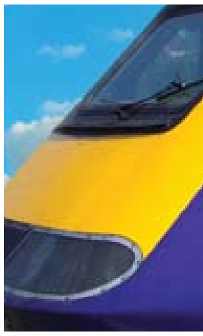
SNIFFER
SCOTLAND & NORTHERN IRELAND FORUM FOR ENVIRONMENTAL RESEARCH

$PM_{2.5}$ IN THE UK

Enhancing the general understanding of the issues relating to the regulation of fine particulate matter



December 2010

Project funders
Scottish Environment Protection Agency
Northern Ireland Environment Agency
Environment Agency

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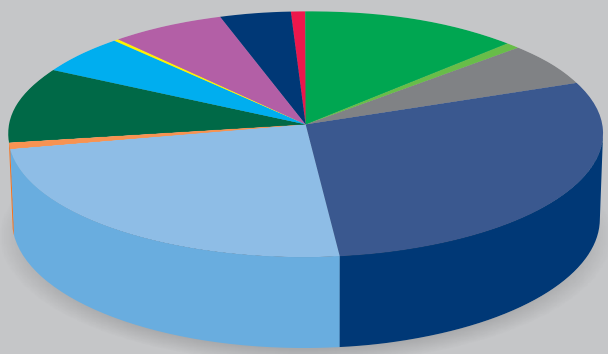
Introduction

This document summarises the findings of a SNIFFER project designed to provide regulators with an understanding of $PM_{2.5}$, which is a measure of particles less than 2.5 µm diameter. It covers health effects, sources, speciation, pathways, regulatory requirements, monitoring and modelling tools. It will be used to advise regulators on how airborne particulate matter (PM) sources need to be regulated to achieve the air quality limit values and objectives. The full report is available electronically at www.sniffer.org.uk.

Background to research

It is recognised that exposure to PM can give rise to significant health effects and there is no evident safe level. Attention was initially directed towards PM of less than 10 µm diameter (PM_{10}), but epidemiological evidence regarding the health effects of smaller particles has now changed the focus to $PM_{2.5}$. As a consequence, new legislation has recently come into effect to control exposure to $PM_{2.5}$ (with a continuation of controls on PM_{10}), and the United Kingdom (UK) Government will need to develop approaches to reduce exposure to $PM_{2.5}$. To ensure this is carried out in the most cost-effective way it is first necessary to have a good understanding of the sources, pathways and health effects of $PM_{2.5}$, and of the legislation that can contribute to its control. The focus is on annual mean concentrations of $PM_{2.5}$, as these are the most significant in terms of health outcomes, and on concentrations within urban areas, where most people are exposed.

Emissions of primary $PM_{2.5}$ from the UK in 2008.



	Residential	13.0%
	Commercial/Institutional	0.7%
	Power stations	6.0%
	Industrial operations	28.9%
	Road transports	23.5%
	Rail	0.8%
	Shipping	10.1%
	Off-Road mobile	5.3%
	Aviation	0.1%
	Waste	6.5%
	Agriculture	4.2%
	Other	0.8%

Sources and Behavior of $PM_{2.5}$

- There are many different sources, both natural and anthropogenic, contributing to $PM_{2.5}$ concentrations. These can be primary particles, which are emitted directly into the atmosphere, or precursor gases, which form secondary particles through atmospheric reactions.

- Industrial sources and power stations contribute most to national primary anthropogenic emissions (35%), followed by road transport (24%), residential (13%) and shipping (10%).

- The $PM_{2.5}$ fraction of PM is removed only slowly from the atmosphere; the dispersion of $PM_{2.5}$ in the near-field can thus be treated like that of a gas.

- Primary anthropogenic particles (from all sources) make a relatively small contribution to urban background $PM_{2.5}$, probably less than 25% (although there is some uncertainty with regard to this estimate). Primary emissions from combustion sources are made up largely of elemental and organic carbon. These particles will have trace metals and trace organic compounds associated with them.

- In general terms, motor vehicle emissions (both exhaust, and brake and tyre wear) contribute slightly more than industrial sources (including point sources) to urban background $PM_{2.5}$.

- More specifically for $PM_{2.5}$ from traffic, the overall breakdown is broadly 64% vehicle exhaust, 32% brake and tyre wear, and 4% resuspended road particles. Thus around 36% of traffic emissions are likely to be from sources that are currently uncontrolled.

