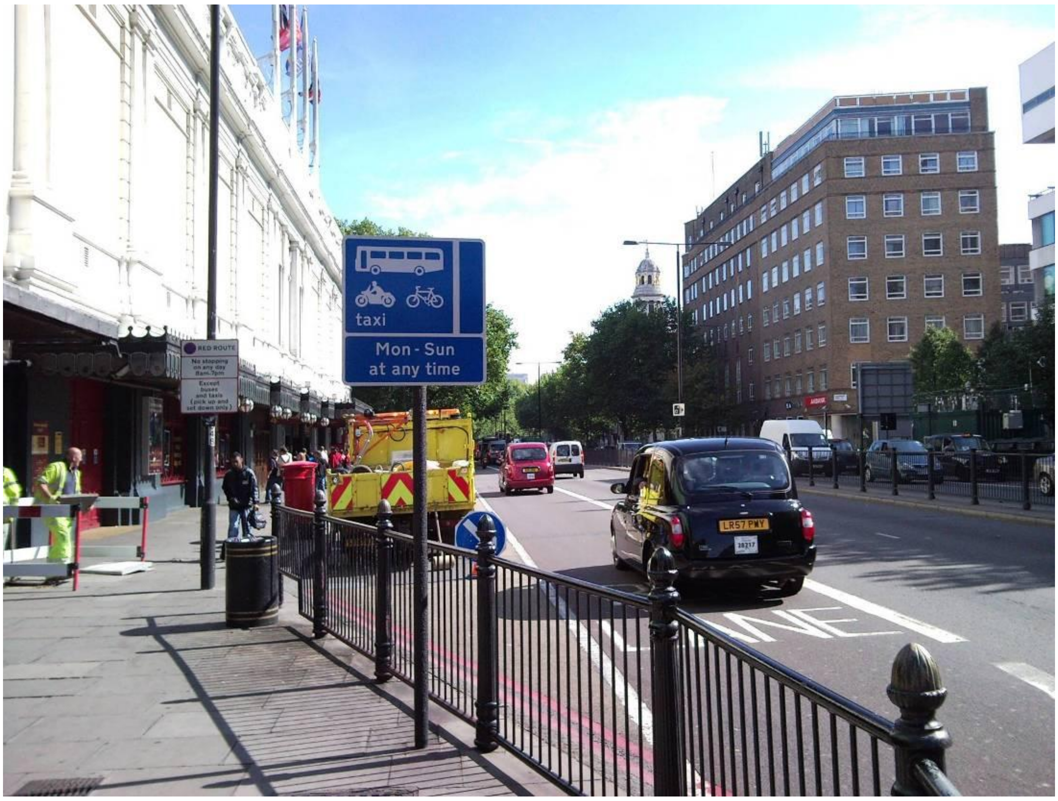

Figure 3: Link B – west to east view

Figure 4: Link B –east to west view

Figure 5: Link C – west to east view

Figure 6: Link C –east to west view

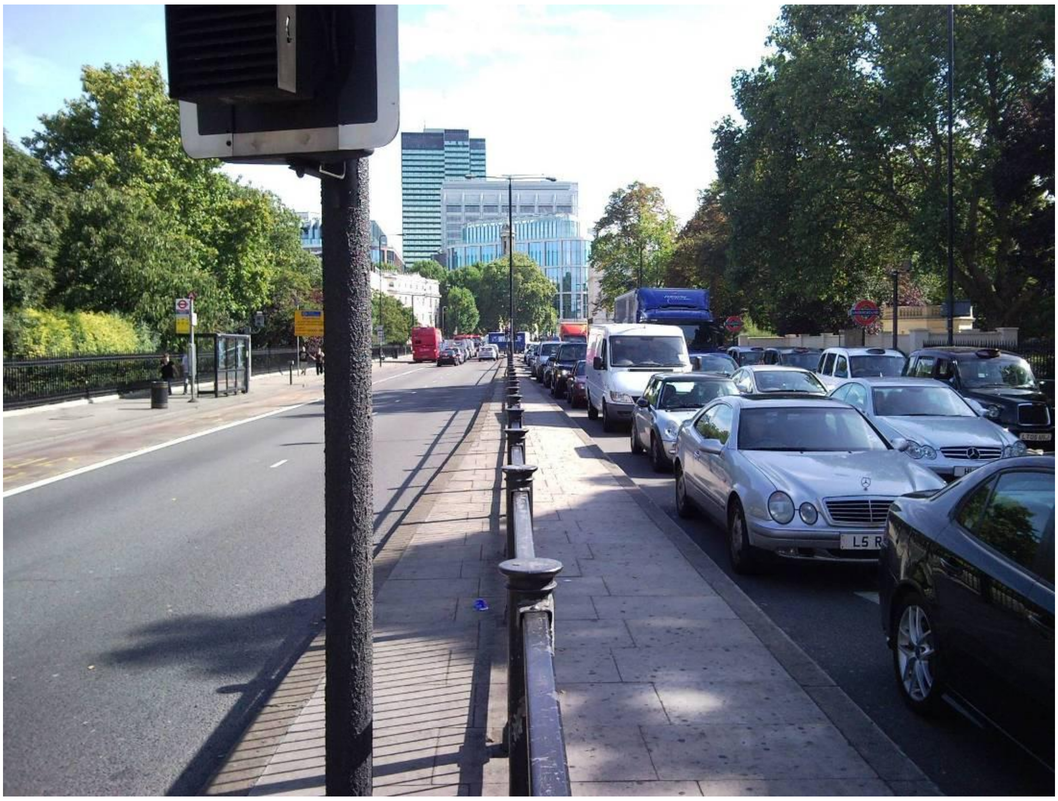

Figure 7: Link D – west to east view

Figure 8: Link D –east to west view

Figure 9: Link E – west to east view

Figure 10: Link E –east to west view

Figure 11: Link F –east to west view

Physical Attributes Euston Road

Link	Length (m)	Typical Road Width (m)	Orientation	Number of Lanes	Bus Lanes	Cycle Lanes	Width of Central Reservation (m)	No. Major Junctions	Pedestrian Crossings	Average Width of Pavement (m)	Red Route
A	83	18.2	NE-SW	5	0	0	2.2	One at either end, both signalised		north side is 3m for length of fire station and then 7m; south side is 7.5m	Y
B	60	18.1	NE-SW	5	0	0	0	One at south end	One at junction at SW end of link.	5 (both sides)	Y
C	170	18.3	NE-SW	4	1	0	3	One at either end.	2 (either side of junction with Mabledon Place / Ossulton Street.	5 (both sides)	Y
D	70	22	NE-SW	5	2	0	2	0	0	3-4	Y
E	39	22	NE-SW	n/a (chequered box)	n/a (chequered box)	n/a (chequered box)	0	1	One at all four junction arms	3-4	Y
F	100	18	NE-SW	4	2	0	1.5	0	0	2.5 to the north; 3.5 to the south	Y
G	50	20	NE-SW	4	1	0	2 to 4	1	1 (plus a dedicated cycle crossing)	3-5	Y

Link	Sources of Dust	Description of Vegetation	Street Canyon	Description of Buildings	Typical Building Height	Road Surface
A	Some visible dust in gutter. Bare earth around bases of trees.	Large mature trees growing from mid-point of pavements on north and south sides of road.	Y	Set 15-20m back from road on both sides. Mixture of old, very old and new.	12m (with one skyscraper)	Metalled in fair condition
B	Some visible dust in gutter. Construction north of road	Mature trees on north side of road (growing from mid-pavement). Nothing on south side of road.	Y	South of road, a Travel Inn is right on the edge of the pavement. Hoardings to the north on edge of pavement.	18m	Metalled in fair condition
C	Some visible dust in gutter. Bare earth around bases of trees.	Mature trees on north side of road (growing from mid-pavement). Nothing on south side of road.	Y	Right on edge of pavement on both sides of road.	15m	Metalled in fair condition
D	Some visible dust in gutter. Bare earth around bases of trees. When wind gusted, could feel dust in eyes.	Sparsely-planted mature trees in pavement (near kerb). Only a few trees on either side of road for length of link. Also, some younger trees in the grounds to the British Library.	Y	South of road - at edge of pavement, forming a canyon wall on either side of road	South of road 19m. North of road British Library (bits of about 10m and some bits with no buildings)	Metalled in fair condition
E		n/a	Y	n/a	10m	Metalled in fair condition
F	Man sweeping pavement. Some visible dust in gutter. Bare earth around bases of trees. When wind gusted, could feel dust in eyes.	Three mature trees on either side of road	Y	South of road: Camden Town Hall (old and new buildings); straight up in wall from edge of pavement. North of road: British Library - Old redbrick ornate set well back from road.	10-20m	Metalled in fair condition
G	Some visible dust in gutter. When wind gusted, could feel dust in eyes.	One mature tree on south side	Y	South side shops with flats above. North of road: British Library - Old redbrick ornate set well back from road.	10m (with one exception)	Metalled in fair condition

Euston Road

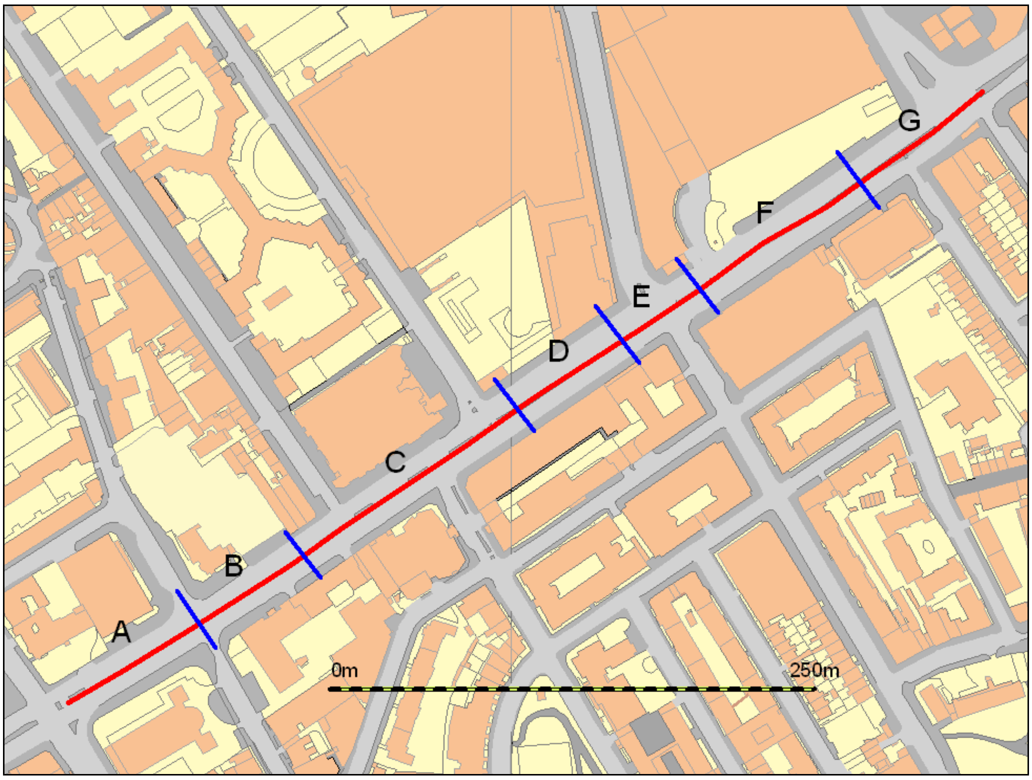

Figure 12: Euston Road

Figure 13: Link A – west to east view

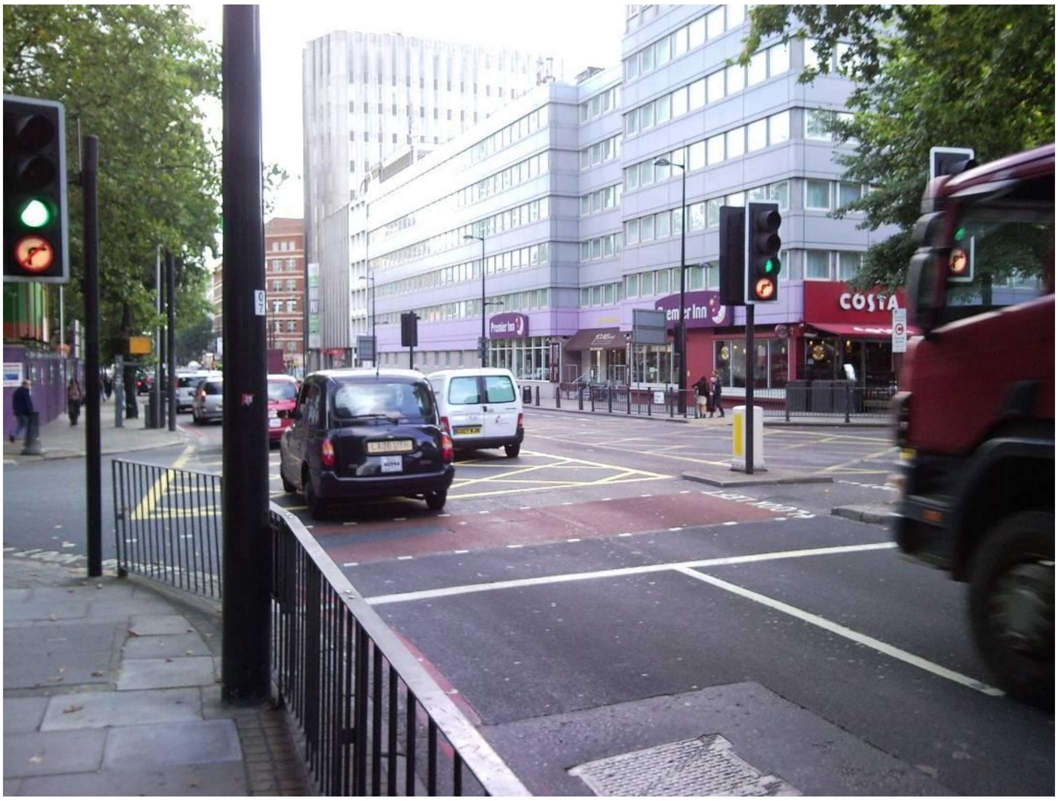

Figure 14: Link B – west to east view

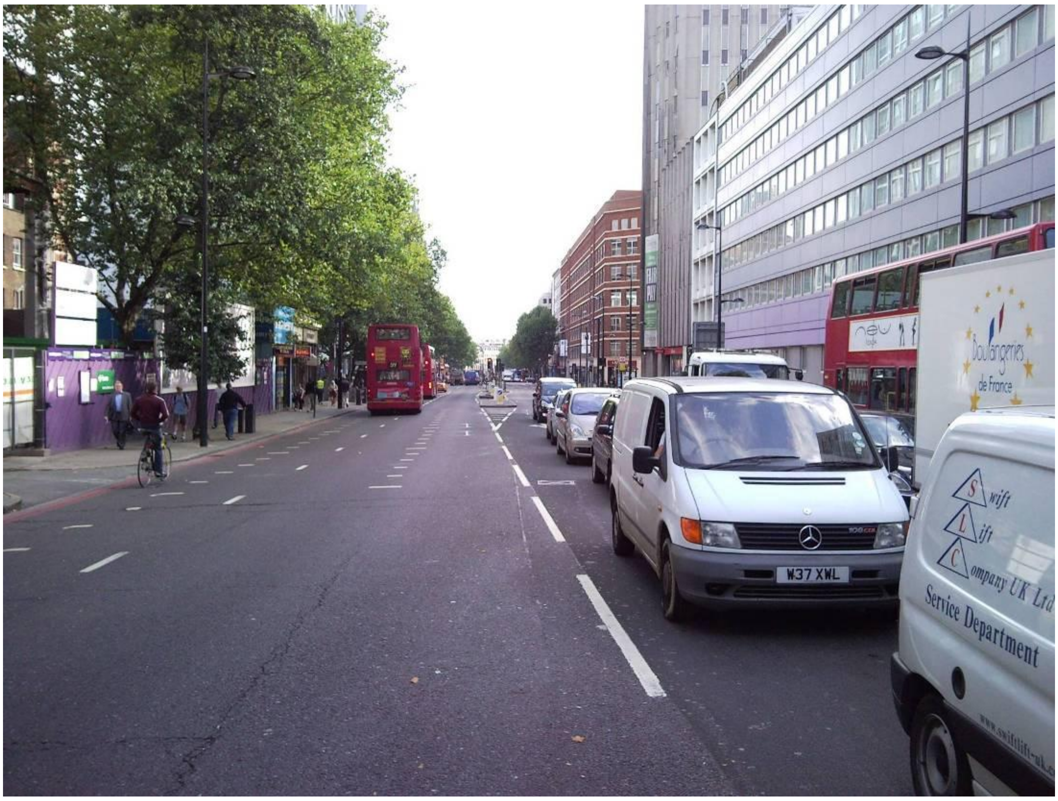

Figure 15: Link C – west to east view

Figure 16: Link C – east to west view

Figure 17: Link D – west to east view

Figure 18: Link E – west to east view

Figure 19: Link F – west to east view

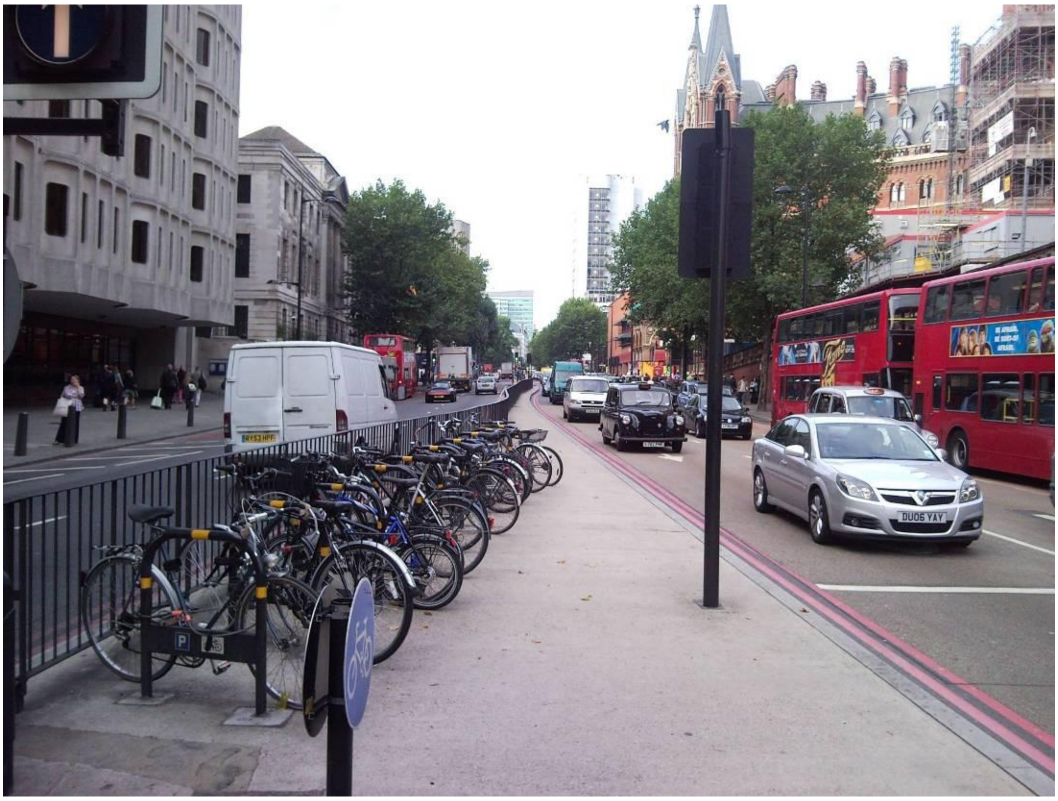

Figure 20: Link G –east to west view

Physical Attributes Marble Arch

Link	Length (m)	Typical Road Width (m)	Orientation	Number of Lanes	Bus Lanes	Cycle Lanes	Width of Central Reservation (m)	No. Major Junctions	Pedestrian Crossings	Average Width of Pavement (m)	Red Route
A	48	20.1	N-S	4	1	0	n/a	Start and finish	I at n end	None (W); ~3 (E)	Y
B	55	8.5	NE-SW	2	0	0	n/a	Link is a slip road forming part of a Jcn	1 at SE end	none (NW); ~2 (SE)	Y
C	62	15	E-W	4	Bus stop filling much of lane	0	n/a	1 at east end	no	1 (N); 3.5 (S)	Y
D	73	15	E-W	4	Bus stop filling lane	0	n/a	1 at west end	At western end	none (N); 3.5 (S)	Y
E	62	13.7	SSE-NNW	4	0	0	n/a	2 - one at either end	0	5 (W); none (E)	Y
F	28	10.6	SW-NE	3	0	0	n/a	Link forms park of Jcn slip road	1	None on either side - NW side is a traffic island	Y
G	53	11.5	W-E	5	0	0	n/a	one at either end	0	6.7 (including underpass entrance) (N); 1 (S)	Y
H	47	10.8	W-E	4	0	0	n/a	Adjacent	1	Traffic island (N), 1 (S)	Y
I	99	19.3	W-E	6	0	0	n/a	1	2	2.2 (N); 1 (S)	Y
J	66	8.73	S-N	0	2	0	n/a	0	0	1.5 (E); 1.5 (E)	Y