- Natural sources of PM include sea salt, which accounts for ~5-15% of urban background $PM_{2.5}$, with higher contributions found towards the western coastal areas of the UK, while windblown dust contributes ~5-8%.

- The formation of secondary particles happens relatively slowly (hours to days), thus secondary $PM_{2.5}$ is found well downwind of the sources of emission of the precursor gases. As a consequence there is a reasonably even distribution of secondary $PM_{2.5}$ on a regional scale.

- Secondary particles are mainly formed from emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and volatile organic compounds (VOCs). Emissions of these precursor gases have declined significantly over the last three decades, especially for SO_2, followed by NO_x, VOCs and to a limited extent NH_3.

- Secondary particles dominate urban background $PM_{2.5}$ in the UK, accounting for some 30-50% of the $PM_{2.5}$ in urban areas. They are predominantly ammonium sulphate, ammonium nitrate, and organic particles. A significant proportion of secondary $PM_{2.5}$ is imported into the UK, having been formed from precursor emissions in continental Europe.

Exposure to $PM_{2.5}$

- Rural annual mean concentrations of $PM_{2.5}$ range from around 3.5 µg/m³ in Scotland to around 10 µg/m³ in southern England. Urban background concentrations are a few µg/m³ higher, and are highest in central London at around 15 µg/m³. Annual mean concentrations close to busy roads will be a few µg/m³ higher still, although concentrations decline rapidly on moving away from the carriageway, such that they are indistinguishable from the background after about 20-50 m

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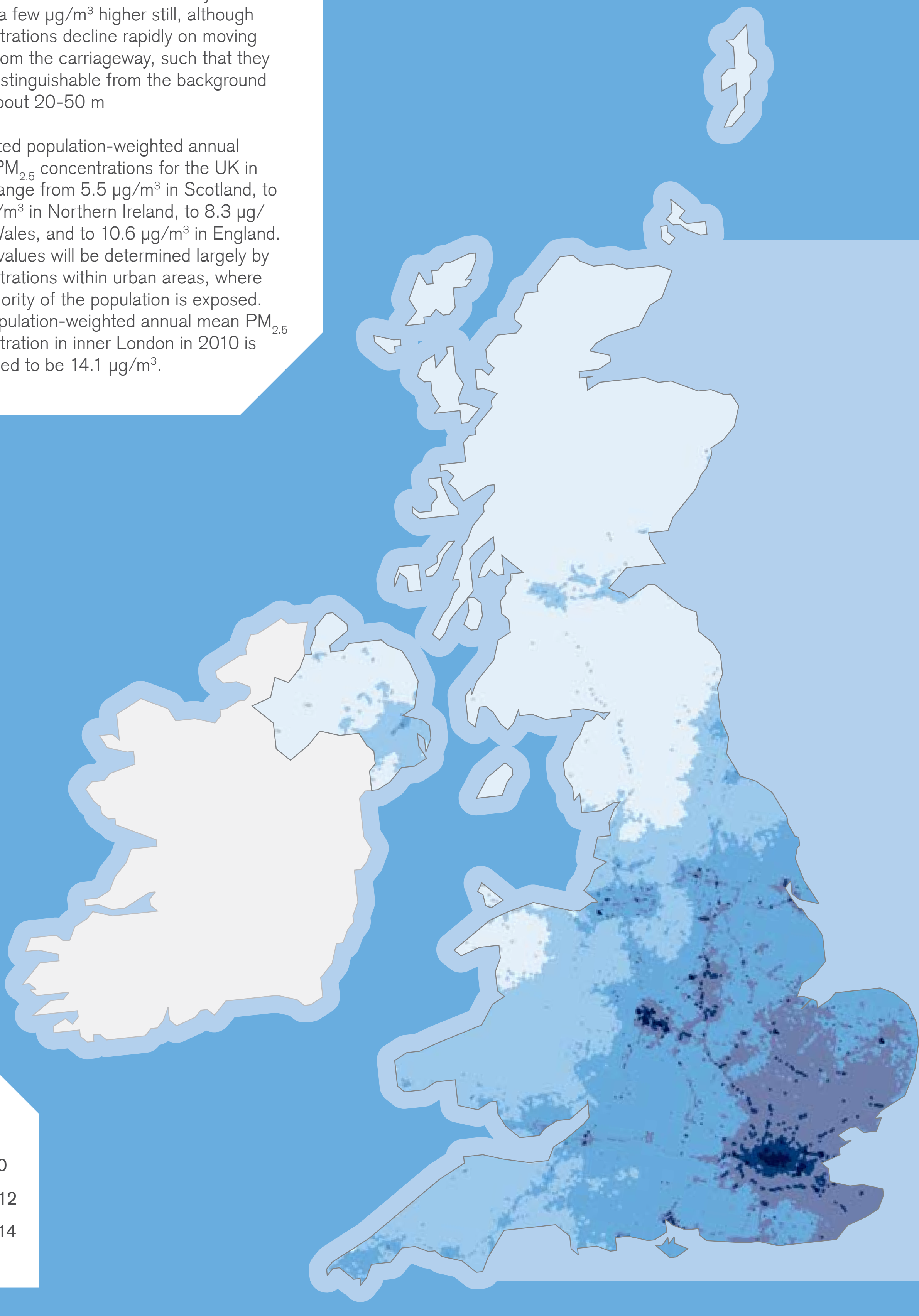
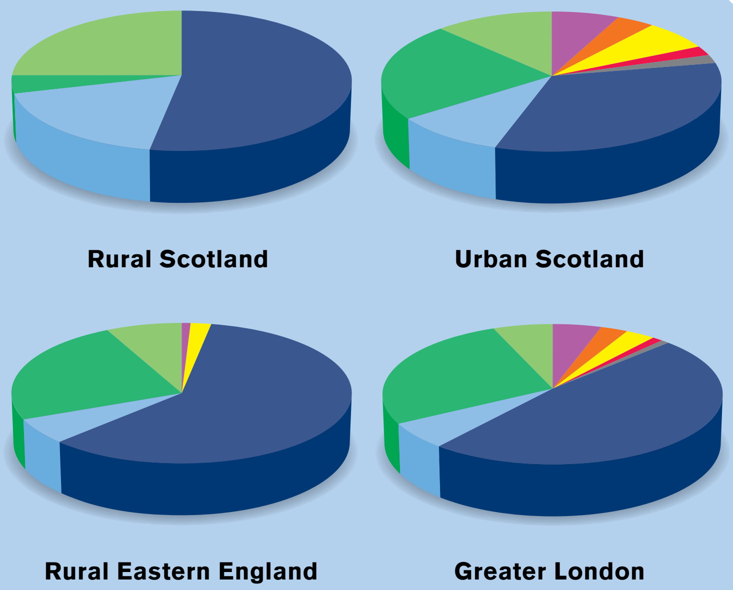
- Estimated population-weighted annual mean $PM_{2.5}$ concentrations for the UK in 2010 range from 5.5 µg/m³ in Scotland, to 6.4 µg/m³ in Northern Ireland, to 8.3 µg/m³ in Wales, and to 10.6 µg/m³ in England. These values will be determined largely by concentrations within urban areas, where the majority of the population is exposed. The population-weighted annual mean $PM_{2.5}$ concentration in inner London in 2010 is estimated to be 14.1 µg/m³.

Background annual mean $PM_{2.5}$ concentrations (µg/m³) across the UK, estimated for 2010.



Health Effects of $PM_{2.5}$

- Both short- and long-term exposure to $PM_{2.5}$ gives rise to a range of health effects. These include hospital admissions and mortality from respiratory and cardiovascular diseases.
- The effects of long-term exposure are more significant than those of short-term exposure, in terms of the overall impact on the nation's health.
- There is no recognised threshold below which there are no health effects.
- There is no clear evidence as to which of the $PM_{2.5}$ components give rise to the toxic effects. Thus, at this stage, all components need to be considered capable of giving rise to these effects.
- Interventions to reduce exposure to PM, such as the ban on coal burning in Dublin, have been shown to be beneficial in health terms, with fewer respiratory and cardiovascular deaths following the interventions.
- Exposure to $PM_{2.5}$ reduces life expectancy by around six months averaged over the whole of the UK. For those individuals who are particularly sensitive the reduction in life expectancy could be much greater. For instance, if 10% of the population is affected then the loss of life expectancy for these individuals would rise to an average of around 6 years. Whilst it is not straightforward to compare health risks, it is estimated that eliminating exposure to man-made $PM_{2.5}$ would yield greater benefits than eliminating road traffic accidents or exposure to passive smoking.
- Significant health benefits across the UK and European Union (EU) populations have been calculated for a given reduction in exposure to $PM_{2.5}$. These translate into financial benefits, which more than offset the costs of mitigation programmes currently in place.