Link	Sources of Dust	Description of Vegetation	Street Canyon	Description of Buildings	Typical Building Height	Road Surface
A	n/a	East forms boundary of park/green area	N	Mariott Hotel to the west	n/a	Metalled in fair condition
B	n/a	Park and mature trees on both sides	N	n/a	n/a	Metalled in fair condition
C	Loose soil in park.	Park on either side with mature trees	N	n/a	n/a	Metalled in fair condition
D	Loose soil in park.	Park on either side with mature trees	N	n/a	n/a	Metalled in fair condition
E	Loose soil in park.	Park/ trees on either side	N	n/a	n/a	Metalled in fair condition
F	Roadworks. Cutting into pavement with inadequate water suppression	Park on SW side	N	n/a	n/a	Metalled in fair condition
G	Loose soil in park.		N	Tall old buildings set back from the road on the northern façade	n/a	Metalled in fair condition
H	Big hole in roundabout (looked like digging for a water main etc) and therefore loose soil.	Park to the south; mature trees on both sides	N	At junction - no adjacent buildings	n/a	Metalled in fair condition
I	n/a	Park (s) Mature Trees	N	Tall buildings to the north	n/a	Metalled in fair condition
J	Loose soil in park.	Park and trees on either side	N	n/a	n/a	Metalled in fair condition

Marble Arch

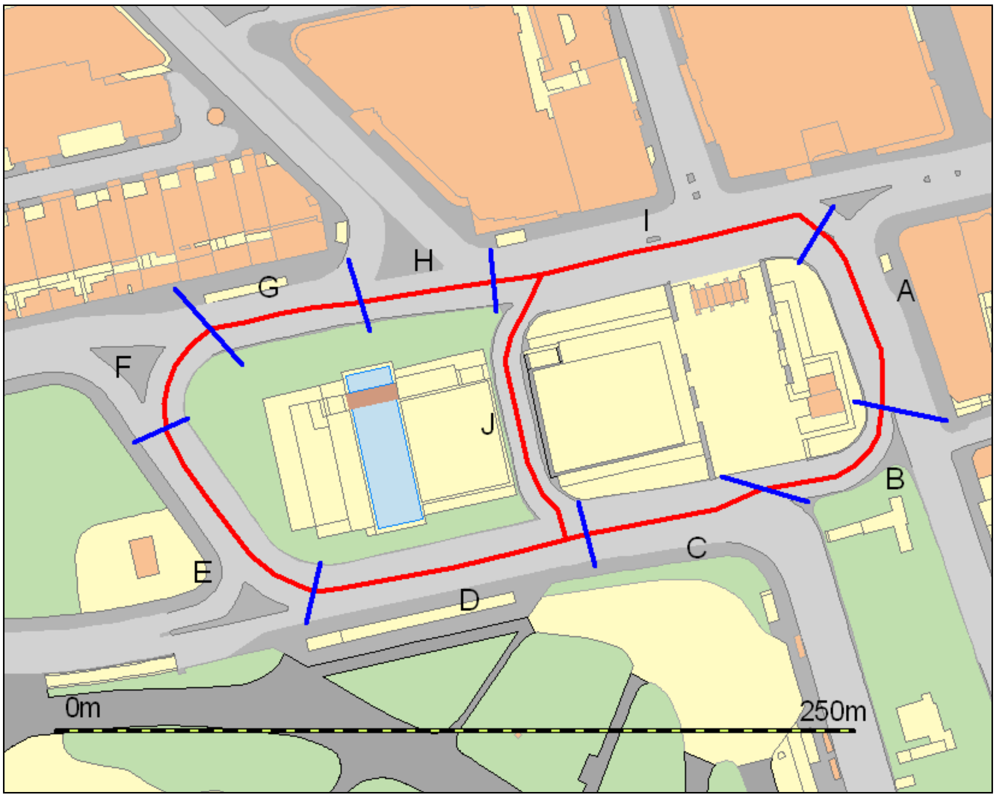

Figure 21: Marble Arch

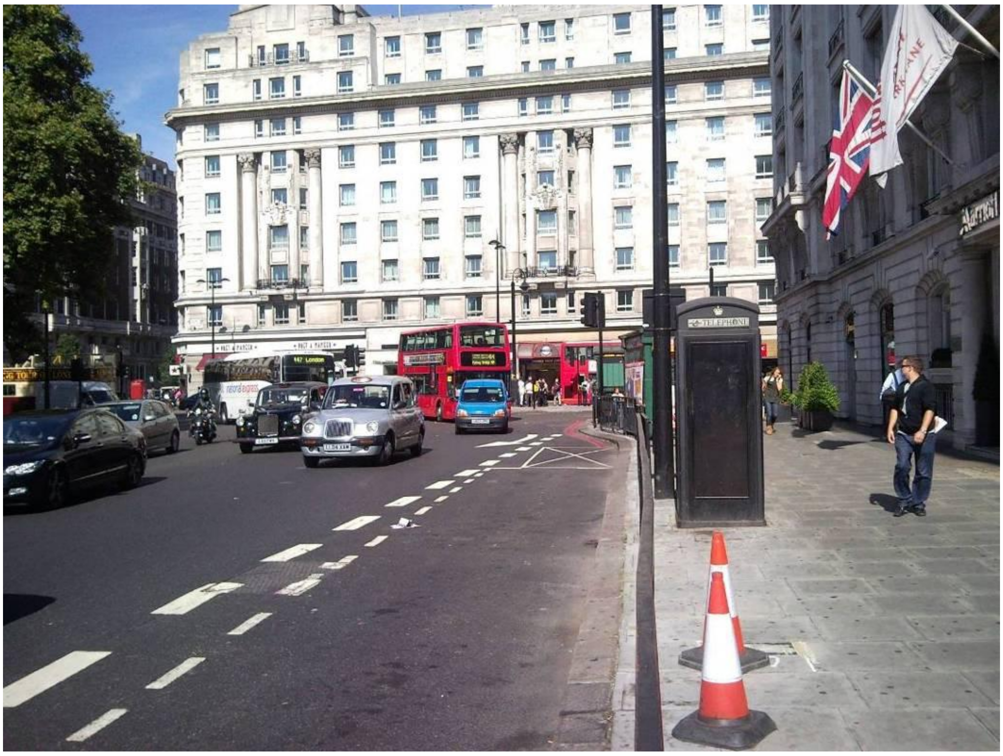

Figure 22: Link A – south to north view

Figure 23: Link B – north to south view

Figure 24: Link C – west to east view

Figure 25: Link D – west to east view

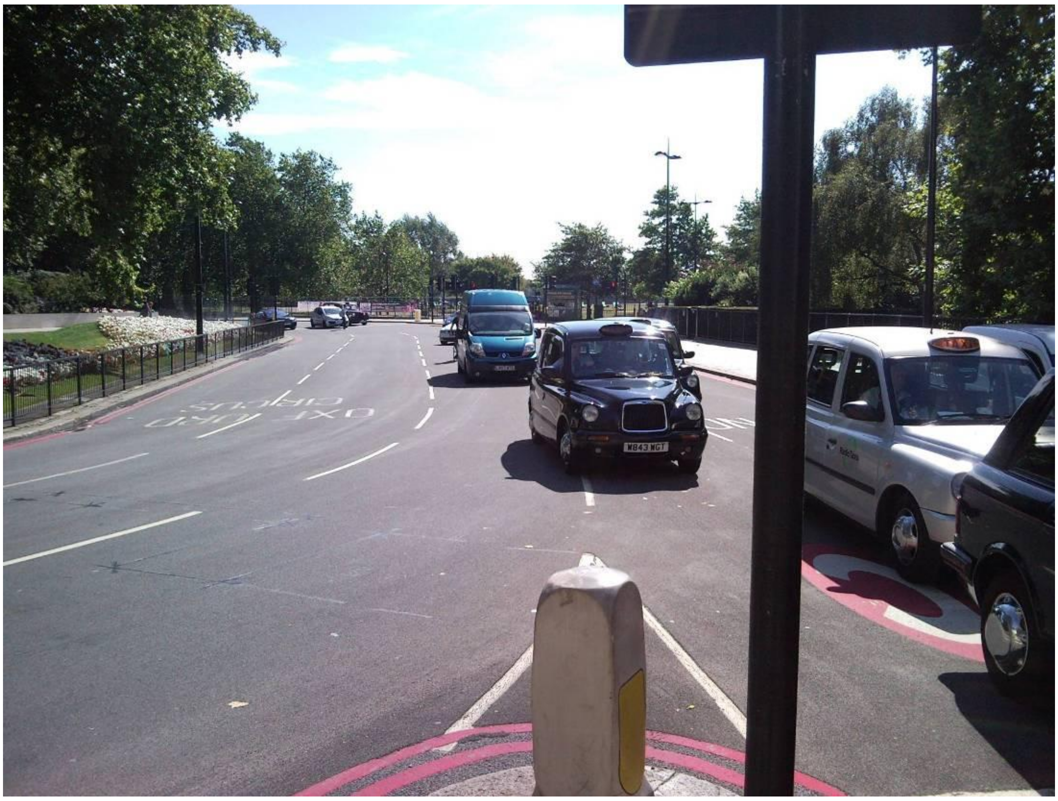

Figure 26: Link E – north to south view

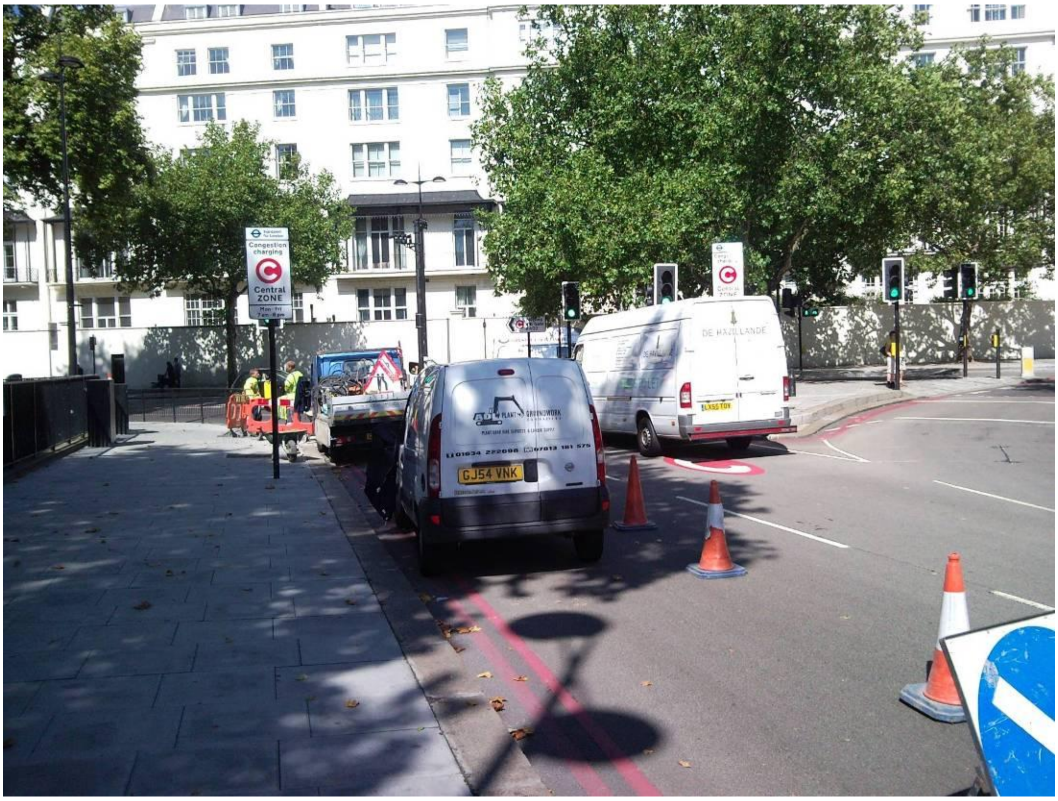

Figure 27: Link F – south to north view

Figure 28: Link G – east to west view

Figure 29: Link H – east to west view

Figure 30: Link I – east to west view

Figure 31: Link J – south to north view

Physical Attributes Tower Hill

Link	Length (m)	Typical Road Width (m)	Orientation	Number of Lanes	Bus Lanes	Cycle Lanes	Width of Central Reservation (m)	No. Major Junctions	Pedestrian Crossings	Average Width of Pavement (m)	Red Route
A	58	12.7	W-E	4	0	0	0	0	1 (signalised)	3.8 (N), 3.2 (S)	Y
B	177	19.8	W-E	5 (3 eastbound)	0	0	0.5	1 (signalised)	0	3-4.3.0 (N), 3.7 variable (S)	Y
C	83	7.7	W-E	2 (one way westbound)	0	0	0	1 (signalised)	0	2	Y

Link	Sources of Dust	Description of Vegetation	Street Canyon	Description of Buildings	Typical Building Height	Road Surface
A	Noted that street cleaner was sweeping dust from pavement into road.	Little vegetative cover	N	All main buildings set well back from road.	n/a	Metalled in fair condition
B	Areas to both north and south of road given over open to grassed spaces - in parts these are very worn with bare, exposed soil. May generate wind blown dust.	Mature trees planted at back of pavements bordering onto parkland or Tower. Vegetation will not affect PM emissions from traffic to pavement.	N	All main buildings set well back from road.	n/a	Metalled in fair condition
C	Muli storey car park at Minories, but unlikely to be significant.	Some mature tree planting on south pavement, but canopy at 3 m height.	Y	Shorter Street forms a short street canyon, with buildings to 7 storeys (approx 20m) either side	20m	Metalled in fair condition

Tower Hill

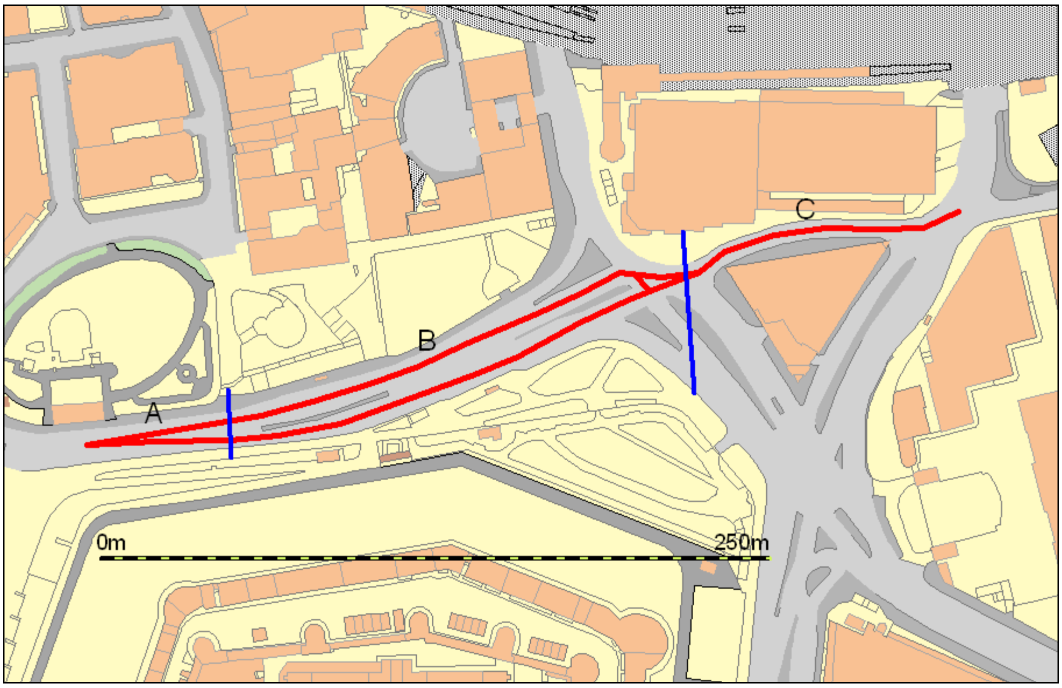

Figure 32: Tower Hill

Figure 33: Link A – west to east view

Figure 34: Link A – west to east view

Figure 35: Link B – east to west view

Figure 36: Link B – west to east view

Figure 37: Link C – east to west view

Physical Attributes Victoria Embankment

Link	Length (m)	Typical Road Width (m)	Orientation	Number of Lanes	Bus Lanes	Cycle Lanes	Width of Central Reservation (m)	No. Major Junctions	Pedestrian Crossings	Average Width of Pavement (m)	Red Route
A	225	18.5	W-E	4	0	0	1.7	1 (signalised) Temple Pl East	1 (signalised) at mid point of link	5.7 (N), 6.7 (S)	Y
B	196	18.5	W-E	4	0	0	1.7	1 (signalised) Temple Pl West	1 (signalised) at mid point of link (Cleopatras Needle)	6.0 (N), 6.1 (S)	Y
C	500	18.5	SW-NE	4	0	0	1.7	2 (signalised) Savoy Stett and Charing Cross	1	5.2 (N), 6.2 (S)	Y

Link	Sources of Dust	Description of Vegetation	Street Canyon	Description of Buildings	Typical Building Height	Road Surface
A	No obvious sources. No significant dust accumulated in gutter	Mature trees planted at both north and south pavements at distances of approx 15m apart, and close to kerbside. Canopy height approx 3 m. On north side, Temple Gardens is to north with additional mature trees and shrubs.	N	North side bounded by Temple gardens: south side bounded by river.	n/a	Metalled in fair condition
B	No obvious sources. No significant dust accumulated in gutter	Mature trees planted at both north and south pavements at distances of approx 15m apart, and close to kerbside. Canopy height approx 3 m. North side bounded by Somerset House.	N	North side bounded by Somerset House: south side bounded by river.	n/a	Metalled in fair condition
C	No obvious sources. No significant dust accumulated in gutter	Mature trees planted at both north and south pavements at distances of approx 15m apart, and close to kerbside. Canopy height approx 3 m. On north side, Victoria Embankment Gardens contains further mature planting.	N	North side bounded by Victoria Embankment Gardens: south side bounded by river.	n/a	Metalled in fair condition

Victoria Embankment

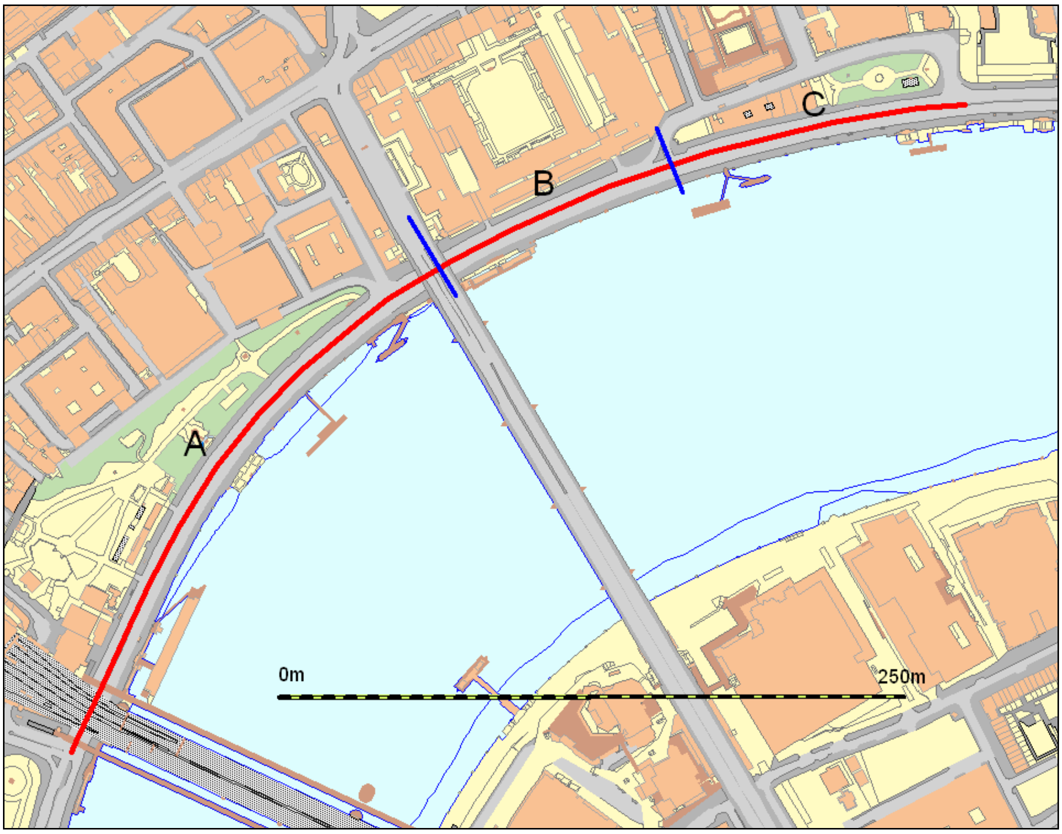

Figure 38: Victoria Embankment

Figure 39: Link A – east to west view

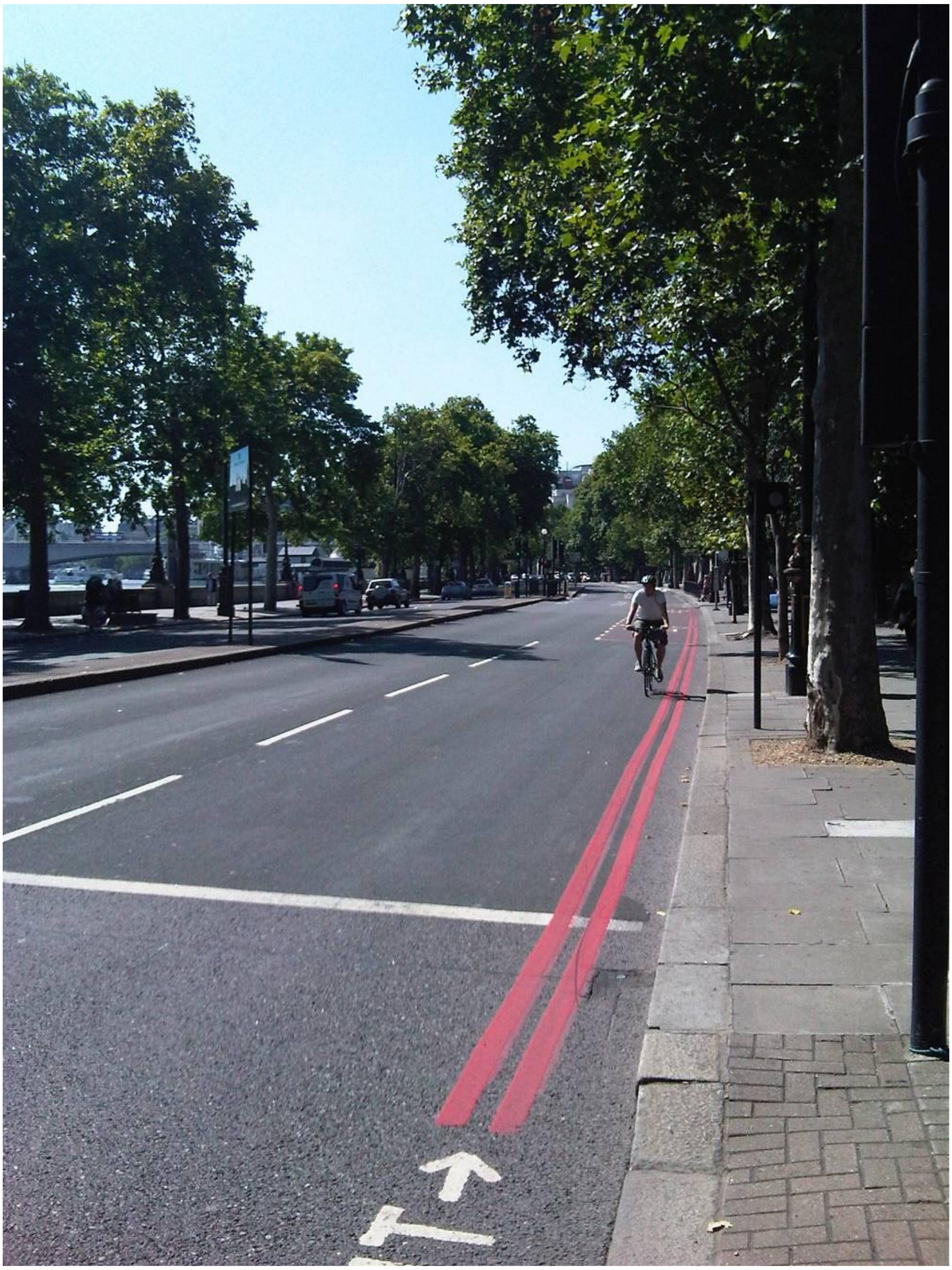

Figure 40: Link A – east to west view

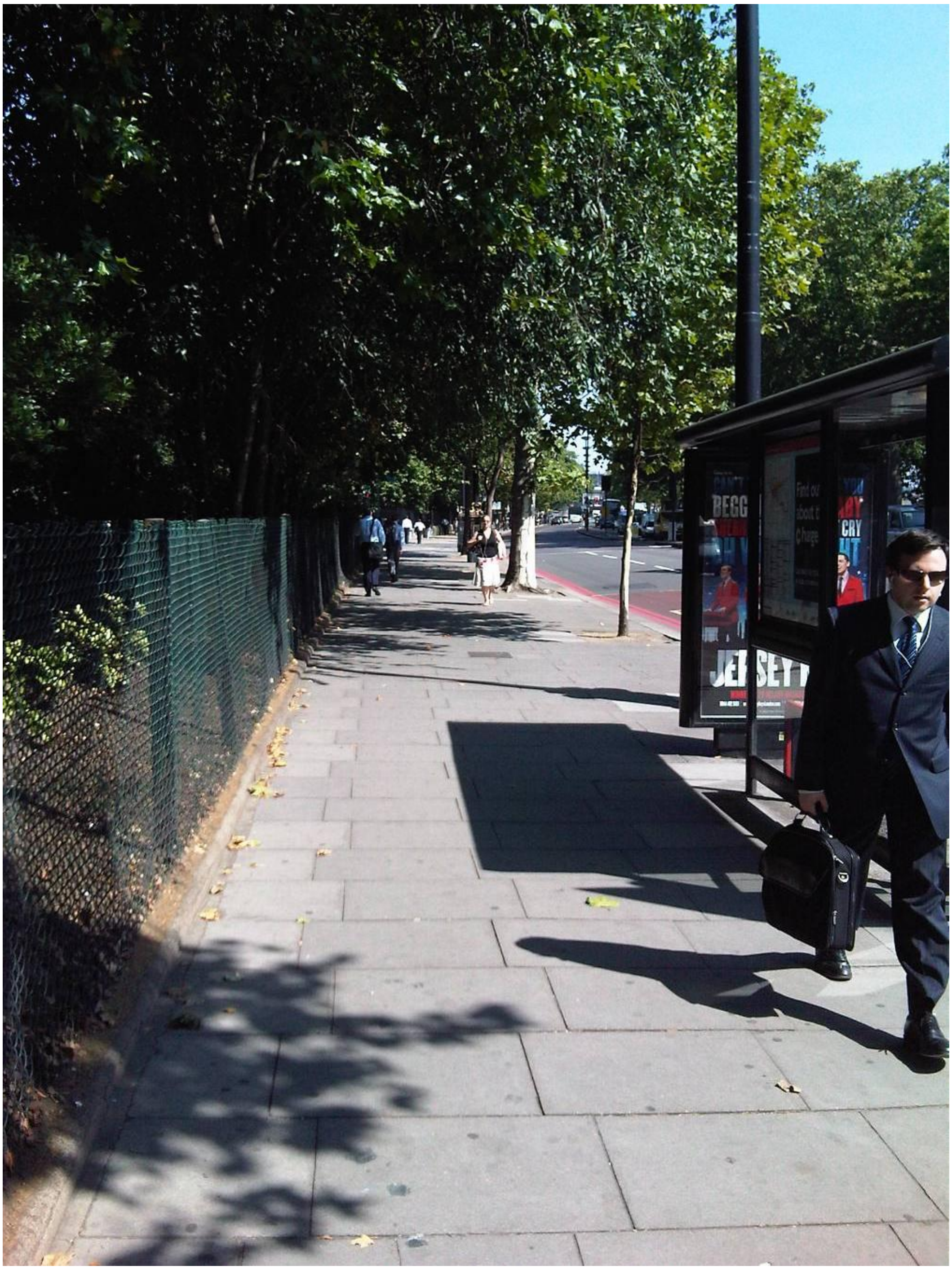

Figure 41: Link A – west to east view

Figure 42: Link C – east to west view (Savoy Place junction)

Figure 43: Link C – west to east view

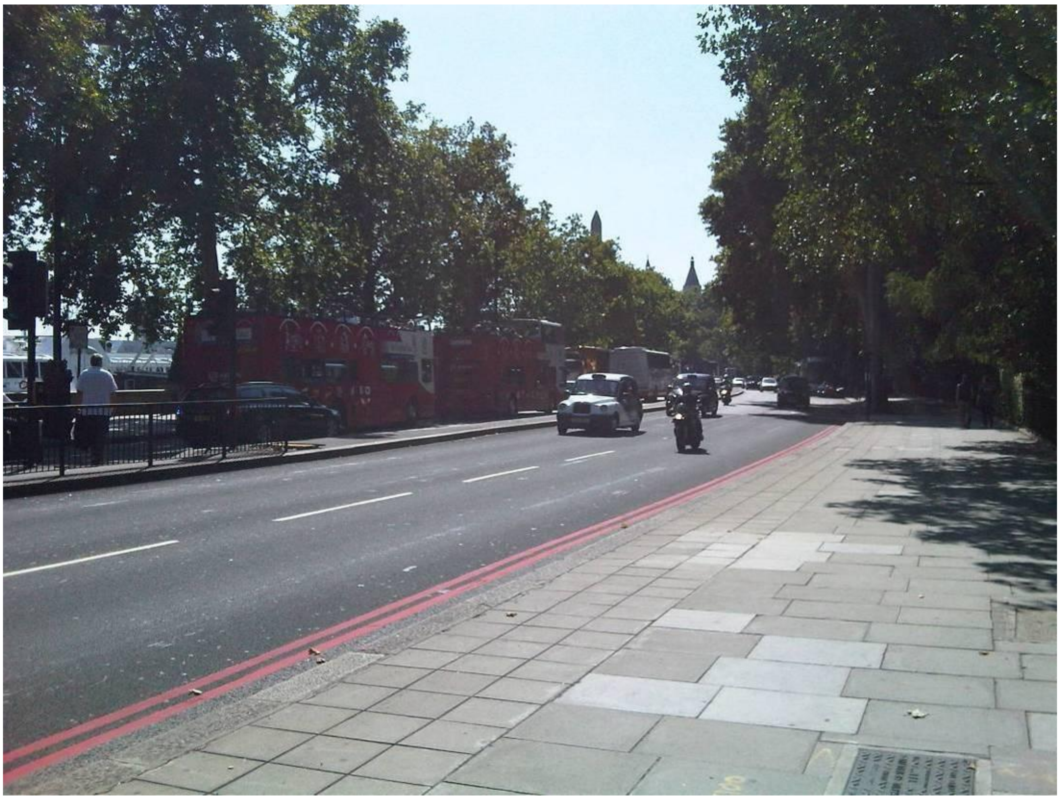

Figure 44: Link C – east to west view

13 Appendix 2: Literature Review

Introduction

13.1 This Appendix presents the detailed findings from Phase 1 - the literature review of local measures. The review takes into account journal publications, reports, and experience from recent projects in other countries, such as the Dutch Air Quality Innovation Programme (IPL)[13]. The measures can usefully be divided into those which reduce the amount of PM emitted into the air around the hotspots and those which reduce exposure to the PM that has already been introduced into the atmosphere.

13.2 The following measures are considered in the subsequent Chapters:

Reducing emissions

- Road and vehicle cleaning (*e.g.* sweeping, washing) (Chapter 1)
- Dust suppressants (Chapter 2)
- Traffic management (*e.g.* shared space, car-free-days) (Chapter 3)
- Other measures to limit emissions (Chapter 4)

Limiting Exposure

- Barriers and tunnels, including noise barriers, conventional tunnels and lightweight canopies (Chapter 5)
- Vegetation (Chapter 6)
- Other measures to limit exposure (Chapter 7)

13.3 The report draws heavily on, and updates where appropriate, previous TRL reviews of abatement measures for non-exhaust PM (Boulter *et al*., 2007a; Reeves *et al*., 2008).

[13] IPL was established in 2005 to identify measures which could be used to improve air quality alongside motorways in the Netherlands. The aim of IPL was to identify, develop and test local measures that could contribute to improving air quality (NO_2 and PM_{10}) alongside motorways. By the end of 2009 IPL will make policy and implementation recommendations on the potential and the limitations of the measures which have been identified.

Road and Vehicle Cleaning

Overview

13.4 The suspension (or resuspension) of material previously deposited on the road surface can be an important source of PM_{10}, and will increase in importance as exhaust emissions decrease. In order to reduce resuspension, either prevention or mitigation strategies can be adopted. Prevention strategies - such as covering truck loads – aim to avoid the deposition of dust on the road in the first place. Mitigation measures attempt to remove or bind those particles already deposited. This Chapter considers the potential impacts of cleaning roads and vehicles on roadside PM_{10}.

Road cleaning

13.5 The cleaning of the road surface is a commonly used mitigation method for removing road dust. Sweeping and vacuuming have regularly been applied in several countries as means of decreasing the silt loading of paved roads (thus reducing PM re-entrainment), and there is a significant body of literature relating to these control options.

13.6 Purpose-built vehicles are usually employed, but the method of operation varies. The cleaning process can involve mechanical (broom) sweeping, vacuuming, spraying (with water), or a combination of these. The US Federal Highway Administration lists various types of street sweeper, and their main characteristics are summarised below (FHWA, 2008):

Mechanical broom sweepers. The conventional mechanical sweeper typically uses a rotating broom to lift material from the road surface or gutter area. The removed particles are then carried onto a conveyor belt and into a storage hopper. A water spray is generally used to control dust.

Vacuum-assisted sweepers. The vacuum sweeper also uses a broom to loosen dirt and debris from the road surface. However, the material is then placed in the path of a vacuum intake that transports it to the hopper. Again, the transported dirt is usually saturated with water.

Tandem sweepers. Tandem sweepers employ two successive cleaning passes: a mechanical (broom and conveyor belt) sweeper, followed immediately by a vacuum-assisted sweeper.

Vacuum-assisted dry sweepers. These combine the important elements of tandem sweeping into a single unit. The mechanical sweeping component is completely dry. A specialised rotating brush is used to scratch and loosen dirt and dust from impervious surfaces, allowing the vacuum system to recover practically all particulate matter. A continuous filtration system prevents very fine particulate matter from leaving the hopper. Vacuum-assisted dry sweepers are noisier and more expensive to purchase than mechanical sweepers, but they require less maintenance than water-based sweepers. They are also slower than a mechanical sweeper, and cannot be used in rain or on wet roads.

Regenerative air sweepers. In regenerative sweepers the cleaning air is filtered and re-used. Air is blown onto the pavement and immediately vacuumed back to entrain and capture accumulated sediments. Air is regenerated for blowing through a dust-separation system.

13.7 A simpler approach is the spraying of water onto the road surface in an attempt to reduce resuspension on dry days (an example is shown in Figure 1). Indeed, a water flushing approach is routinely deployed in many European countries, where the edges of roads are routinely washed.

Figure 1: Spraying with a water tank (Municipality of Nijmegen et al., 2007).

13.8 In the past, the primary objective of street sweeping was to remove debris from the road for reasons of aesthetics and safety, and to prevent the blockage of gulley pots and drains. Most sweepers were not designed for fine particle removal. However, some new street sweepers are specifically designed to reduce PM_{10} concentrations. In California, Rule 1186 of the South Coast Air Quality Management District requires local governments to procure street sweepers which are certified as being PM_{10} efficient (greater than 80% reduction in PM_{10} material). Regenerative and vacuum-assisted dry sweepers are used to meet the requirements. According to FHWA (2008), vacuum-assisted dry sweepers are especially effective at removing PM_{10} compared with conventional sweepers (Table 3). It states that vacuum-assisted dry sweeping can remove 99.6%

of PM_{10}. On the other hand, the data in Table 3 suggest that older, mechanical sweepers can, in fact, create more airborne particulate matter.

Table 3: PM_{10} removal efficiencies for various sweepers (FHWA, 2008).

Sweeper type	Removal efficiency (%)
Mechanical - Model 1	-6.7 to 8.8
Regenerative air	31.4
Vacuum-assisted wet	40 to 82
Vacuum-assisted dry	99.6

NB: The values in this Table relate to the reduction in PM on the road and not to roadside concentrations of PM.

13.9 The effectiveness of a particular street sweeping programme depends upon several factors, including the time of year, the silt loading of the road, the type of road surface, the type and operation of the equipment, the sweeping frequency, the number of passes, and the climate (USEPA, 1995; FHWA, 2008). Sweeping appears to be most effective in areas with distinct wet and dry seasons.

13.10 A substantial body of research exists on the effectiveness of road cleaning approaches, and some of this work has previously been reviewed by TRL (Boulter *et al*., 2007a; Reeves *et al.,* 2008). The following paragraphs update the earlier TRL reviews.

13.11 Early studies in the 1980s showed promising results in terms of the removal of particles from the road surface. Ellis and Revitt (1982) found street sweeping to be particularly efficient at removing solid particles larger than 250 µm, and Duncan *et al.* (1985) designed an 'improved' sweeper to remove finer solids. It was found that a broom sweeper removed 20% of the solid particles on the road surface, a vacuum sweeper removed 70%, and the improved sweeper removed 80%. It was estimated that a thorough sweeping programme could reduce the emissions from paved roads by approximately a third. Similarly, Cowherd *et al.* (1988) found that the emission reduction for PM_{10} on paved roads was in the range of 33–37% following a street sweeping programme.

13.12 More recently, Fitz and Bumiller (2000) noted that most sweepers achieved greater than 97% collection efficiency on their first pass. Bris *et al.* (1999) tested the efficiency of particle removal of the water jet street-cleaning procedure used by Paris city workers. The cleaning efficiency for solids was highly variable (20–65%), and somewhat higher for larger solid particles. The removal efficiency for the total street deposit was around 25%. The authors also concluded that the removal and collection efficiency for particles smaller than 50 µm was probably small. Gromaire *et al*. (2000) found that the pollutant load removed from the street surface by cleaning with water on a daily basis was similar to that removed during one rainfall event, and that street cleaning can preferentially wash away the suspendable solids and organic matter on road.

13.13 However, several studies have shown a tendency towards only limited effects on ambient PM_{10}. When Chow *et al.* (1990) determined the source contributions to PM_{10} concentrations during street sweeping periods and non-street sweeping periods in Reno, Nevada, no significant differences in the resuspended contributions to PM_{10} were detected. Work in California indicated that the use of vacuum street sweepers had no significant effect on PM_{10} levels (Fitz, 1998; Fitz and Bufalino, 1998), and Kantamaneni *et al.* (1996) only observed a significant decrease in PM_{10} emission by sweeping when the relative humidity was lower than 30%.

13.14 The Regional Environmental Agency for Lombardy undertook a field test in Milan during the winter of 2002 aimed at determining whether any reduction in PM_{10} concentrations could be obtained by the washing and mechanical brushing of roads (cited in CAFE, 2004). An area of 1 km^2 in the city centre was washed several times every night for ten days. The variation in PM_{10}, both in concentration and composition, at two different heights (2 m and 25 m) was investigated and compared with a reference site outside the test area. No substantial reductions in PM_{10} concentrations were observed.