The composition of annual mean $PM_{2.5}$ for different areas of the UK in 2008.

	Rural Scotland	Urban Scotland	Rural Eastern England	Greater London
Vehicle exhaust	0%	7%	1%	5%
Break & tyre wear	0%	4%	0%	3%
Industry	0%	7%	2%	3%
Point sources	0%	2%	0%	1%
Domestic	0%	2%	0%	1%
Secondary	53%	33%	60%	48%
Sea salt	18%	10%	6%	6%
Other	4%	23%	24%	27%
Unknown residual	25%	12%	7%	6%

Legislation to Control Exposure to $PM_{2.5}$

- The focus for $PM_{2.5}$ is on limiting long-term exposure through use of annual mean standards.
- There are two strands to the legislation to control exposure to $PM_{2.5}$:
  - > exposure standards to define the level of control required; and
  - > measures to limit emissions to meet the standards (including emission standards used to control emissions from both transport and industrial sources, and measures such as the National Emissions Ceilings Directive).
- Control strategies to reduce emissions that contribute to $PM_{2.5}$ include:
  - > continued efforts to reduce emissions of precursor gases, to limit the formation of secondary PM, which will require national controls within a European-wide structure; and
  - > continued efforts to reduce emissions from primary sources giving rise to the urban enhancement of $PM_{2.5}$ concentrations, which will need to focus on industrial sources, road transport and to a lesser extent on domestic sources.
- There is a large body of legislation already in place to control exposure to PM, much of it involving the control of emissions. This is often focused on PM in general and has not been specific to PM_{10} or $PM_{2.5}$. However, measures to control total PM and/or PM_{10} will in general result in lower $PM_{2.5}$ concentrations.
- The concentration standards to limit public exposure, which previously were focused on PM_{10}, have, in the last few years, been extended to include $PM_{2.5}$.
- A new exposure-reduction approach has been introduced for $PM_{2.5}$. This is in recognition of the absence of an identified safe level for exposure to PM, and requires a reduction of $PM_{2.5}$ background concentrations in urban areas across the UK over the period 2010 to 2020.

Measurements of $PM_{2.5}$ Concentrations

- Little monitoring of $PM_{2.5}$ concentrations was carried out in the UK prior to the expansion of the national network (as part of the Automatic Urban and Rural Network (AURN)) in 2009 to meet the requirements of the EU Clean Air for Europe (CAFE) Directive. The AURN uses Filter Dynamic Measurement System (FDMS) analysers, which provide hourly mean concentrations that are equivalent to the EU reference method, *i.e.* the concentrations from these analysers are reference equivalent. The AURN currently comprises of 67 sites, of which 43 are classified as urban background[1], 17 as roadside/kerbside, 4 as industrial and 3 as rural.

- Additional monitoring is carried out by some local authorities, such as that undertaken within the London Air Quality Network (LAQN).

- Annual mean concentrations have been collated for 36 sites that had >90% data capture in 2009 (mostly AURN sites, but including some local authority sites). Urban background concentrations (27 sites) were mostly between 12-16 $\mu g/m^3$, with the highest concentration recorded at the London Eltham site in east London, at 17.6 $\mu g/m^3$.

- Analysis of the 2009 data indicates the following overall pattern for annual mean $PM_{2.5}$ concentrations:
  - rural background concentrations are ~3-10 $\mu g/m^3$, with the lowest values in Scotland and the highest in southern England;
  - urban background concentrations are ~ 3-6 $\mu g/m^3$ above the rural background in major urban areas;
  - roadside concentrations alongside busy roads are ~1-2 $\mu g/m^3$ above the urban background; and
  - kerbside concentrations alongside busy roads are ~7-8 $\mu g/m^3$ above the urban background.