13.15 The effectiveness of measures to control the resuspension of paved road dust has also been investigated in the United States using a vehicle-based method for measuring road dust emissions called TRAKER[14]. Using TRAKER in Idaho, Kuhns *et al.* (2003) and Etyemezian *et al*. (2003) compared the PM_{10} emissions from paved roads that had been swept or vacuumed with roads with no treatment. Although large particles were removed, neither the sweeping nor the vacuum cleaning had any significant effect on the emitted PM_{10} levels compared with the upswept control section. Indeed, the results indicated that PM_{10} emissions immediately after sweeping increased by up to 40% (Kuhns *et al.*, 2003).

13.16 Trials in Helsinki and Oslo also did not show reductions in PM_{10} concentrations after sweeping (Gustafsson, 2004).

13.17 In Taiwan, Chang *et al.* (2005) undertook extensive measurements to evaluate the effectiveness of modern street-sweeping equipment (a modified regenerative vacuum sweeper and an efficient washer) for controlling ambient TSP. Various wind speeds, traffic volumes and silt loading levels were investigated. The results showed that street sweeping followed by washing offered a

[14] TRAKER = testing re-entrained aerosols kinetic emissions from roads.

reduction in TSP of up to 35%. However, the direct impact of sweeping was short-lived, lasting no more than 3-4 hours.

13.18 Norman and Johansson (2006) evaluated the PM_{10} levels associated with intense sweeping of the road surface in Stockholm. A road in the city was cleaned nightly using mechanical sweepers, and the PM_{10} levels were compared with those on another street having the same orientation and similar meteorological factors, such as wind direction, wind speed and road surface dryness. No statistically significant reduction (<10%) in PM_{10} concentrations was observed alongside the swept street during the periods with intense sweeping. Indeed, in most cases the results showed an increase in the PM_{10} during days with sweeping. PM_{10} levels were also found to be higher than during the same period of the previous year, when the street was swept at a normal frequency.

13.19 Another recent study during winter conditions in Nevada by Gertler *et al*. (2006) also found a significant increase in the PM_{10} emissions (from 660 mg/km per vehicle to 735 mg/km) after the sweeping and washing of the roads. For $PM_{2.5}$ there was a more dramatic increase after sweeping (from 133 mg/km to 211 mg/km).

13.20 In Seoul, South Korea, Kee-Young and Yu-Mee (2006) estimated that typical street cleaning - consisting of vacuum sweeping an average of 1.5 times a day, and washing once a day - removed only 0.56% of PM_{10} on the road surface. They recommended that a speed of 10 km/h was used for vacuum sweepers and washers and that a minimum of 120 m^3 of water per square kilometre was used for effective washing.

13.21 Using a combination of analytical techniques - including the determination of road dust composition, factorial analysis, a chemical mass balance model and the ISC3 dispersion model - Yu *et al.* (2006) estimated the improvement in air quality due to street washing and sweeping in Kaohsiung, Taiwan. The results showed that road washing reduced the annual mean PM_{10} concentration by 1.5-2.1%. The maximum improvement in the annual mean PM_{10} concentration was around 2 $\mu g/m^3$.

13.22 The study in Taiwan by Chang *et al.* (2005) showed reductions in TSP concentrations of up to 35% when both street sweeping and high-pressure washing were used, but no reductions in PM_{10} were observed. Following a review of the literature, Gao and Chen (2006) concluded that washing has minimal impact on PM_{10} concentrations. Tests of the effects of washing with a high-pressure water system were also performed in Stockholm by Norman and Johansson (2006). The verge next to the carriageway was washed during the night when the weather forecast predicted dry road conditions for the next day. On most days slightly lower PM_{10} concentrations were observed due to the washing. The reduction was often greater than 10%, but on two days there were increases in

PM_{10} levels of more than 10%. The average reduction for the study period (21 days) was 6%. For 10 out of the 21 days the daily average PM_{10} level exceeded 50 µg/m^3 compared with 12 days for the untreated stretch. The reduced PM_{10} levels on the washed stretch could, however, have been due to the wetting of the road surface, which reduced suspension of dust, rather than actually removing PM_{10} particles.

13.23 Wet-cleaning trials were conducted on Frankfurter Allee in Berlin during the autumn of 2003 and between June and October of 2004. The road was cleaned twice daily prior to each rush hour, but this failed to generate any measureable reduction in ambient PM concentrations (Senate Department of Urban Development, 2005).

13.24 In the summer of 2006 a trial was undertaken in Nijmegen to determine the effects on PM_{10} of wet sweeping and spraying road surfaces (Municipality of Nijmegen *et al*., 2007). The trial was conducted within the framework of IPL. Different types of road surface - closed asphaltic concrete (CAC) and pervious coated macadam (PCM) - and cleaning regime were examined. PCM was chosen since it has an open structure, whereby rainwater and waste materials pass through the road pavement via small channels and pores towards the hard shoulder. Along the highway the hard shoulder is cleaned once or twice per year using a PCM cleaner (high-pressure spray and vacuum) which cannot be driven on the carriageway. During a two-week period of June 2006 the roads were sprayed four times a day with a water tank behind a tractor unit. In the following period spraying was conducted twice per day. In July 2006 the PCM cleaner was used instead of the tank. Initially, only the hard shoulder was cleaned in conformity with the operational restrictions. One week later the whole road pavement was cleaned. The CAC test section was cleaned regularly over this period with the PCM cleaner. It was concluded that the effect of rainfall on airborne PM was greater than for wet cleaning. This is due to the fact that precipitation not only reduces fine dust emission from the road, but also from all fine dust sources in the vicinity. The PM_{10} emissions from the PCM road were reduced following the use of the PCM cleaner. The PM_{10} emissions from the CAC, on the other hand, were not reduced following the use of the PCM cleaner. Conversely, the PM_{10} emissions from the PCM were not reduced by spraying with water, whereas the PM_{10} emissions from the CAC were reduced. Calculations undertaken using a fugitive dust model indicated that the use of (new) PCM can result in a maximum reduction in PM_{10} concentrations of 8 µg/m^3 at 10 metres from the road compared with the impervious asphalt (CAC). The wet cleaning of CAC under the same conditions resulted in a maximum reduction in PM_{10} of 4 µg/m^3, 10 metres from the road. It was therefore concluded that both the laying of PCM and wet spraying of CAC seem to be potentially effective measures for reducing PM concentrations alongside busy roads.

13.25 As part of an investigation of the effects of dust suppressants inside the Strømsås road tunnel in Drammen, Norway (see Chapter 0), Aldrin *et al.* (2007) observed no clear effect of road sweeping and washing.

13.26 Chou *et al.* (2007) evaluated the effects of street sweeping and washing on the silt load and PM_{10} concentrations. A modified regenerative vacuum sweeper and a washer were used. It was found that the impact of sweeping alone on ambient PM_{10} concentrations was short-lived, lasting no more than about 2-3 h. Sweeping followed by washing was found to offer a measurable reduction in ambient PM_{10} (by up to 16.5%).

13.27 John *et al.* (2007) examined the effectiveness of street cleaning at reducing ambient PM_{10} concentrations in Düsseldorf, Germany. Street cleaning by high pressure watering was carried out between August 2004 and September 2005 on a four-lane road with around 40,000 vehicles per day. PM_{10} concentrations were measured simultaneously, and data of other traffic and urban monitoring sites in Düsseldorf were used for comparison and to correct for changes in meteorological conditions and traffic flows. Analysis of the data showed that PM_{10} concentrations on street cleaning days were between 0.6 µg/m³ and 5.8 µg/m³ lower than those on non-cleaning days. On average, the reduction in the daily mean PM_{10} concentration was 1.8 µg/m³ per cleaning day. When only days without precipitation were considered, the average reduction was 2.9 µg/m³. A reduction of 1.8 µg/m³ per cleaning day equated to a reduction in the annual average of 0.3 µg/m³ for cleaning once per week, and 0.5 µg/m³ for cleaning twice per week. About 6 % of the exceedences of the PM_{10} daily limit value could have been avoided assuming an average reduction of 1.8 µg/m³ (9% for a reduction of 2.9 µg/m³ on dry days). It was noted that additional street cleaning could be carried out when limit value exceedences are predicted. However, the reductions were only achieved for a limited area, and this has to be taken into account when evaluating different abatement strategies.

13.28 Amato *et al.* (2009) evaluated the effectiveness of mechanical sweeping and water flushing on a busy road (a street canyon) in Barcelona, and quantified the benefits in terms of ambient PM_{10} concentrations. Street washing was carried out on eight occasions over several weeks using pressured water. The washed area included active traffic lanes, parking spaces and pedestrian walkways. Prior to the last three washes a mechanical sweeper was used with the aim of removing coarser deposited particles. Two air pollution monitoring facilities were installed alongside the road (one downwind of the other). Both were equipped for PM_{10} filter sampling and continuous measurement of PM_{10}, NO, NO_2, NO_x, wind speed and wind direction. The PM_{10} filters were analysed to determine concentration of various elements, ions, organic carbon and elemental carbon. Continuous PM_{10} monitoring was also performed at four urban background stations, and levels of deposited PM_{10} dust were monitored by periodical sampling from treated and untreated areas. The daily evolution of PM_{10} was evaluated in order to detect any short-term effects of the street washing. At the downwind site, the mean daily PM_{10} concentration decreased by 8.8 μg/m^3 during the 24-hour period after washing. However 3.7–4.9 μg/m^3 of this decrease was due to the meteorological variability at the upwind site, as well as at two of the background sites. Therefore, it was concluded that that the net effect of street washing was a reduction in PM_{10} of 4–5 μg/m^3 (7–10%). The analysis of the PM_{10} filters revealed that, beside a relative increase of exhaust particles during days with treatment, road dust mineral particles were depleted at the downwind site. An opposite trend was observed at the upwind site. Similarly concentrations of Sb, Cu and Fe decreased at the downwind site relatively to elemental carbon, suggesting a mitigation of re-entrainment of deposited brake particles. High efficiencies in reducing deposited dust load were found both for water flushing and mechanical sweeping/water flushing treatment, achieving efficiencies >90% of the deposited PM_{10}. Given these results, it was concluded that street washing represents a useful strategy to mitigate ambient kerbside PM_{10} concentrations.

13.29 The impacts of road cleaning on concentrations of airborne particulate matter are summarised in Table 2. In general, and in spite of the claimed removal efficiencies, the literature indicates that the general effectiveness of road sweeping as means of controlling airborne PM_{10} is limited, and there are some indications that it can actually increase the concentrations of finer particles. The results are rather mixed, probably because ambient particle concentrations are influenced by several factors which add large uncertainties to what appears to be a small effect (Kuhns *et al.*, 2003). Some experiments have indicated that the washing of roads does have some potential benefits. However, these have tended to be rather short-lived or have been observed in areas with quite dry conditions and low relative humidity. In London the levels of humidity and precipitation are considerably higher, and therefore it is unlikely that such potential benefits will be realised. Nevertheless, the effects need to be better quantified.

13.30 Explanations for the limited effectiveness of road cleaning may include the silt loading being rapidly replaced after sweeping to an equilibrium level - which is dependent on factors such as vehicle speed and traffic density - and, in some cases (the Reno study, for example), the equipment not being sufficiently sensitive to detect a change (Fitz and Bufalino (2002). Experiments by Kuhns *et al.* (2001) also demonstrated that distribution of suspendable material on roadways is highly variable. Vaze and Chiew (2002) found that the particle size distribution of street dust after street sweeping is finer compared to that before sweeping. Street sweeping may have an adverse impact on pollutant wash-off because the street sweeper releases the finer material but only removes some of it. Other potential explanations were raised by Aldrin *et al*. (2007). These included the frequency of sweeping/washing being too low to result in any detectable effect given the high natural variation in concentrations of particulate matter, and the removal of only particles which are larger than PM_{10}.

Table 4: Summary of changes in airborne particulate matter following road cleaning.

Study	Location	Cleaning method	Reduction in airborne PM following road cleaning		
			TSP	PM_{10}	$PM_{2.5}$
Cowherd *et al.* (1988)	Colorado (US)	Mechanical sweeper	-	33-37%[a]	-
Chow *et al.* (1990)	Reno (US)	Mechanical sweeper	-	N/S	-
Kantamani *et al.* (1996)	Spokane (US)	Mechanical sweeper	-	30%[b]	-
Fitz (1998)	California (US)	Vacuum sweeper	-	N/S	-
Kuhns *et al.* (2003)	Idaho (US)	Sweeper and vacuum	-	N/S[c]	-
CAFE (2004)	Milan	Washer and mechanical brusher	-	N/S	-
Gustafsson (2004)	Helsinki	Mechanical sweeper	-	N/S	-
Chang *et al.* (2005)	Taiwan	Regenerative vacuum sweeper and washer	Up to 35%[d]	N/S	-
Norman and Johansson (2006)	Stockholm	Mechanical sweeper	-	N/S (<10%)[e]	-
Norman and Johansson (2006)	Stockholm	High-pressure washer	-	6%	-
Gertler *et al.* (2006)	Nevada (US)	Sweeper and washer	-	Increase	Increase
Kee-Young and Yu-mee (2006)	Seoul	Vacuum sweeper	-	<1%	-
Yu *et al.* (2006)	Taiwan	Sweeper and washer[f]	-	1.5-2.1% (≤2 μg/m^3)	-
Municipality of Nijmegen *et al*. (2007)	Nijmegen	Washer	-	≤4 μg/m^3	-
Aldrin *et al.* (2007)	Drammen (tunnel)	Sweeper and washer	-	N/S	N/S
Chou *et al.* (2007)	Taiwan	Regenerative vacuum sweeper and washer[g]	-	≤16.5%	-
John *et al.* (2007)	Düsseldorf	High-pressure washer	-	1.8 μg/m^3 [h]	-
Amato *et al.* (2009)	Barcelona	Sweeper and high-pressure washer	-	4-5 μg/m^3 (7-10%)[i]	-

-	Not reported	*a*	Emissions.
N/S	Not significant	*b*	Only when relative humidity was less than 30%.
		c	Increase in PM_{10} emissions of up to 40% after sweeping.
		d	Lasted 3-4 hours.
		e	Some increases in PM_{10} were reported after sweeping.
		f	Modelled.
		g	Impact of sweeping lasted 2-3 h. More efficient with washing.
		h	Average reduction per cleaning day.
		i	During the 24-hour period after cleaning.

13.31 However, if sweeping or washing can remove particles that could evolve into TSP or PM_{10}, then sweeping may have a beneficial effect on air quality over a long term. Norman and Johansson (2006) considered that although the sweeping did not cause any significant decrease in the PM_{10} levels during the following days, it might still have an effect in the long term, as the removal of large particles might prevent some of the formation of smaller PM_{10} particles later.

13.32 Reductions in average vehicle weight ought to have significant benefits in terms of reducing resuspension. However, it should be noted that passenger car weights have increased over the last two to three decades (Boulter *et al*., 2007a).

13.33 Studies have also shown the PM_{10} resuspension is highly dependent on vehicle speed with the maximum PM_{10} concentrations generated at speeds of 70 km/h (Gustafson *et al.*, 2009). This study also found that the measured PM_{10} concentrations increased linearly with speed (around 680 $\mu g/m^3$ for each 10 km/h increase).

Vehicle cleaning

13.34 There is a tendency for mud and dust to accumulate on vehicles when in service (*e.g.* at industrial, agricultural and other sites), and especially under the wheel arches. The mud and dust, together with corrosion products, can fall onto the road surface during dry conditions, or when affected by spray from the wheel, and subsequently contribute to resuspension.

13.35 The regular washing of vehicle wheels, wheel arches, chassis, bodywork and brakes could therefore reduce the amount of material deposited on the road. It is also fairly undemanding technically, and forms part of best practice in the site management plans for vehicles operating at construction sites. However, for other heavy-duty vehicles and private vehicles this source of road dust is difficult to control, and changes to the infrastructure would probably be required (Boulter *et al.*, 2007a). There is the possibility of installing wet or dry[15] wheel washes in areas with slow-moving traffic, but trials would be required to assess their effectiveness at reducing PM_{10} concentrations. Inexpensive, vehicle-mounted systems for use at construction sites have also been described in the literature (*e.g*. Gambatese and James, 2001).

13.36 An important issue is the origin of the material which collects under vehicles and inside wheel arches. As most drivers keep their cars on the road rather than in, say, muddy fields, the material inside the wheel arch must come predominantly from the road surface itself, and probably occurs during wet weather. In this sense, the wheel arch could potentially be viewed as a short-term sink as long as cleaning takes place. The timing of the cleaning may well be important – if most of the material accumulates during wet weather, then it would be preferable for cleaning to take place once the wet-weather period has ended (Boulter *et al.*, 2007a).

13.37 No information was found in the literature which related specifically to the effects of vehicle washing on airborne particulate matter.

[15] Dry wash systems use an angled grid which flexes the tyre treads open and closed as the vehicle drives over them, loosening mud and debris.

Dust Suppressants

13.38 Dust suppressants (or binders) appear to be an obvious choice for the reduction of resuspension due to road vehicles. Suppressants are chemicals applied to surfaces to maintain the moisture levels or to actually chemically bind the surface material to reduce fugitive dust emissions. Many different forms of suppressant are available, but the main ones in use are summarised below.

Water: Water is probably the oldest, and undoubtedly the cheapest, of all dust suppressants. Moisture leads to the agglomeration of fine particles so that they cannot be resuspended by traffic. The moisture can be added either through spraying or through the application of hygroscopic and deliquescent salts (see below). Water's dust-suppression capacity is short-lived because of evaporation, and cannot be used in cold weather because of the risk of ice formation on the road. Heavy applications of water can penetrate the road to the sub-base, causing major road failure. Regular, light watering has therefore been found to be better than less frequent, heavy watering at reducing dust (Bolander and Yamada, 1999).

Salts: Chloride compounds such as calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$) attract and absorb moisture from the atmosphere and retain it for extended lengths of time, which significantly reduces the evaporation of moisture from the road surface. Thus, they are more effective dust suppressants than water alone. In Helsinki, $CaCl_2$ is used as an acute measure, and in Oslo and Trondheim, $MgCl_2$ is used in combination with road surface cleaning. However, solutions of such salts can cause vehicle corrosion and slippery roads, and can be washed out during wet weather conditions. Calcium magnesium acetate (CMA) has been used at some locations.

Organic non-petroleum dust suppressants: These include lignosulfonates and resins. Lignosulfonates result from the manufacture of paper when lignin is extracted from wood. Lignin is a natural polymer and can bind soil particles together. Lignin occurs in solution with sodium, calcium, ammonium, or magnesium bisulphate. Resins made from combining lignosulfonates and additives can neutralise adverse effects. Lignosulfonates are water soluble and can move out of, or deeper into, a roadway surface with rainfall. These products corrode aluminium unless calcium carbonate is present. Lignosulfonates have a useful duration of six months and work best with fine dusts in dry environments.

Electrochemical stabilisers: These include sulphonated petroleum, ionic stabilisers, and bentonite. These products neutralise soils that attract water and allow bonds to form between particles. Electrochemical stabilisers need to be worked into the road surface.

Synthetic polymer products, including polyvinyl acrylics and acetates. These bind soil particles and form a semi-rigid film on the road. These products are either liquids or powders that are mixed with water. Products are applied in liquid form and require drying. Temperatures during the curing should not approach freezing. Traffic should be diverted from treated areas until drying which can take 12 to 24 hours. Clearly, if applied to the London road network this would lead to the severe disruption of traffic.

13.39 Previous TRL reviews have noted that little quantitative information exists on the environmental impacts from the use of dust suppressants. The use of suppressants appears to be mainly restricted to soils and unpaved roads (*e.g.* Succarieh, 1992; Sanders *et al*., 1997; Gillies *et al.*, 1999). However, with the need to control PM_{10} the interest in suppressants is growing and some new research is available, notably from Scandinavia.

13.40 In Stockholm successful results have been obtained using CMA. For example, a 25% solution of CMA in water was found by Norman and Johansson (2006) to reduced average daily PM_{10} concentrations by around 35%. The impact normally lasted around 10 days, and was strongest when the salt was first spread. Magnesium chloride has also been tested in Stockholm by Road Technology Sweden with good results.