- The limited evidence on trends in $PM_{2.5}$ concentrations over the last decade indicates:
  - no change in concentrations at rural background sites;
  - a very slight reduction in concentrations at urban background sites; and
  - a downward trend at roadside sites.

- The 2009 results show that concentrations of $PM_{2.5}$:
  - are substantially higher during the winter months than in the summer, with the highest monthly mean being around 10-15 $\mu g/m^3$ above the lowest monthly mean.
  - increase during the week, to give the highest levels on a Thursday/Friday, before dropping by around 4 $\mu g/m^3$ to a Sunday low. There is currently no full explanation available for this pattern; and
  - have a diurnal pattern that is consistent across central and southern parts of the UK (essentially south of the Lake District) with the lowest concentrations occurring during the afternoon and the highest during the early part of the night. This may be due, at least in part, to loss of semi-volatile $PM_{2.5}$ from the atmosphere during the warmer part of the day, with this material then re-condensing during the evening and night time, although there is no clear-cut explanation for this pattern. The afternoon drop in concentrations is not apparent in the results for the northern parts of the UK.

- A detailed analysis taking into account wind direction and wind speed has shown a consistent pattern across the UK, with the highest concentrations being associated with winds from the northeast through to southeast. These higher concentrations are often associated with stronger winds >10 m/s, and occur throughout the day and night. This is evidence of a significant $PM_{2.5}$ contribution being imported from continental Europe, probably as secondary PM.

[1] There is one site, Harlington, officially classified as 'Airport', however this is around 1 km from Heathrow Airport, and as such, $PM_{2.5}$ concentrations will be affected by the airport to a very limited extent. It is thus better to treat this site as an urban background site for $PM_{2.5}$.

Modelling of $PM_{2.5}$

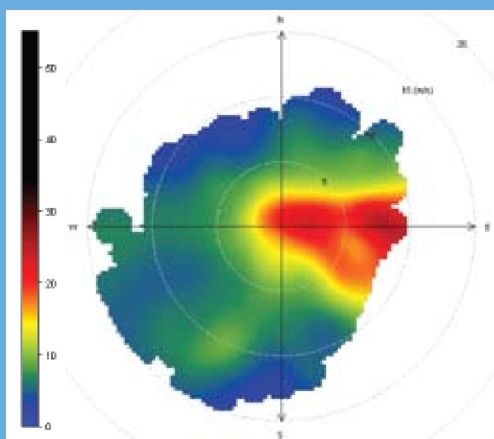
- Annual mean concentrations can normally be modelled with lesser uncertainty than is the case for short-term (hourly or daily mean) concentrations. Thus modelling of $PM_{2.5}$ should, in some respects, be more straightforward (than for PM_{10}, for which 24-hour concentrations are important) given that the focus is on the annual mean.

- A wide range of models can be applied to the modelling of $PM_{2.5}$, although these generally work at different spatial scales. Defra is currently undertaking studies to evaluate which models are best suited to meet policy needs and to identify those that should be investigated and developed.

- Two modelling suites are commonly used in the UK to estimate near-source concentrations of $PM_{2.5}$: ADMS (both ADMS4 for point sources and ADMS-Roads) and AERMOD. These are reasonably well-established and widely used for the assessment of development schemes, industrial permitting etc.

- There is only one national model applied routinely for $PM_{2.5}$. This is the semi-empirical Pollution Climate Mapping (PCM) model developed by AEA and used by Defra for policy development.

A polar plot of $PM_{2.5}$ measured at an urban background site in Reading, using hourly mean data for 2009. Concentrations in $\mu g/m^3$ are shown on the colour scale. They are plotted by wind direction and wind speed. Wind speeds increase from zero at the centre to 15 m/s for the full outer circle. The highest concentrations are seen with easterly winds, especially at higher wind speeds around 8 m/s. This general pattern is seen across all UK sites.



Recommendations

- The following recommendations are proposed for further work to provide a better understanding of $PM_{2.5}$ sources and concentrations, so as to allow appropriate control strategies to be developed. Their justification is described in the full report:

1. Modelling studies should be carried out to establish the contributions of UK and other EU emissions of precursor gases to annual mean $PM_{2.5}$ concentrations, and how these contributions will respond to changes in emissions. This will help guide the development of the most cost-effective control programme;

2. A programme of field, chamber and modelling studies should be carried out to establish the contributions from anthropogenic and 'natural' sources of organic carbon to $PM_{2.5}$, and how these will respond to changes in emissions;

3. Further work should be carried out on quantifying emissions, in particular from the road transport sector under 'real-world' driving conditions, and from industry. The contributions to urban background concentrations from other sources should be investigated using PM speciation studies. Such studies should then be used to inform the source contributions via modelling studies;

4. Improved deterministic modelling approaches should be developed at the national and urban scale, with robust treatments of atmospheric dynamics, chemistry and aerosol processes, so as to give size and composition-resolved information on airborne concentrations. This will enable reliable projections to be made of future concentrations, to complement the findings of more empirical models.

5. Seven additional $PM_{2.5}$ monitors should be set up at rural background sites, as a minimum. These could usefully be collocated with existing ozone monitors;

6. Sufficient resources should be provided to ensure that the results of the PM monitoring programmes are subject to thorough analysis on an on-going basis;

7. A programme of work should be established to support source apportionment of annual mean $PM_{2.5}$ at urban background locations in different areas of the UK; and

8. Consideration should be given to ways of using the planning system to require reductions in $PM_{2.5}$ emissions to be incorporated into the planning of all new developments.

Policy implications

- Analysis of concentrations in relation to the EU limit values and UK objectives has shown that the key driver for action to control exposure to $PM_{2.5}$ will be the exposure-reduction targets that have been established. The UK target is for a 15% reduction in annual mean $PM_{2.5}$ at background locations across the major urban areas, while the EU target will be 10-15% (still to be determined, once monitoring results for the three years 2009-11 are available). These represent reductions in annual mean concentrations of around 1.5-2 µg/m^3 over the ten years between 2010 and 2020. If these reductions are to be achieved from the local sources that give rise to the urban background enhancement of around 3-6 µg/m^3, then these urban source contributions would need to be reduced by some 25-67%. On the other hand, if the whole of the reduction were to be achieved by reducing the secondary PM contribution, which accounts for ~30-50% of urban background $PM_{2.5}$ (around 4-6 µg/m^3), then the required reduction of this secondary PM would be some 25-50%. In either case the reductions required to meet what appears to be a small target reduction, are substantial. If both are tackled equally the percentage reductions would essentially be halved, but would still remain challenging.

- EU limit values established to ensure there are no hot-spots with excessive concentrations of $PM_{2.5}$ are unlikely to be exceeded in the UK. The PM_{10} objectives and limit values have been shown to be more stringent than the $PM_{2.5}$ objectives and limit values, thus the former will drive policies to reduce exposure in hot spots; this will, in general, help drive down $PM_{2.5}$ concentrations at these locations.

- The response of secondary PM concentrations to changes in precursor gas emissions is less than proportional. This implies that greater reductions in precursor gas emissions are required than might at first sight be the case. The chemistry of secondary inorganic PM formation is such that reductions in ammonia emissions may be more effective at reducing PM concentrations than equivalent reductions in sulphur dioxide and nitrogen oxides, although this requires further investigation. The chemistry of secondary organic PM formation is poorly understood and it is not clear which sources of non-methane VOCs (NMVOCs) should be targeted to reduce PM concentrations.

Delivery

- To deliver the additional work and subsequent control strategies:
  - The UK Government and devolved administrations will need to establish a work programme to define the sources contributing to urban background $PM_{2.5}$ in those urban agglomerations where compliance monitoring is being carried out and then predict the changes that will take place between 2010 and 2020, before developing measures to fill any short-fall in the predicted concentration reduction;
  - The Environment Agency, the Scottish Environment Protection Agency and the Environment Agency Northern Ireland should contribute to the understanding of primary and secondary emissions from industrial, agricultural and waste sources that they regulate. They should also assist in modelling the contribution of primary $PM_{2.5}$ emissions to urban background concentrations and identifying measures to limit primary and secondary emissions; and
  - Local Authorities could be expected to help implement national measures to reduce primary $PM_{2.5}$ emissions, as well as consider ways to control $PM_{2.5}$ from new developments. They could also help develop amendments to the Clean Air Act to control emissions from biomass boilers.

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Developed by:

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