13.41 The effects of four dust suppressants on PM_{10} concentrations were also investigated in other Swedish trials on rural road sections to the south of Linköping (Gustafsson, 2008). Each section of road was 600 meters long, and all the sections were separated by a distance of at least 500 meters. The suppressants chosen were CMA, $CaCl_2$, $MgCl_2$ and sugar solution, and these were sprayed on the road at regular intervals during the spring of 2008. Particulate matter monitoring was undertaken using TEOMs (Tapered Element Oscillating Microbalance), active PM_{10} and $PM_{2.5}$ sampling and passive particle sampling. The amount of dust on the road was also studied using a 'wet dust sampler'. Meteorology (wind, temperature and humidity) was measured at one of the locations. Some preliminary results indicated that the suppressants led to an initial reduction to ambient PM_{10} of around 30-60% after one day, with the effect diminishing, but lasting several days in some cases (Figure 3). It can be seen from Figure 4 that the frictional coefficient of the road surface initially decreased following the application of each binder.

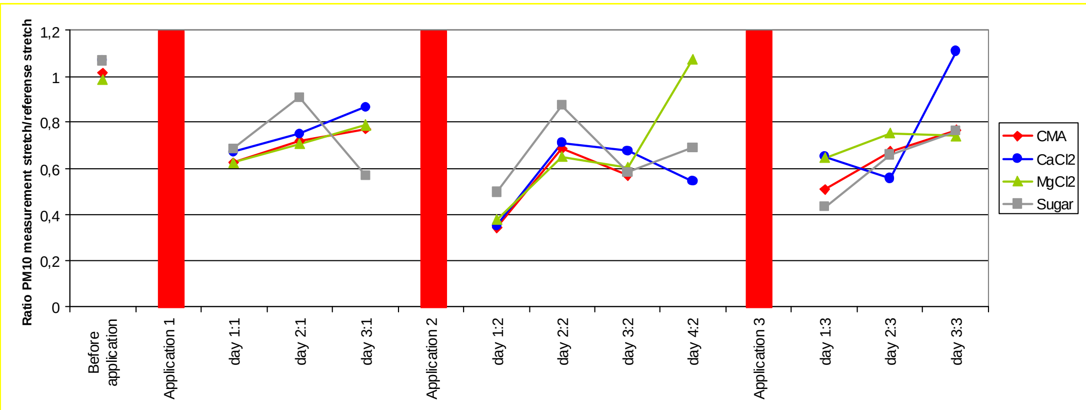

Figure 2: Reduction in PM_{10} following application of dust binders (Gustafsson, 2008).

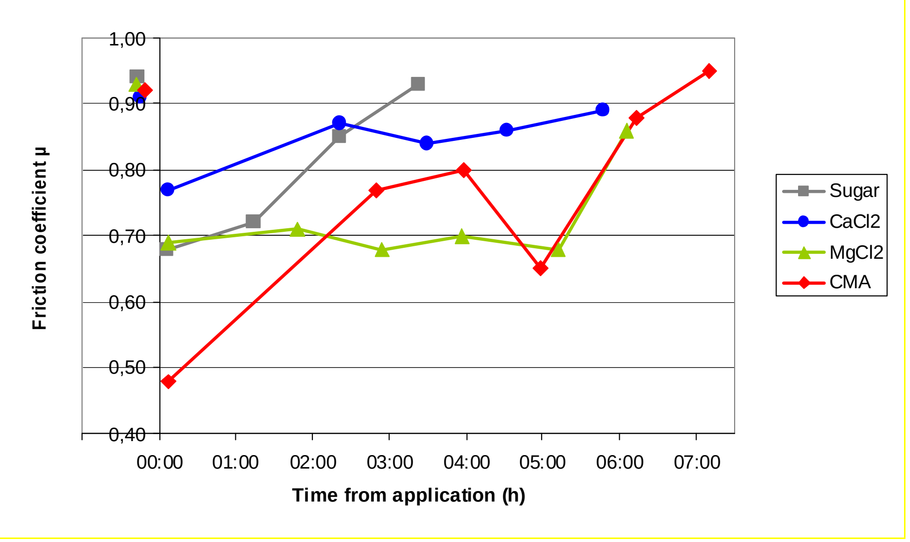

Figure 3: Frictional coefficient following application of dust binders (Gustafsson, 2008).

13.42 In Trondheim (Norway) Berthelsen (2003, cited in Norman and Johansson) reported that following the application of a 15% solution of $MgCl_2$ on a highway, an average reduction in PM_{10} levels of 17% was observed during dry days. The effect was increased if the application was repeated several days in a row.

13.43 In their study conducted inside the Strømsås road tunnel in Drammen, Norway, Aldrin *et al.* (2007) found the application of magnesium chloride reduced the concentration of PM_{10} by 56% ($PM_{2.5\text{-}10}$ by 70% and $PM_{2.5}$ by 17%). The typical duration of the salting effect was estimated to be around 10 days. The effect was largest immediately after salting, and diminished steadily thereafter. It was also found to be more effective to repeat the salting treatment more often than to increase the amount of material being used.

13.44 The effects of $CaCl_2$ as a dust suppressant are also being investigated on high-speed roads in the Netherlands as part of IPL. At the time of writing no results were available from this work.

13.45 Gertler *et al.* (1996) found that following the application of brine (NaCl) solution and the drying out of the road surface there was 30% increase in the paved road emission factors for PM_{10} and $PM_{2.5}$.

13.46 One potential suppressant that does not appear to have been considered is the role of resins released by vegetation which will make the surface sticky and thereby bind the dust, reducing the opportunity for resuspension. This could make a difference along tree-lined streets, but would probably be strongly seasonal and dependent upon the type of tree.

13.47 A summary of the information obtained from the literature is presented in Table 3. It is clear that dust suppressants have the potential to be used in the control of airborne particulate matter for the purpose of compliance with air quality legislation. However, one concern is that some dust suppressants pose environmental hazards which are worse than the dust itself, and the effects of these are unknown. Other concerns are cost, and the possibility that suppressants create an impervious surface, resulting in increased run-off and hydrological impacts during periods of rainfall. Whilst the results from the use of dust suppressants appear to be beneficial, it is important to note that their use has been largely restricted to pilot studies. However evidence from these trials has indicated that whilst there have been concerns over the reduction in road surface skid resistance, no reports are evident on any increases in accident rates. The latter still requires careful consideration, especially for those routes popular with two-wheelers. Therefore, before dust suppressants are used on roads in London there is a need for further research into both their effectiveness on paved roads and their health impacts.

Table 5: Summary of changes in airborne particulate matter associated with dust suppressants.

Study	Location	Suppressant	Reduction in airborne PM following road cleaning		
			PM_{10}	$PM_{2.5}$	$PM_{2.5-10}$
Aldrin and Steinbakk (2003)[a]	Oslo (motorway)	N/A	N/S	-	-
Berthelsen (2003)[a]	Trondheim	$MgCl_2$	25%	-	-
Værnes (2003)[a]	Trondheim (tunnel)	N/A	~50%	-	-
Tønnesen (2006)[a]	Oslo (tunnel)	N/A	~50%	-	-
Norman and Johansson (2006)	Stockholm	CMA (25% solution)	35%	-	-
Hafner (2007)[a]	Klagenfurt	CMA	29-43%	-	-
Aldrin *et al.* (2008)	Drammen (tunnel)	$MgCl_2$ (20/40 g/m^2)	56%	17%	70%

-	Not reported	N/S	Not significant
N/A	Not available	*a*	Cited by Aldrin *et al.* (2007)

Traffic management

Overview

13.48 The term traffic management applies to any measure that is designed to improve traffic flow or road safety, or to reduce congestion, emissions and noise from traffic. It therefore applies to a wide range of measures, from traffic lights to complex road junctions and bus priority schemes, as well as 'softer' policies that encourage people to use modes of transport other than the private car. This Section reviews local traffic management measures which may be appropriate to the London hot spots.

Measures which influence vehicle operation

13.49 There has been some research into the effects of different types of traffic calming measure on the way drivers operate their vehicles. These types of measure include road humps, pinch-points, speed camera enforcement systems and bus-priority lanes. The effect on emissions from different studies is mixed, with evidence of some measures causing increased emissions. For example, a study by Van Mierlo (2003) showed that road humps caused drivers to slow down then accelerate away, causing an increase in fuel consumption and emissions of more than 50%. Boulter *et al*. (2001) showed that some traffic calming measures increased emissions of NO_x and PM emissions (from diesel cars) by 30%. The more 'severe' traffic calming measures tended to result in the greatest speed reductions, the greatest accident savings, and some of the largest increases in emissions. Therefore, local authorities often may need to adopt a balanced approach when deciding whether to implement such measures.

13.50 A study in Copenhagen found that buses driving in bus lanes avoided the stop-start driving pattern of other traffic in urban areas, and this resulted in a reduction of 5 to 15% in bus emissions of NO_x and PM. By incorporating bus priority signals in connection with bus lanes, there was estimated to be a further reduction of NO_x and PM emissions of 15 to 30% (Krawack, 1993). However, although this may increase bus speeds, signal priorities can often delay the other traffic, outweighing any benefits seen in terms of reduced bus emissions.

13.51 Traffic signals that are designed to operate to control speed have been shown to increase NO_x emissions by up to 40% as drivers change their characteristics from idling, to acceleration, deceleration and cruising past the signal (Coelho *et al*, 2005).

13.52 Urban traffic control systems which modify traffic signal timing in response to traffic demand - such as SCOOT (Split Cycle Optimisation Offset Technique) and MOVA (Microprocessor controlled Vehicle Actuation) - can reduce fuel consumption and emissions within the area covered by a network. Data on the effect of SCOOT on fuel consumption show that such systems have the potential to reduce fuel consumption by up to 15-18% compared with uncoordinated signals. Evidence of a reduction in emissions is less well documented, but may be up to 15% for HC, CO and NO_x (Cloke *et al.*, 1998). Ash *et al.* (1999) suggest that from experience in Leicester using SCOOT in normal mode to co-ordinate signals could reduce emissions of NO_x by 6% and PM_{10} by 10%. Co-ordinating the signals for emissions could lead to an additional 4% reduction in emissions. Krawack (1993) found that modifying signal timing to smooth traffic flow reduced NO_X emissions by 10-25% compared with emissions from normal rush hour traffic conditions, and Van Mierlo *et al.* (2003) found that in situations where phasing traffic lights can cause vehicle speeds to remain more constant than before, emissions of NO_x can decrease by 40% and fuel consumption by 20%. TfL already uses SCOOT systems on many traffic lights in London as a means to smooth traffic flow, and this type of control system may be applicable to the five hot spots.

13.53 There are many examples where roundabouts have been introduced to replace crossroads or traffic light controlled junctions in order to reduce traffic congestion and stop-start conditions. A Swedish study (Várhelyi, 2002) used a car-following method to measure emissions before and after the introduction of roundabouts. The study found a larger reduction in emissions and fuel consumption where a roundabout replaced a traffic light controlled junction (29% reduction in NO_x and 28% reduction in fuel consumption) compared with an increase in emissions (6% increase in NO_x and 3% increase in fuel consumption) where a roundabout replaced several junctions. Mandavilli *et al.* (2003) also found that where a roundabout replaced a controlled junction, traffic delays and queues decreased, causing a reduction in NO_x emissions in the afternoon peak by nearly 50%. A similar effect was also observed in a study by Zuger *et al.* (2001), who found that the emission effects were favourable where a traffic light-controlled crossing was replaced by a roundabout. However, when a roundabout replaces a crossroads without signals, it can cause an increase in fuel consumption and emissions, since the roundabout disturbs previously uninterrupted travel, causing vehicles to increase in speed as they approach and brake causing stop-start conditions causing queuing at the roundabout. In such situations Coelho *et al.* (2006) found that NO_x emissions can increase substantially (*e.g.* by over 250%).

13.54 The DfT TRAMAQ project (Traffic Management and Air Quality Research Programme) considered appropriate traffic management measures that could be employed by local authorities during high pollution episodes (McCrae et al, 2000). The project looked at measures such as road pricing, access control, traffic re-routing, signal controls and information provision. The project found that although enforced and voluntary measures were reasonably effective in reducing peak concentrations of pollutants once an episode had commenced, a reliable forecasting/ warning system would be needed to trigger the measure. The costs of some of these measures also outweighed the benefits (Davison *et al*., 2001).

13.55 The application of a traffic management measure as a means to smooth traffic should be considered for the five hot spot areas in Central London. The choice of measure will need to be specific for each hot spot, depending on the reasons for high emissions and suitability of the site for the introduction of these types of measure.

Car clubs and car-sharing

13.56 There are many examples of car club schemes operating in UK cities, including London. Although such schemes can reduce transport emissions the benefits are spread across the city, rather than occurring at a specific location. However, information on these schemes has been included in this review as they could be implemented at these hot spot areas.

13.57 A report produced by the Technology and Policy Assessment Function of the UK Energy Research Centre (UKERC) entitled *What Policies are Effective at Reducing Carbon Emissions from Surface Passenger Transport?* (Gross *et al.*, 2009) states that car clubs appear to help reduce total car miles driven, with members who previously owned a car walking, cycling and using public transport more often. A supporting document[16] - produced in conjunction with the main report - summarises the findings of research into car clubs.

13.58 In the UK, Kollamthodi and Watkiss (2005) estimated a reduction in total road transport emissions of NO_x, PM_{10} and CO_2, based on the assumptions that each person that joins a car club reduces their annual vehicle mileage by 4,500 miles per year, and that an average of 20 people use each car club vehicle (this is based on a target scenario of 1,000 car club vehicles operating in the UK by 2010). The estimated reductions in PM_{10} emissions are provided in Table 6. The impacts on PM_{10} emissions were predicted to be marginal (less than 0.01%).

[16] http://www.ukerc.ac.uk/Downloads/PDF/09/0904TransCarClubsTable.pdf (accessed 2009, August).

Table 6: Estimated reduction in PM_{10} emissions from road transport due to the increase in the number of car clubs (Kollamthodi and Watkiss, 2005).

PM_{10} emissions (kt)	2005	2006	2007	2008	2009	2010	Total (2005-2010)
Baseline total PM_{10} emissions from road transport	25.59	24.16	22.40	20.70	19.14	17.83	129.82
Estimated total PM_{10} emissions with increased number of car clubs	25.59	24.16	22.40	20.70	19.14	17.83	129.82
Emissions abatement against baseline	0.000	-0.001	-0.001	-0.001	-0.001	-0.001	-0.004
Percentage reduction against baseline	-0.002	-0.002	-0.003	-0.004	-0.004	-0.005	-0.003

13.59 Any emissions reductions are likely to be dependent on the change in car mileage, the types of vehicles used and the public transport usage that are expected to result from joining a car club scheme (Ryden and Morin, 2005). As mentioned above, Kollamthodi and Watkiss (2005) assumed a reduction of 4,500 miles per year in the UK. Mulheim and Reinhardt (1999) suggested a slightly lower reduction - around 4,200 miles per year - which equated to a reduction of 72% in vehicle-km travelled. This was partly compensated by an increase in distance travelled by motorcycle and public transport. In a Canadian study, it was calculated that, on average, each club member reduces car distance travelled by approximately 1,800 miles per year (Shaheen and Lipman, 2007). A UK survey of car club members in 2007[17] found that the number of trips made by car reduced as a result of joining a car club scheme by 3.1%-15.8%, and that people made 13.2%-15.2% more journeys by walking and cycling after joining (based on a small sample of members).

13.60 A number of car club scheme case studies are cited in the report entitled *Sustainable Urban Transport Plans (SUTP) and urban environment: Policies, effects and simulations* (Wolfram *et al.*, 2005), including the national framework 'Iniziativa CarSharing' in Italy, where car clubs have been introduced in Turin and Palermo as part of the European funded Mobility Services for Urban Sustainability (MOSES) project. The MOSES project has shown that car club schemes can reduce car use and change mobility patterns towards a larger use of environmentally friendly modes of transport (Ryden and Morin, 2005). It is stated that there is great potential for car club schemes in European cities, where at least 500,000 private vehicles could be replaced by car club services: in Bremen, each car-share vehicle replaces 7-10 private cars, with a resulting car mileage reduction of 45%, and in Belgium each car-share vehicle replaces 4-6 private cars, with a car mileage reduction of 28% (Ryden and Morin, 2005). The MOSES report estimates that car-sharing results in a 40-50% reduction in carbon dioxide (CO_2) emissions, with emissions of other pollutants expected to decrease more (Ryden and Morin, 2005). Associated benefits of car-sharing include a

[17] http://www.carplus.org.uk/Resources/pdf/Monitoring_car_clubs_2007_Report.pdf (accessed 2009, August).

reduction in fuel consumption and a reduction in the number of shorter trips (Ryden and Morin, 2005).

13.61 Ryden and Morin (2005) also identified a shift in the type of fuel used associated with car-sharing: in Bremen and Belgium, approximately 25% of private cars ran on diesel, whereas the share of diesel cars in the car-sharing fleet was lower than 5%. It was concluded, therefore, that the introduction of car club schemes in urban areas is likely to lead to reductions in concentrations of particulate matter due (in part) to the substitution of private diesel-engined vehicles with petrol-engined car club vehicles. In addition, car-share vehicles are often smaller and newer than the private cars they replace (Ryden and Morin, 2005).

13.62 The potential for car clubs to affect air quality within the hot spots under consideration will depend on the type of traffic on the roads and the reasons for these vehicles being there (which will be addressed in Phase 2 of the project). It is likely that car clubs will be more effective in reducing traffic in residential areas than on main roads.

Cycle hire schemes

13.63 A feasibility study carried out by Transport for London concluded that the situation in London is suitable for a cycle hire scheme due to a pronounced increase in cycling and reduction in cycling accidents, coupled with increased spending on cycling facilities and the perceived financial and health benefits which are encouraging more people to use bicycles (TfL, 2008). The study found that cycle hire in other cities has helped to increase bicycle modal share, and has encouraged more people to cycle on private bicycles. Expected benefits for London include a more walking- and cycling-focused city with less motorised traffic, and a reduction in overcrowding on buses and the underground. One of the main risks of a cycle hire scheme for London includes the need for excessive re-distribution of bicycles, potentially increasing congestion and air pollution (albeit marginally). Complementary measures - such as a safety campaign, 20 mph zones, cycle training, improved cycle paths and signage, engineering measures, and conversion of one-way streets to two-way for cyclists - have been suggested to mitigate some of the risks associated with cycle hire schemes. With reference to air quality improvements, the TfL study cites the *Vélib'* scheme in Paris, which promotes the potential for air quality improvement as part of the 'urbanism' agenda and involves the closure of roads and bridges along the Seine to motorised traffic every Sunday. There are several similar examples of cycle hire schemes in other cities in France. London already has a city wide cycle hire scheme in progress which will be complete by May 2010. When complete there will be up to 6,000 bicycles available (GLA, 2009a). This scheme will promote cleaner air, in support of the Mayor's Air Quality Strategy (GLA, 2002), Energy Strategy (GLA, 2004) and Climate Change Action Plan (GLA, 2007). As this type of scheme already exists in London, it would not be suitable as a local measure for these hot spots. TfL also has an extensive cycle network in London and is looking into cycle 'super highways' which could also help reduce the number of cars on the road.

13.64 The UK's National Cyclists' Organisation has conducted research[18] into the attitudes of cyclists and pedestrians towards shared facilities. It was concluded that "shared-use facilities can have a role to play in supporting and encouraging cycling, but they must be well-designed and maintained… it is vital that the environment offered to users is clearly safe, attractive, convenient and of a high quality".

'Shared Space'

13.65 The concept of 'shared space' was first conceived by Hans Mondermann, a traffic engineer from The Netherlands, as a means of achieving traffic speed reductions in a village in North Holland (Clarke, 2006). The term is used to describe "a radically different approach to street design, traffic flow and road safety", which has evolved most rapidly in Denmark, Germany, Sweden and the northern part of Holland, and for which there is a growing range of examples in France, Spain, the UK and other European countries (Hamilton-Baillie, 2008).

13.66 The concept involves controlling behaviour by manipulating the environment in such a way as to encourage drivers to slow down, take more care and to rely on eye contact and human interaction (Clarke, 2006). Shared space streets are different to conventional ones in that they often feature minimal use of traffic signs, road markings and traffic management features. Some shared space streets also feature a 'level surface' that is not physically divided by kerbs or level differences. Clarke (2006) cites an example from Drachten in Holland, where the removal of traffic lights and road markings has prompted traffic to move more freely, with vehicles able to cross the centre in 'rush hour' within 10 minutes, saving over 10 minutes compared with the situation with the traffic lights in place. Existing London examples can be seen on Long Acre (Covent Garden), The Cut (Southwick) and Kensington High Street.

13.67 The European Shared Space research project was undertaken between 2004 and 2008 by seven project partners from five countries (The Netherlands, Belgium, Denmark, Germany and the UK). TRL is currently undertaking a two-year research project for DfT aimed at producing guidance on shared space and level surface schemes.

[18] Cyclists and Pedestrians – attitudes to shared-use facilities. http://www.ctc.org.uk/resources/Campaigns/Cyclists_and_Pedestrians.pdf (accessed 2009, August).

13.68 Shared space schemes in progress in London include Exhibition Road and Walworth Road. Recent examples of Level Surface schemes include New Road, Brighton and Ashford Ring Road (Figure 5).

Figure 4: Ashford ring road before and after reconstruction[19].

13.69 At present there is little quantitative information on the impacts of shared space and level surface schemes on road traffic emissions and air quality. Perceived air quality has occasionally been included in attitude surveys, but such information is of little use where the concern is compliance with a quantified limit value.

13.70 Given the evidence of a successful implementation of shared spaces on the Ashford Ring Road, it is clear that this type of traffic management could be applied, not just to residential streets, but also to those with relatively high traffic flows. The application of shared spaces to Marylebone Road might not be suitable, due to the relatively high existing traffic flows and the knock-on effect of traffic re-routing from this main arterial route. With reference to the 5 hotspots, it is evident that Tower Gateway already has a high pedestrian foot fall and tourist bus services, due to its close proximity with historic buildings and ancient monuments. The application of shared spaces to this location is worth consideration.

[19] *Transportation Professional*, October 2009, pp 30-31.

Home Zones

13.71 A report by TRL (Webster *et al.*, 2006) defines Home Zones as "residential areas designed with streets to be places for people, instead of just for motor traffic". They are residential streets with very light vehicle flows (ideally less than 100 vehicles per hour) (Quimby and Castle, 2006). Examples of the types of measure introduced in Home zones include gateways, 20 mph speed limits, road humps and planting. Home zones are clearly not relevant in the context of this study, which is focussing on hot spots, but they are included for the completeness and because the findings may have some relevance.

13.72 Webster *et al.* (2006) investigated the effectiveness of nine pilot Home Zone schemes by carrying out 'before' and 'after' monitoring, including traffic flow and speed measurements, air quality measurements and noise surveys (air quality and noise surveys were only undertaken for a scheme in Leeds). Traffic speeds were reduced on average by approximately 5 mph (to less than 15 mph) as a result of the Home Zone schemes. It is possible that this reduction was limited by the fact that all nine Home Zones were 'retro-fit', and hence designers were constrained by the geometry of the existing built environment. Traffic flows also reduced at all schemes by an average of approximately 25% (with the exception of one *cul-de-sac*, which showed no change). The results for air quality and noise impacts of the schemes were inconclusive, with a lack of substantial changes in measured noise levels and air pollutant (benzene and NO_2) concentrations detected at the scheme in Leeds (supported by two-thirds of respondents to a questionnaire survey, who thought that traffic and noise pollution had not changed since the Home Zones had been introduced). Approximately three-quarters of respondents at a Home Zone in Ealing reported that noise and pollution had decreased, which could be attributed to the traffic in the Home Zone having been halved (Webster *et al.*, 2006).

Development of mixed priority routes

13.73 Mixed priority routes are defined as streets that carry high levels of traffic and also have a mix of residential use and commercial frontages, a mix of road users, or a mix of parking and deliveries (DfT, 2008a; DfT, 2008b). Following the publication of the strategy for road safety by the Department for Transport, Local Government and the Regions (DTLR) (now DfT) (DTLR, 2002) where mixed priority routes were identified as being the least safe urban road type, the DfT provided grants for local authorities who submitted schemes for inclusion in the Mixed Priority Routes (MPR) Road Safety Demonstration Project (DfT, 2008a; DfT, 2008b). This project reviewed 10 schemes, and aimed to assist in the development of other similar schemes. The main focus of the Demonstration Project was to develop and implement schemes that reduced casualty numbers, provided wider sustainable benefits, and resulted in an improved environment along the route. The objectives were met for all of the selected schemes, including noise and air quality improvements. Some schemes were subject to a quantitative assessment of air quality and noise levels, whereas others were investigated by recording public perceptions of the environment. For example, air quality and noise monitoring associated with a scheme in Crewe showed substantial improvements after the scheme was introduced.

Car-free days

13.74 The aim of a car-free day is to prevent vehicles driving along selected roads in a city for one day in order to give the people who live and work there a chance to experience an environment with fewer vehicles. Car-free days are often organised events, held each year on 22nd September throughout Europe, where entire town centres or streets are closed to traffic and opened up for pedestrians and cyclists to enjoy. In some cases, cities may hold car-free days more frequently or for longer than one day.

13.75 There are some perceived benefits in terms of air quality, noise and CO_2 emissions if streets are closed to traffic, and there is some evidence of these improvements for specific cities. For example, Central Jakarta, Indonesia holds monthly car-free days and continuously monitors air quality (CO, NO and PM) during these events. The monitoring results showed that within the car-free areas on event days, concentrations of dust (total suspended particles) typically decrease by 30 - 52%, CO by between 47 and 73% and NO by between 23 and 79% (Jakarta Environmental Management Board, 2008). However, it has been found that levels of pollution increase in neighbouring streets where diversions cause traffic congestion. Studies in Montreal showed that car-free days have a measurable reduction in concentrations of CO and NO. For example, monitoring of the event in 2003 found that concentrations reduced by 40% in the area closed to traffic, compared to levels on a regular weekday. Levels of PM_{10} were not reported. (Envirozine, 2003).

Access restrictions

13.76 An access restriction applies to either a policy or physical measure that limits the numbers of vehicles entering a specific area. This definition would include a city-wide or local low-emission zone scheme (such as that already existing in London or in cities in Sweden), where certain types of vehicles are only allowed into an area if they meet minimum emission standards. It would also include barriers (such as gates or rising bollards) that physically prevent vehicles from driving to an area, often operating at a certain time of day.

13.77 There are many examples of small-scale access restriction schemes in the UK, including in city centres such as Oxford and Cambridge, where enforced bus gates operate during weekdays or peak times to only allow buses and taxis through. There appears to be no information in the literature to quantify the impacts on these types of restrictions on emissions and air quality.

13.78 In the context of the London hot spots, consideration could be given to the restriction of access (either by physical barriers or by financial measures such as zonal charges or tolls) to the main roads carrying most of the traffic. However, considerable care would be required to ensure that the simple diversion of traffic onto other routes (and possibly the creation of new pollution hot spots) is minimised.

Other traffic management schemes

13.79 The London Road Safety Unit (LRSU) commissioned TRL to undertake a review of simplified streetscape schemes and to consider their applicability in London. The review (Quimby and Castle, 2006) examined schemes from across Europe and reported on safety, access and public attitudes. A scheme in Kensington High Street involved redesigning the area by introducing improvements such as pedestrian crossings, changes to the road layout, footway widening, new paving, trees, cycle parking, removing street clutter and some guard railings. The impacts of the scheme included an overall increase of 7% in pedestrian flows, an increase in cycle flows and a decrease in traffic flows (although in the period between the ‘before’ and ‘after’ studies, congestion charging was introduced and was likely to have had an effect). No specific evidence of impacts on emissions is provided in the report (Quimby and Castle, 2006).

Other Measures to Control Emissions

Active asphalt

13.80 'Active Asphalt' is a material developed jointly by Shell and the Norwegian company Applied Plasma Physics. Active Asphalt is a highway surfacing material that prevents the build up of static charges due the friction between vehicle tyres and the road surface. On a conventional asphalt surface this friction produces an electrostatic charge. The positively charged road surface repels the particulates which are also normally positively charged, thus keeping them suspended in the air. Using the "conductive" Active Asphalt prevents this build-up of charge, enabling the particles to fall onto the road surface under gravity. The particulate matter can then be removed by rainfall or mechanical cleaning. According to Shell, particulate matter in the air will be reduced by up to 10% by this surfacing. According to Hansford (2001) a trial of 300 m of the Active Asphalt surfacing was carried out in Trondheim, Norway, but no details of the trial appear to have been reported in the scientific literature. Further research is required to establish if the surface does in fact reduced resuspension or the lack of change generates a greater silt load which in turn produces greater resuspension when subject to the action of traffic.

Engine switch-off

13.81 In large cities, where traffic congestion is often widespread, engines running at idle are a significant source of air pollution. Whenever it is safe to do so, switching off the engine can reduce fuel consumption and emissions. A number of national and local authorities have introduced engine switch-off campaigns which are designed to reduce emissions and allow motorists to save money by reducing their fuel consumption. For example, some local authorities in the UK use signs to encourage drivers to switch off the engines of their vehicles if they are going to be waiting at traffic lights or level crossings. A campaign in Canada to encourage HGV drivers to reduce the time they spent idling found that over a 4-month period a reduction in idling time of 550 hours resulted in a saving of 2,200 litres of fuel, 1.64 kg of particulate matter and 77 kg of NO_x (Canadian Centre for Pollution Prevention, 2005).. In Warwickshire similar benefits were observed following a 2-week campaign to encourage HGV drivers to turn off their engines. The campaign resulted in a saving of 1,300 litres of fuel and 3.4 tonnes of CO_2 per week (North Warwickshire Council, 2008).

13.82 The cooling effect of the engine and after-treatment system after switch-off can result in a relatively high emission level on restart, and therefore there is a need to determine the optimum length of time for which the engine can be left at idle before it is switched off. However, there has been little research to determine this. According to Natural Resources Canada[20] the recommended guidelines for turning engines off are 10 seconds in Italy and France, 20 seconds in Austria, 40 seconds in Germany and 60 seconds in the Netherlands. In the United States, the Environmental Protection Agency's *Smartway*[21] and *Drive Wise*[22] programs both recommend turning the engine off after 30 seconds. It is noted by the same source that the 10-second rule was originally published by the Canadian Office of Energy Efficiency, and the results were replicated by the American Society of Mechanical Engineers. As a practical guideline, balancing factors such as fuel savings, overall emissions and potential component wear on the starter and battery, a period of 60 seconds would seem sensible.

13.83 This concept has now extended to a number of new cars, which are manufactured to automatically switch off the engine when stationary. Some hybrid cars have catalyst heaters to avoid catalyst cooling problems during periods when the engine is not used.

13.84 If engine switch-off measures were to be introduced in London, and in particular in the vicinity of the hot spots, implementation and enforcement would need to be considered. As in other local authorities, signage could be used to identify locations at which regulations apply. However, the objective identification and enforcement of breaches of the regulations is far from straightforward. Firstly, there is a need to indentify which engines are not switched off. In busy traffic environment it is unlikely that measurement techniques based on, for example, sound levels or temperature levels will be practical. Remote sensing of vehicle exhaust may be an option, but this requires a clear, unobstructed view of the exhaust plume of each individual vehicle. Simple gas sensors could also be considered. However, this may require the presence of an enforcement officer in the traffic, and again this is unlikely to be practical. Secondly, there is a need to determine how long the engine is switched off for, as this type of measure has limited use if the minimum switch-off period is not enforced. Again, this introduces a number of technical issues. The situation is further complicated by the possibility of a delay between a vehicle coming to a standstill and the driver actually turning off the engine, and also the likelihood that the possible duration of the switch-off period will vary according to the location and the traffic conditions. To summarise, effective and consistent enforcement will be very difficult, and this is likely to remain a measure which is 'encouraged' rather than strictly enforced.

[20] http://oee.nrcan.gc.ca/transportation/idling/impact.cfm?attr=8
[21] http://www.epa.gov/otaq/smartway/vehicles/buy-and-drive-smart.htm
[22] http://www.epa.gov/air/actions/drive_wise.html

Barriers and Tunnels

Overview

13.85 Vehicles emit pollutants along the entire length of a road section, with the total quantity emitted being dependent upon the volume, composition and operation of the traffic. On open roads the emissions are subject to the normal processes of atmospheric dilution and dispersion. However, various measures have been developed to improve local air quality by modifying dilution and dispersion. The types of measure addressed here are noise barriers, conventional tunnels and lightweight canopies. The use of vegetation as effective barriers is discussed in the next section.

13.86 The initial dispersion of pollutants from road traffic is affected by vehicle-induced turbulence and by local obstacles, such as noise barriers and buildings. Barriers are common features of roads with high levels of traffic, particularly those which run through populated areas. These features may block dispersion, increase turbulence and initial mixing, and filter or otherwise enhance deposition. Any air flow perpendicular to the barrier can be deflected upwards by the structure, and this can increase the apparent release height of the pollutant, increase vertical mixing due to the flow separation at the top of the barrier, and lead to plume reattachment further downwind. In addition, a recirculation cavity forms in the lee of the structure, and this can also reduce pollutant concentrations relative to an open area with no barrier. Furthermore, when the elevated plume encounters other downwind obstacles (*e.g.* trees or buildings), increased mixing occurs, leading to decreased concentrations. Pollutant concentrations can be affected up to several hundred metres from the road (Bowker *et al*., 2007).

13.87 In the context of this study it needs to be borne in mind when considering the individual studies that the requirement is principally to reduce PM concentrations within the hot-spot zone, which runs essentially from the kerb to the back of the pavement or building facade. Thus the focus is on the measures that reduce concentrations in this near road zone.

13.88 Inside a road tunnel there is clearly no dilution and dispersion of pollution, and unless there is the injection of fresh air the concentration of pollutants will increase from the entrance to the exit, and the emissions will be concentrated at the portals or ventilation points. Therefore, although the road traffic source of pollution is effectively removed along the length of the tunnel, atmospheric concentrations of vehicle-derived pollutants can be particularly high in the vicinity of the portals. The air quality at the portals or ventilation points will depends upon the level of traffic and whether or not the polluted air is treated in some way before release. In some situations it might be possible to improve local air quality by covering a roadway with a lightweight (plastics, synthetic resins or glass) canopy, thereby achieving substantial cost savings compared with a heavier tunnel structure, but in terms of pollution control the principles remain the same.

13.89 When considering the potential for tunnels to improve ambient concentrations it should be borne in mind that vehicle occupants may well be exposed to higher concentrations within their vehicles, which will be detrimental in public health terms.

Noise barriers

13.90 The effects of noise barriers on local air quality have recently been studied in some detail. Bowker *et al*. (2007) explored the effects of roadside obstacles on the near-field dispersion patterns of traffic emissions using two independent methods to investigate the effect of a barrier on pollutant concentrations with wind perpendicular from the road: fine-scale numerical modelling and direct measurements of ultrafine particles (aerodynamic diameter <0.1 µm) using a mobile monitor. The work was conducted near a heavily-trafficked (125,000 vehicles per day) 8-lane segment of Interstate 440 in Raleigh, North Carolina. Three representations of the field site were examined, each progressively increasing in complexity: (a) a 'base' case consisting of a uniform flat domain with no obstacles and no noise barrier, (b) a 'noise barrier-only' case, where a noise barrier (6m tall, 352 m long, and 2 m wide) was introduced parallel to the road, and (c) a representation of the complex 'field study site' including the barrier, buildings and vegetation. The concentration predictions were based on the trajectories of simulated neutrally buoyant 'massless' particles. The concentration values were then normalised by the median concentration value found in the open area of the base simulation at a height of 3 m above ground.

13.91 The simulations showed the influence of the roadside barriers on the pollutant dispersion pattern. Figure 5 shows vertical cross-sections of modelled concentrations for the three simulations in the area behind the barrier.

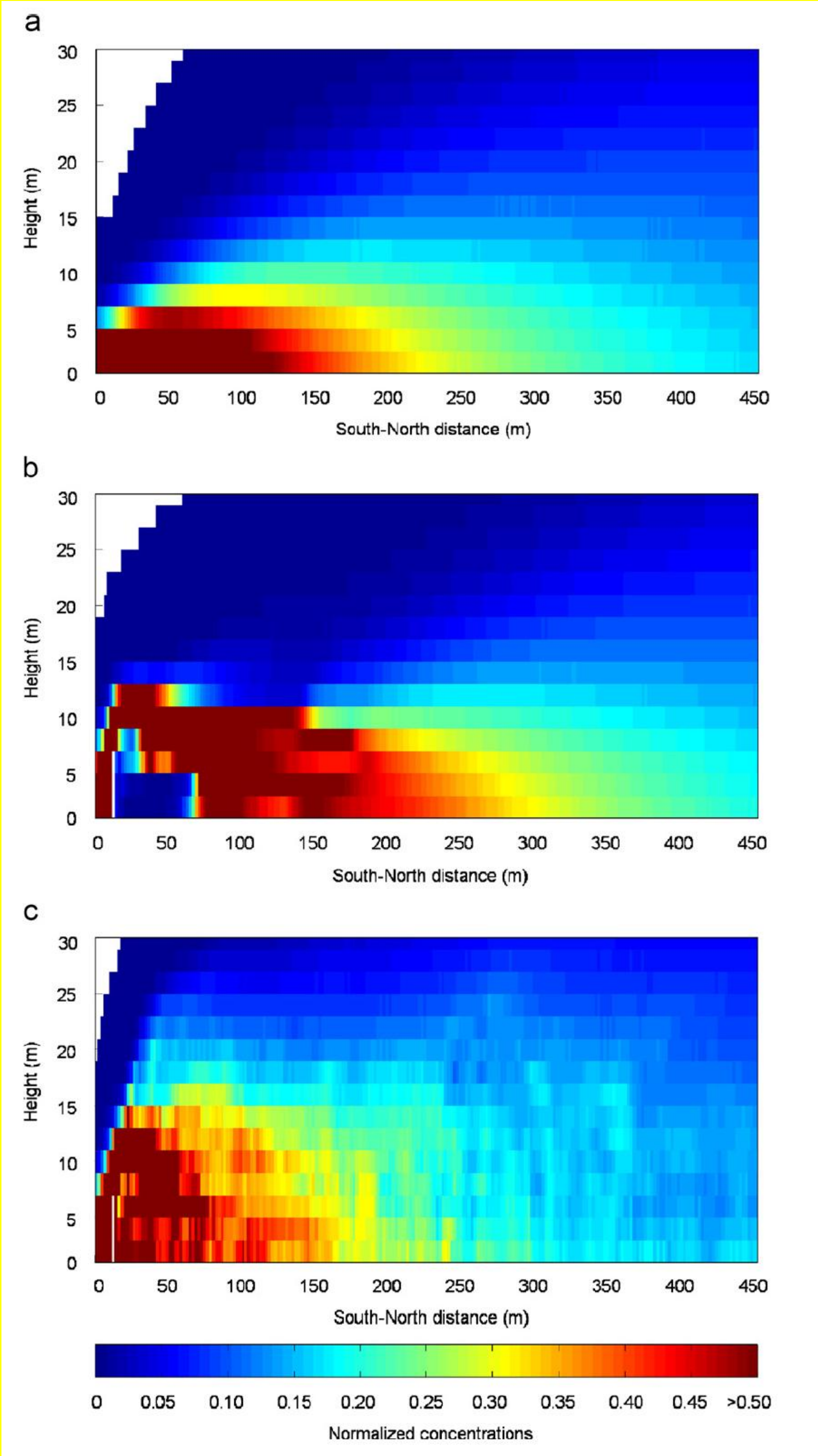

Figure 5: Vertical sections showing the median concentration behind the barrier as a function of downwind distance for (a) the base, (b) barrier-only, and (c) field site simulations. The 6 m barrier is located at 12 m (Bowker *et al*., 2007).

13.92 The highest concentrations were seen in the base simulation, due to the lack of vertical mixing and dispersion of the plume. The wind movement over the noise barrier lifted the plume relative to the base simulation. There was little mixing of pollutant into the recirculation cavity for the barrier-only simulation, leading to extremely low concentrations. Along the lee side of the barrier (between 14 m to 34 m, and at a height of 3 m, the highest concentrations were found for the base simulation, followed by the field-site (barrier with trees) simulation (~50% of the base simulation values), and finally the barrier-only simulation (~5% of the base simulation concentrations). For the barrier-only simulation, the results suggested that after the plume was elevated by the barrier and passed over the recirculation zone it returned to ground level. Concentrations were around 35% higher where the plume reattachment occurred (at ~80m). At greater distances from the road, the barrier-only concentrations remained higher, approaching the base simulation values near the edge of the domain. In the field-site simulation (noise barrier and vegetation) the plume was extremely well-mixed vertically after encountering the barrier and going through the trees, leading to decreased average concentrations at all downwind distances.

13.93 Observations from the mobile measurements were compared with the model predictions. Highly time-resolved measurements of ultrafine particles were collected. Number concentrations of 20 and 75 nm particles, as well as total particle number, were measured. All the concentrations from the mobile measurements were normalised by taking the median value in the open area along the access road directly adjacent to the highway.

13.94 Comparison of normalised measurement data with normalised modelling data allowed a comparison to be made between the simulations and the measurements. In both cases, it was found that the change in concentration with distance from the road was similar.

13.95 The monitoring results for the same site were described in more detail by Baldauf *et al.* (2008). The data indicated that the average total particle number concentrations behind the barrier were lower than concentrations at an equivalent distance from the road without any barrier. The barrier reduced average concentrations by 15–25% within the first 50 m of the road, with concentrations becoming equivalent approximately 150–200 m from the road.

13.96 The concentrations of both the 20 and 75 nm particles decreased with distance from the road (Figure 6). The presence of a noise barrier resulted in larger reductions of the smaller, 20 nm particles than the larger 75 nm particles.

13.97 For the 20 nm particles, equivalent average concentrations in the open terrain and behind the barrier occurred approximately 120 m from the road. However, the larger, 75 nm diameter particle number concentrations became equivalent only 50 m from the road. Average number concentrations for the 75 nm particle size actually increased behind the barrier between 70 and 100 m from the road. The results in Figure 6 also indicate that the transect with a noise barrier and mature vegetation (trees generally greater than 10 m in height with leaves) resulted in the lowest pollutant concentrations for both particle sizes.

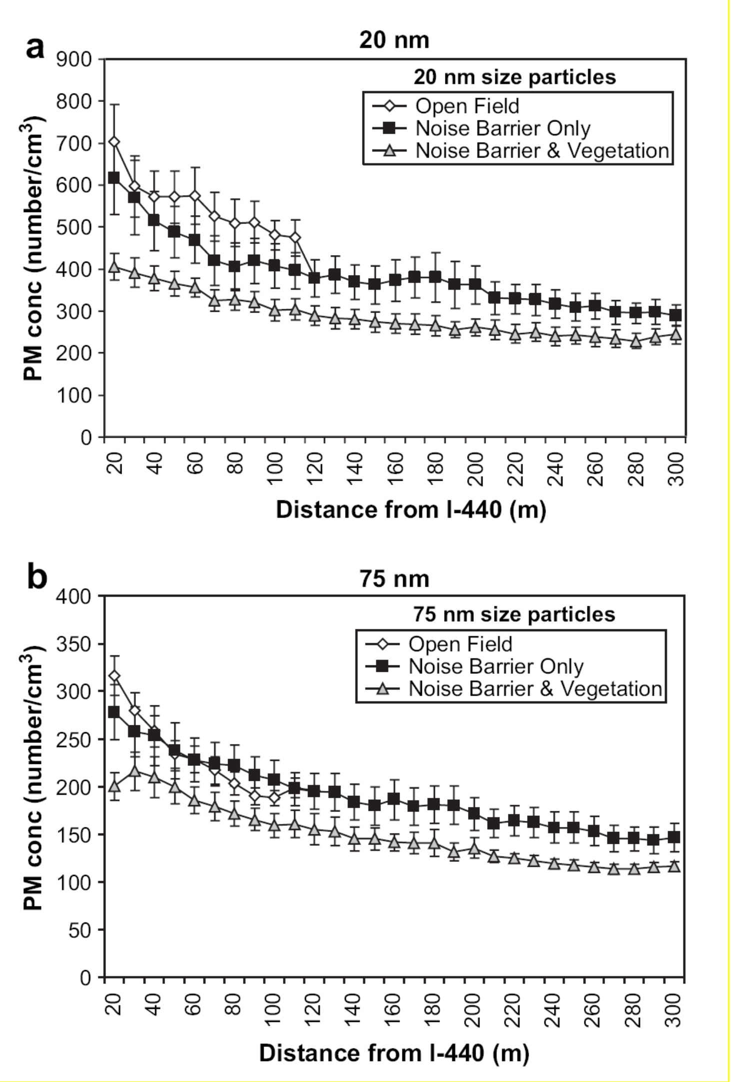

Figure 6: Measurements of (a) 20 nm and (b) 75 nm particles using at varying distances from the road (I-440) for open terrain, behind a noise barrier only, and behind a noise barrier with vegetation (Baldauf *et al.*, 2008).

13.98 The presence of vegetation in addition to the noise barrier probably increased turbulence and mixing to further reduce pollutant concentrations. In addition, this vegetation may have provided a filtering effect, although the isolated effect of vegetation on near-road air quality could not be determined The reductions from the noise barrier and vegetation appeared to continue more than 300 m from the road.

13.99 The development of noise barriers for air quality improvement has also been explored in IPL. Two key questions were addressed: what contribution could noise barriers make to air quality improvement, and to what extent could barriers be optimised to that end? A literature study and wind tunnel experiments were initially conducted to examine whether noise barriers could be redesigned in such a way as to improve air quality in the vicinity of the barrier.

13.100 The literature study (Hofschreuder *et al.,* 2005) was based on earlier studies on the impact of noise barriers on air quality, and summarised current knowledge on the issue. The following conclusions were drawn from the literature study:

- The main impact of a noise barrier is to disperse pollutants at a greater height. A secondary effect is the additional turbulence created by the barrier, which improves dispersion.
- In comparison with the situation without such provisions, roadside barriers in the first place lead to an increase in pollutant concentrations over the road and in its direct vicinity, as a result of a reduction in wind speed. However, barriers also create turbulence, thus adding air with background concentrations, leading in turn to a decrease in pollutant levels (because background concentrations are below concentrations in the motorway air).
- The addition of cleaner air can be boosted by increasing the height of the barrier and/or by planting tall trees immediately behind it.
- Porous and non-porous barriers combined with vegetation were deemed promising options as dedicated 'pollution barriers' (*i.e*. a barrier with fans installed at the top, creating vertical uplift of air).
- Increasing the particulate deposition rate by increasing the surface area available for pollutant capture should lead to a major reduction in particulate levels. Planting barriers with ivy can lead to an average reduction of 13% in concentrations close to the rear of the barrier (20 m) and at a modest height (up to 4 m). Under stable atmospheric conditions the reduction is 10%. With their greater surface area, porous barriers covered with vegetation are more effective (30% and 50% reduction, respectively), but will be problematic in terms of noise reduction. Installing an air-permeable 'pre-barrier' will lead to an even greater improvement in air quality.

13.101 However, the results should be treated with some caution, because they depend very much on the height above the carriageway at which emissions are assumed to be mixed. In the case of dedicated pollution barriers, it is above all the estimate of additional admixing of air with background levels as a function of height that is uncertain. When it comes to the use of vegetation, the estimated impact may be somewhat optimistic, because allowance was not always made for the influence of deposition on the concentration pattern, and thus for deposition further away from the road. The calculations were performed with the vegetation 'optimised', moreover, whereas in practice the total leaf surface will often be smaller.

13.102 In wind tunnel experiments a 1:200 scale model was constructed to represent a standard 2x3 lane motorway. For each barrier variant (14 in all) a one-figure value was derived for the relative reduction in the share of the road contribution to PM_{10} concentrations, calculated as the mean of the various wind directions and measurement locations, as compared with a control situation without a barrier (Bouter and Koopmans, 2006). This one-figure value provided an approximate indication of the contribution of the road as a percentage of the situation without a barrier. The background concentration was not considered.

13.103 Two sets of measurements were performed: (i) sub-study 1- rural, lightly built-up environment, and (ii) sub-study 2 - highly urbanised environment. In an environment with fewer structures (sub-study 1) the effects of the barrier on both turbulence and effective pollution release height both played important roles. In sub-study 2 (highly urbanised environment) the turbulence effect was less pronounced because there was already a substantial amount of turbulence due to the buildings. A noise barrier will therefore have a relatively greater impact on air quality in a more open environment than in a highly urbanised environment.

13.104 For the environment with few structures, the one-figure value[23] for the various barrier variants was 13 - 53 %. For the highly urbanised environment and a barrier close to road, the one-figure value was between 6 and 60%. For the urbanised environment and a barrier further away from road, the one-figure value between 21 and 78%.

13.105 In all these wind tunnel experiments the measurements were carried out 2 m above ground level. If this had been lower (1.5 m above ground level, for example) concentrations close behind the barrier would probably have been lower for all barrier variants. This means that the ultimate relative impact of noise barriers on air quality behind the barriers may well be greater, particularly close to the barriers, if a lower measuring height is adopted. Further behind the barriers the differences will be less pronounced, one reason being the substantial horizontal dispersion of the polluted air.

13.106 In order to validate the wind tunnel measurements, large-scale field measurements were conducted in 2007 and 2008. The planned measurements were described in detail by Hooghwerff and Van Blokland (2007). A dedicated test site (Figure 7) was established for IPL, where the impacts of different types of barrier on $PM_{2.5}$, PM_{10} and NO_2 concentrations could be measured.

[23] This one-figure value provides a rough indication of air quality as a percentage of the situation without barriers, excluding accumulation of background concentrations.

The site was located along the A28 motorway in the municipality of Putten. The A28 is a dual carriageway with two main lanes and a hard shoulder. However, the results from the IPL field measurements were not available at time of writing.

Figure 7: Model of dedicated IPL test site.

13.107 An EU LIFE project SPAS (sound and particle absorbing system) investigated the use of noise barriers with integrated dust filters ()[24]. Their results showed that the noise barrier itself (with or without filters) reduced both PM_{10} and NO_x emissions by 15-20%. In the city of Wöflnitz, in addition to SPAS filter elements were found to lower PM_{10} caused by resuspension by about 15% in specific meteorological wind conditions. At the Lendorf underpass, a slight decrease in the PM_{10} value could be measured due to the implementation of the SPAS. However this location had not been equipped with the ultimate design of the SPAS and it is considered that further improvements in efficiency may be expected. The service life of the filter elements is reported to be well over one year.

Figure 8: Barriers from the EU SPAS project.

[24] Project webpage at http://www.life-spas.at/english/startseite.htm

13.108 To summarise the implications for the current project, it appears that the introduction of a noise barrier can lead to reduced concentrations of airborne particulate matter close to the barrier itself, but concentrations may increase further away where plume re-attachment occurs. The combination of a noise barrier and vegetation can lead to additional benefits in terms of air pollution, but the implications for noise, amenity and aesthetics would also need to be considered in densely populated areas of Central London. There are also questions concerning the relevance of the work of Bowker *et al*. (2007) and Baldauf *et al.* (2008) – which are based upon numbers of ultrafine particles – to PM_{10}, and this requires further research. According to Bowker *et al*. (2007), further research is also needed to identify the effects of roadside structures under varying wind and topographic conditions, and further evaluation of numerical models will be necessary before use in regulatory and urban planning applications.

Tunnels and lightweight canopies

13.109 It is considered unlikely that construction of a new road tunnel in Central London would be feasible, particularly in the short-term, but measures such as lightweight canopies that cover a busy road could have the same effect as a tunnel, by restricting the pollutant release to portals and vents.

13.110 Lightweight canopies would be much more straightforward to implement in London, and vegetation could also form part of the structure. The air inside the effective tunnel can then be filtered to remove particulates and other pollutants. There are several patents referring to this. For example, Wieser-Linhart (2003) has patented a system consisting of a roof and walls held together by release mountings and an exhaust extractor attached to a cleaning unit. The roof also has acoustic dampers to absorb traffic noise. These types of canopy are being deployed in Switzerland, largely to prevent the transmission of roads traffic noise along valley sides. However, their effectiveness at reducing road surface deposition and roadside PM concentrations remains unclear. There are other patents relating to methods of cleaning air in tunnels. This method may have potential at locations where the alternative would be to reroute the road. The filters and biological cleaning agents would need regular replacing.

13.111 This approach is being investigated as part of the IPL. Several designs have been put forward that meet the requirements for a safe and durable canopy. Costs of around 6 to 60 million euro per km (2 x 3 lanes) have been calculated. Air filtration devices, such as those used in tunnels or car parks are also been investigated for their application in the artificial tunnels. IPL has commissioned a feasibility study on this and are considering glass fibre mats as an option for trapping particulates.

Pollution control in tunnels and canopies

13.112 The methods for controlling air pollution in road tunnels were described by Boulter *et al.* (2007b), and these methods are summarised briefly in this section. A detailed review of around 30 different air pollution treatment technologies for use in road tunnels was undertaken in Australia by Child & Associates (2004). The Child review has been drawn upon heavily within this work.

Road tunnel ventilation design and operation

13.113 There are several reasons why a tunnel needs to be ventilated, whether by natural or mechanical means. The needs for ventilation can be grouped according to three categories: control of the internal environment (exposure to in-tunnel air pollution), control of the external environment (ambient air quality), and management of emergency situations (fire, release of toxic chemicals).

13.114 A two-fold approach to ventilation design is generally adopted. Firstly, the amount of fresh air required to dilute pollution concentrations to acceptable levels is calculated based on the likely emissions from vehicles in the tunnel, and the ventilation system is designed accordingly. Secondly, sensors are installed in the tunnel to initiate the operation of the ventilation system in order to maintain the level of pollutants below limit values, or to force the closure of the tunnel should certain limit values be exceeded.

13.115 The choice and design of a suitable ventilation system depends upon several factors, including tunnel length, number of bores and location, traffic flow and composition, admissible air pollution levels and fire safety considerations. In UK tunnels, ventilation design is specified in accordance with the BD78/99 document contained in Volume 2, Section 2, Part 9 of the DMRB.

13.116 Short tunnels can be adequately and safely ventilated by the natural airflow without the installation of a mechanical ventilation system. In longer tunnels mechanical ventilation is required. There are three basic concepts for mechanical tunnel ventilation: (i) longitudinal ventilation, (ii) transverse ventilation and (iii) semi-transverse ventilation[25]. Longitudinal ventilation is generally used in road tunnels up to two kilometres in length, but is effective in tunnels of up to five kilometres in length where traffic in the tunnel is unidirectional. Full transverse ventilation is usually favoured for long

[25] With longitudinal ventilation fresh air is introduced to, or removed from, the tunnel at a limited number of points. The usual arrangement is for air to enter at one portal and to leave at the other. With transverse ventilation air may be introduced into the tunnel at various points along its length, and may also be extracted at other points along its length. The fresh air flows across the traffic flow, rather than in the direction of the traffic. Semi-transverse ventilation involves a combination of longitudinal and transverse ventilation, with either the fresh air being delivered transversely, or the fresh air being removed transversely.

tunnels with heavy traffic loads. Semi-transverse ventilation involves a combination of longitudinal and transverse ventilation, and is usually used in medium-length tunnels, with medium-to-heavy traffic loads.

Traffic management and public information

13.117 Traffic management may be employed by tunnel operators to control exposure to vehicle-derived air pollution. Measures might include the enforcement of speed limits, signalling, traffic restrictions, *etc.* There are a number of additional measures which are not normally employed, but might be used under certain circumstances. For example, in toll tunnels higher charges could be levied on older, more polluting vehicles, or vehicles with only a single occupant. In addition, the dissemination of information to the public can be used to control exposure. Methods of traffic management used include contraflow measures, vehicle escorting, incident detection and response systems, and public information systems. However, there appear to be few reported studies of the effects of such measures on pollutant concentrations (Boulter *et al.*, 2007b).

Filtration

13.118 Filtration can be used to remove airborne particulates by passing the extracted air through a porous medium. This can be a fabric filter or bio-filtration (e.g. through soil or compost). Filters can be used to clean the air inside tunnels. However, particle filtration efficiencies can be low.

Electrostatic precipitators

13.119 One widely-used method of removing particulate matter from tunnel air is the dry electrostatic precipitator (ESP). Dry ESP processes are effective in removing particles between 1 and 10 microns in diameter. Varying efficiencies have been claimed and reported in relation the removal of sub-micron particles. ESPs are in widespread use in Norway and Japan. It appears that the policy in Japan is to consider ESPs for tunnels longer than 2 km, although ESPs have been installed in shorter tunnels on an experimental basis. Some ESPs can be retro-fitted to tunnels, although based on the above tunnel length criterion, only a handful of tunnels in the UK would be worth considering for ESP installation. The manufacturers Matsushita and Mitsubishi claim an efficiency of at least 80% removal of particles for their ESPs (Willoughby *et al*., 2004). The removal efficiency appears to be close to 100% for particles larger than 10 µm, but less than to 70% for particles smaller than 1 µm. However, a number of the ESPs installed in tunnels appear to have been rarely (or never) used, with the reasons given including low traffic flows, variable efficiency, complexity of operation, and particle levels being well within limit values. Some dust filtration systems remove airborne particulate matter using physical filters. However, these systems appear to be less efficient than ESPs and their use is being discontinued in some tunnels (Child and Associates, 2004).

13.120 In the Netherlands a novel ‘fine dust reduction system’ (Figure 10) has been developed to control the release of PM from tunnels and roads. The system creates an electrostatic ‘roof’ above a road, and charges the particles under this roof. Passive screens are used to collect the charged particles. The system does not affect communication systems and is harmless to humans and animals (Delft University of Technology and BAM, 2009).

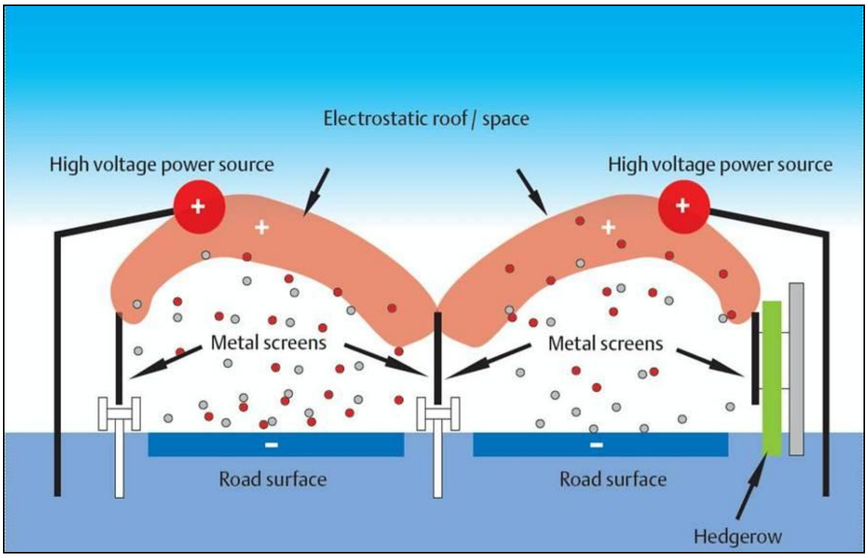

Figure 9: Fine dust reduction system (Delft University of Technology and BAM, 2009).

13.121 The concept has been tested in a full-scale experiment in the Thomassentunnel (on the A15 motorway) in the Rotterdam industrial area (TNO, 2009). The electrically-charged wires were mounted on one tunnel wall (Figure 11), and the electrically grounded metal ‘collector’ screens were mounted on the opposite wall. Measurements were conducted at four locations (three inside and one outside the tunnel) between June and September of 2009. The parameters measured included PM_{10} (GRIMM and TEOM). NO_x (Airpointer), air temperature, humidity and wind speed. During the experiment the system led to a reduction in the PM_{10} concentration in the tunnel of around 10%.

Figure 10: Fine dust reduction system installed in the Thomassentunnel (Delft University of Technology and BAM, 2009).

Other technologies

13.122 Other techniques include wet ESP, chemical absorption, bio-filtration, agglomeration, scrubbing and turbine technology.

13.123 One of the advantages argued for wet electrostatic precipitation, compared with the conventional process, is that the presence of a continuously wet environment increases the level of efficiency in removing particles smaller than 1 µm and soluble gaseous contaminants. Wet electrostatic precipitation has been used in a number of industrial applications, but does not appear to have been used in road tunnel applications (Child and Associates, 2004).

13.124 In bio-filtration systems polluted air is passed through an aeration layer into soil beds. Removal efficiencies of >90% for TSP been claimed (Child and Associates, 2004).

13.125 From a road tunnel viewpoint, agglomeration of particles remains an emerging or developing technology, but would appear to have the potential to enhance the effectiveness of other particle removal systems. Scrubbing has a potential application in the treatment of road tunnel emissions, but at this stage remains an emerging or developing technology in such applications.

13.126 The use of turbines in road tunnel applications would require the introduction of a combustible gas as a fuel, and the turbine process would generate both heat, and nitrogen oxides. Removal efficiencies of 99% for PM_{10} and 80% for $PM_{2.5}$ have been claimed (Child and Associates, 2004).

Vegetation

13.127 It is a generally accepted that vegetation planted at the roadside has the potential to reduce the concentration of airborne particles. A number of mechanisms are involved, but the main effects are dry deposition at the leaf surface and the modification of dispersion. However, according to Hesen and Koopmans (2006) few studies have permitted unambiguous interpretation

13.128 The height of the vegetation, the plant type and the leaf surface (shape, size, density and texture) are important parameters. Trees and tall shrubs are generally more effective than short vegetation because their greater height and aerodynamic roughness increases the transfer of pollutants from the air to the plant surface (ARIC, 1999). Theoretically, greater deposition can occur on coniferous plants than on broadleaf plants due to the larger leaf surface area per unit ground area (Cavanagh, 2006). The planting density and extent are also likely to be important. For example, Cavanagh *et al*. (2009) observed a spatial attenuation of PM_{10} concentrations with distance inside an evergreen broadleaved urban forest patch during high wintertime particulate air pollution. However, there are few opportunities for introducing dense, extensive vegetation at roadside environments in Central London.

13.129 Over an entire year, plants are most effective at absorbing pollutants deposited on external surfaces rather than through leaf stomata. Evergreen plants provide a good absorbing surface all year round, although faster growing deciduous trees offer enhanced pollutant uptake during the summer compared to the slower growing evergreens (ARIC, 1999)

13.130 However, whilst vegetation might filter dust particles out of the air it is also acts as an efficient windbreak. This effect can work against the potential benefits of the filtering capacity. If located in the wrong place, vegetation can actually increase the local pollutant concentration as a consequence of the reduced wind circulation. In the Dutch CAR model, for example, it is assumed that the increase in concentration due to reduced air circulation is much greater than the filter effect of the vegetation (Teeuwisse, 2003). In addition, vegetation is a temporary repository for particles, which may be removed later by wind or rain (Cavanagh, 2006).

13.131 In order to assess the filtration performance of plants with respect to atmospheric dust, deposition on vegetation has been investigated by a number of different methods (field studies, numerical and physical modelling). According to Litschke and Kuttler (2008) the particle deposition velocity can be used as a measure of the filtration efficiency of vegetation - some examples are therefore provided in Table 7. It should be noted that many more examples are available in the literature (*e.g.* Petroff *et al*., 2008).

13.132 Litschke and Kuttler (2008) noted that there are differences of an order of magnitude between measured values and the results of model calculations. The average published value obtained by Litschke and Kuttler (2008) of ~1 cm/s corresponds to a reduction in PM_{10} concentration of about 1% in urban areas. In addition, analyses carried out for a busy arterial road show that very large vegetation areas (in excess of 10,000 m^2) would be needed to compensate for local emissions of particles (PM_{10}) by vehicles at a deposition velocity of 1 cm/s (Litschke and Kuttler, 2008). However, current in-situ measurements indicate deposition velocities considerably higher than 1 cm/s and, for PM_1, velocities above 10 cm/s. If these results were confirmed by further measurements, local planting campaigns covering small areas could also be beneficial for a reduction of particle concentrations (Litschke and Kuttler, 2008).

Table 7: Examples of particle deposition velocities by vegetation type.

Reference	Species	Deposition velocity (cm/s) by particle size fraction			
		PM_{10}	$PM_{2.5\text{-}10}$	$PM_{0.1\text{-}2.5}$	$PM_{0.1}$
Chamberlain (1967)[a]	Grass	0.16-0.12			
Wesley *et al.* (1985)[a]	Nature grass	0.22			
Vong *et al.* (2004)[a]	Rye grass	0.16			
Fowler *et al.* (2004)[a]	Urban grass	0.33-0.38			
	Urban woods	0.7-1.07			
Hicks *et al.* (1989)[a]	Deciduous trees	0.1			
Pryor (2006)	Beech	0.15-0.45			
Freer-Smith *et al*. (2005)	Pine		2.79-4.65	1.75-6.09	29.88-36.24
	Cypress		3.43-6.15	3.71-4.58	19.49-33.72
	Maple		1.75-3.64	2.52-9.22	11.60-31.72
	Poplar		0.44-0.57	0.75-0.81	12.3-25.43
	Whitebeam		3.25-5.35	4.54-11.04	16.94-27.20
Yang *et al.* (2008)	Short grass	0.10-0.19			
	Tall herbaceous plants	0.10-0.25			
	Deciduous trees	0.13-0.36			

a Cited by Yang *et al.* (2008).

13.133 The London Plane has been widely planted in parks, squares and avenues in the capital. It combines resistance to pollution with an ability to cope with restricted root spaces. Although no deposition velocities for London Plane were found in the literature, its leaves are very similar to those of maple (see Table 7), and one might assume that it particle-trapping capacity would be similar, although factors such as leaf density would also be important.

13.134 Beckett *et al.* (2000) attempted to identify tree species which maximise the benefit to local air quality. Five species were examined. The results showed that all trees examined captured large quantities of airborne particulates in the PM_{10} fraction and below. Coniferous species were found to capture more particles than broad-leaves, with pines (*Pinus spp*.) capturing significantly more material than cypresses (*Cupresses spp*.). Of the broad-leaved species, whitebeam (*Sorbus aria*) captured the most and poplar (*Populus spp*.) the least weight of particles. Trees situated close to a busy road captured significantly more material from the largest particle size fraction than those situated at a rural, background site. There was very little variation between the sites in the weight of particulates from the smallest particle size fractions (PM_1 and $PM_{1\text{-}2.5}$).

13.135 Tiwary *et al.* (2005) developed a CFD model of particle collection efficiency for three types of hedgerow species with different degrees of aerodynamic porosity. The model examined particles in the range 0.5 to 20 µm and simulated the velocity and turbulence of the approach air flow. Collection efficiency was described in terms of the coupled effects of the deviation of the approach flow and the filtration through the foliage elements. Computational fluid dynamic methods were used to simulate velocity and turbulence fields which were subsequently used to predict particle deposition. Probably the most useful results of the paper are the experimental measurements of particle collection efficiency. The results are shown in Table 7, which includes a comparison of the theoretically estimated collection efficiencies and those measured experimentally in the case of a hawthorn hedge. The hawthorn was far more efficient than either the holly or yew hedge, but in the relevant range of sizes (2.75-6.25 µm diameter) had an experimentally measured collection efficiency for particles of only 0.75-5.8%. The holly and yew were significantly less efficient. Although the yew hedge is denser it tends to lift the approaching airflow more strongly and increase turbulence in its wake, thereby encouraging recirculation of fine particles on the downwind side. Consequently, the overall efficiency of hedges appears to be very modest in the context of the collection of particles in the appropriate size range.

Table 7: Collection efficiencies (%) of the three hedges after accounting for the flow and filtration effects (from Tiwary *et al*., 2005).

Particle diameter (µm)	Hawthorn		Holly	Yew
	CE (%)	CE_{exp} (%)	CE (%)	CE (%)
0.875	1.8	1.2	1.3	0.8
1.5	1.1	0.8	1.1	0.7
2.75	0.9	0.75	0.6	0.5
4.25	2.6	3.5	0.5	0.4
6.25	7.0	5.8	1.7	0.5
8.75	15.0	12.7	4.6	0.8
12.5	19.8	17.6	11.7	1.9
15	29.4	27.3	17.7	3.0

CE = calculated value CE_{exp} = measured value

13.136 Using simple models, Wesseling *et al.* (2004) estimated the effects of porous vegetation (trees, shrubs) on the concentrations of NO_2 and particles near roads and in towns. It was noted that for the optimum effect, the distance between the road and the vegetation must be sufficiently large, and the traffic emissions uniformly mixed with the air. Depending on the situation, the vegetation trapped a maximum of 15-20% of PM_{10} and reduced the concentration of NO_2 by a maximum of 10%. However, at short distances behind the vegetation PM_{10} and NO_2 concentrations increased. The authors therefore advised against the use of vegetation to reduce pollution concentrations in built-up areas at short distances from busy roads (or hot spots). They added that at short distances from a road, a noise barrier is more effective at reducing PM_{10} and NO_2 concentrations than vegetation.

13.137 As noted earlier, some studies have addressed the combined effects of noise barriers and vegetation. Modelling by Bowker *et al.* (2007) indicated that the combination of noise barriers and tall trees led to enhanced mixing and pollutant dispersion, leading to lower downwind pollutant concentrations. Trees and other vegetation may also reduce pollutant concentrations by enhancing deposition of certain pollutants. A desk top study for IPL (Hofschreuder *et al*., 2005) has shown that a noise barrier covered in vegetation such as vines or ivy would improve local air quality, trapping particulates. The reduction obtained is related to the surface area, therefore using porous surfaces and increasing the height is more effective. However, it should be noted that the emphasis in the IPL Programme is on high-speed roads, and such findings may not be applicable to London.

13.138 Some studies have examined the effects of increasing the surface coverage of vegetation, rather than using plants as barriers between roads and populations. For example, to estimate the potential of urban tree planting for the mitigation of urban PM_{10} concentrations, McDonald *et al*. (2007) used an atmospheric transport model to simulate the transport and deposition of PM_{10} across two UK conurbations (the West Midlands and Glasgow). Tree planting was simulated by modifying the land cover database, using GIS techniques and field surveys to estimate reasonable planting potentials. The model predicts that increasing total tree cover in West Midlands from 3.7% to 16.5% reduces average primary PM_{10} concentrations by 10% from 2.3 to 2.1 µg/m^3 removing 110 ton per year of primary PM_{10} from the atmosphere. Increasing tree cover of the West Midlands to a theoretical maximum of 54% by planting all available green space would reduce the average PM_{10} concentration by 26%, removing 200 ton of primary PM_{10} per year. Similarly, for Glasgow, increasing tree cover from 3.6% to 8% reduces primary PM_{10} concentrations by 2%, removing 4 ton of primary PM_{10} per year. Increasing tree cover to 21% would reduce primary PM_{10} concentrations by 7%, removing 13 ton of primary PM_{10} per year. These findings are of limited relevance for this study, as they relate to a decrease in background concentrations and not to the near-road environment.

13.139 Studies on the UK motorway network showed that long-term exposure of trees to high levels of pollutants was unlikely to cause pollution related injuries (such as leaf death). However, species such as birch and pine did show adverse changes in leaf surface 'wettability' and control of water loss and photosynthesis, and it is likely that trees at the side of busy roads would suffer from secondary stresses such as drought or pests causing slower growth and reduced capacity to absorb pollution (ARIC, 1999).

13.140 The impacts of vegetation on concentrations of PM_{10} alongside the A50 motorway near Vaassen in the Netherlands were studied by Weijers *et al.* (2007) a part of IPL. The PM_{10} levels with vegetation were found to be approximately the same as in the reference situation with no vegetation. Further measurements were then conducted at Valburg, as well as at Vaassen. As the existing strip of vegetation at Vaassen lost its leaves in winter, both summer and winter conditions were investigated. In addition, the situation was also investigated using a CFD model (PanAir) (Vermeulen *et al.*, 2009). For both the model and measurements the effects on concentrations were relatively low (<5% for PM_{10}). For particles <1 µm the filtering effect was negligible. Overall, the effect of the vegetation was, at best, 10-31% of the traffic contribution. This was only due to the turbulence induced by the vegetation, and only in summer.

13.141 The effects of vegetation on airborne particulate matter have also been investigated in the EPSRC project PUrE (Pollutants in the Urban Environment)[26], The main aim of PUrE was to develop an integrated decision-support framework to enable more sustainable management of urban pollution. A 'PM_{10} uptake' model for different types of vegetation has been developed in the project. The input parameters include area of green space, the leaf area index, the deposition velocity, the wind speed and the canopy height. Some of the results are shown in Figure 12, in which it can be seen that more broad leaf trees and confers in the mix of vegetation, and higher proportions of conifer, are predicted to result in larger reductions in PM_{10}.

13.142 In a similar vein, Bealey et al (2007) have developed a tool for planners to identify the extent to which urban tree planting can be used as a mitigation measure to reduce PM_{10} impacts of new developments. The reductions in PM_{10} across an urban area are calculated using a modified version of the atmospheric transport FRAME (Fine Resolution Atmospheric Multi-species Exchange) model. This model is not suitable for fine scale modelling, thus the findings are not helpful for this study focussed on hotspots.

[26] http://www.pureframework.org/

13.143 'Hairy buildings' or green roofs and green walls (see examples in Figure 13 and Figure 14) are innovative concepts that could be considered as novel measures to capture PM_{10}. It might prove beneficial to cover the walls of buildings fronting onto streets with vegetation (or other pollutant-capturing surfaces), especially within street canyons as this would reduce the PM_{10} circulating within the canyon. The green roof can therefore be used to supplement the use of urban trees in air pollution control, especially in situations where land and public funds are not readily available. The Mayor of London has pledged his commitment to urban greening and increasing green space in London including increasing the number of street trees planted and installing green roofs by 5% by 2030. The Mayor is also considering which buildings are suitable to create green walls (GLA 2009c). As well as the potential reduction in pollutants, green roofs and walls can also create new outdoor spaces, enhance biodiversity, reduce flood risk (by absorbing heavy rainfall) and improve building insulation.

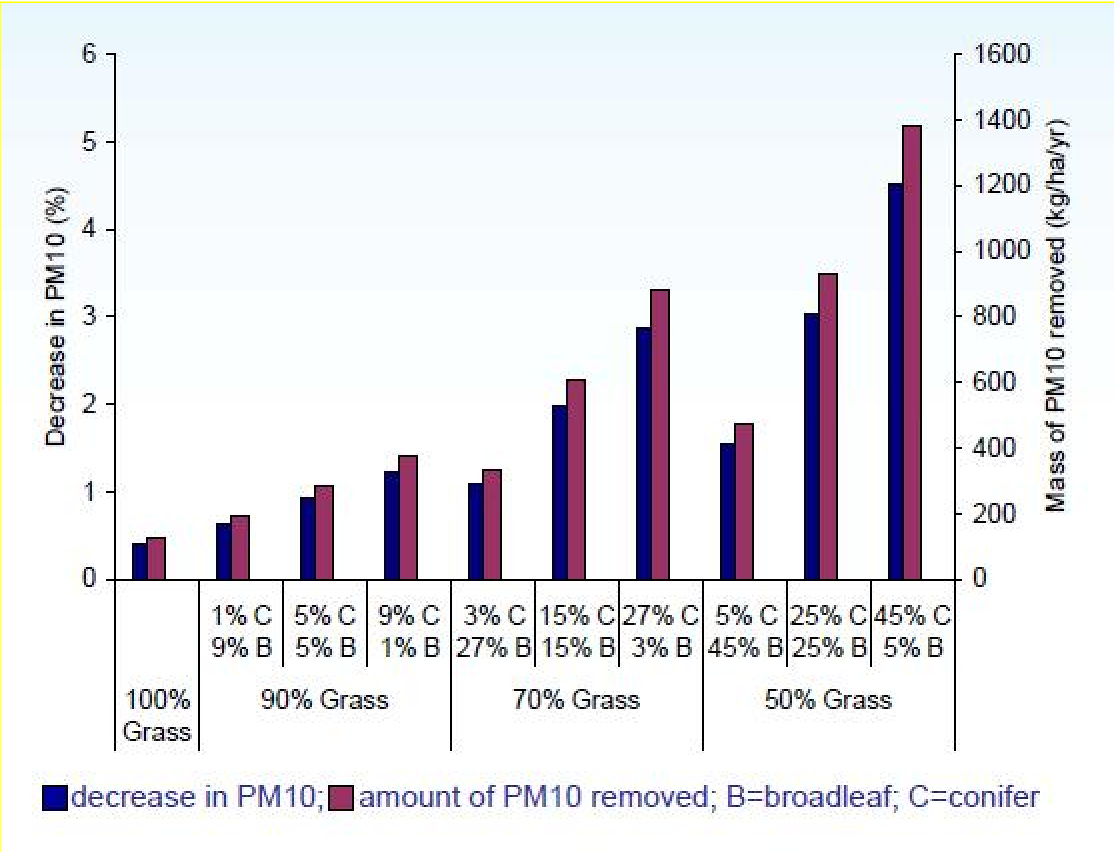

Figure 12: Change in PM_{10} concentration reductions associated with different combinations of plant type.

13.144 Yang *et al*. (2008) quantified the level of air pollution removal by green roofs in Chicago using a dry deposition model. The result showed that a total of 1,675 kg of air pollutants was removed by 19.8

ha of green roofs in one year with PM_{10} accounting for 14% of the total. The highest level of air pollution removal occurred in May and the lowest in February. The annual removal per hectare of green roof was 85 kg/ha/y. However, no studies have been identified that assess the benefits of such an approach on roadside concentrations of PM_{10}. The same limitation applies as noted above (paragraph 8.10), as the measure affects background air quality.

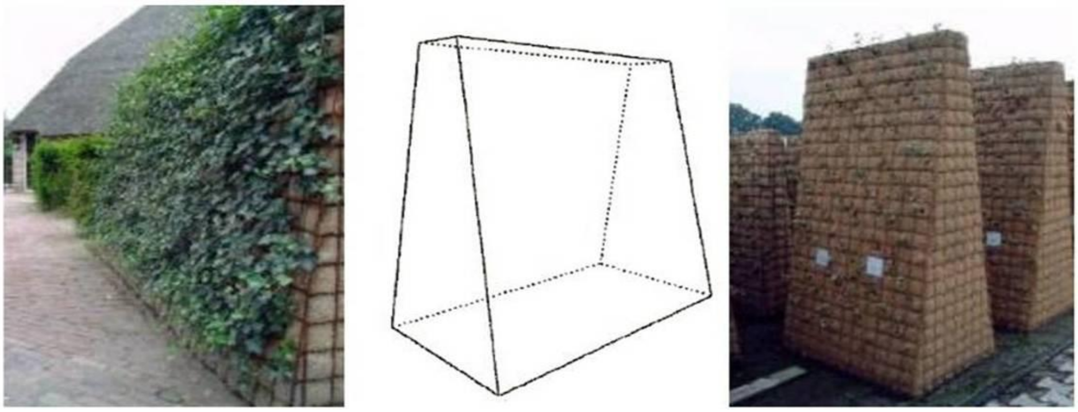

Figure 13: Green wall[27].

Figure 14: Example of green wall on a building.

13.145 In the context of the current project, it appears that there are likely to be several problems associated with the use of vegetative barriers in Central London. For example, there are relatively

[27] http://www.greenwall.nl/

few situations within urban streets where it would be practicable to build a vegetative barrier between the traffic and pedestrians. In addition, vegetation growing very close to the roadside would collect a great deal of very coarse particulate matter by mechanisms including water splashes and spray, and would thereby become extremely soiled. It should also be noted that the roadside environment is one of the most hostile for plants in terms of air quality; some of the pollutants emitted by road vehicles are known to injure plants. However, plants do not appear to exhibit symptoms of pollution-related injury except where there is acute exposure (ARIC, 1999).

Other Measures to Limit Exposure

13.146 It is recognised that concentrations fall-off rapidly with distance from the edge of the road. By installing a cycle lane between the pavement and the carriageway this effectively moves the traffic further from the pavement, which should have the effect of reducing concentrations to which people are exposed on the pavement. The introduction of cycle lanes between the traffic and the pedestrians, is thus worthy of consideration (where none currently exist), although it is unlikely to be practical to introduce cycle lanes in addition to bus lanes. Cost benefit studies in Norway that take into account a wide range of costs and benefits to constructing walking and cycle lanes (including improvements in emissions and health benefits, high journey times and traffic accidents and insecurity) found beneficial net cost/benefit ratios for city schemes (Sælensminde, 2004).

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