

AIR QUALITY EXPERT GROUP

# Particulate Matter in the United Kingdom



Prepared for:  
Department for Environment, Food and Rural Affairs;  
Scottish Executive; Welsh Assembly Government; and  
Department of the Environment in Northern Ireland



**AIR QUALITY EXPERT GROUP**

# **Particulate Matter in the United Kingdom**

Prepared for:  
Department for Environment, Food and Rural Affairs;  
Scottish Executive; Welsh Assembly Government; and  
Department of the Environment in Northern Ireland

This is the second report produced by the Air Quality Expert Group.

United Kingdom air quality information received from the automatic monitoring sites and forecasts may be accessed via the following media:

Freephone Helpline 0800 556677

TELETEXT page 156

Internet <http://www.airquality.co.uk>

<http://www.defra.gov.uk/environment/airquality/>

Department for the Environment, Food and Rural Affairs

Nobel House

17 Smith Square

London SW1P 3JR

Telephone: 020 7238 6000

© Crown copyright 2005

Copyright in the typographical arrangement and design rests with the Crown.

This publication may be reproduced free of charge in any format or medium provided that it is reproduced accurately and not used in a misleading context. The material must be acknowledged as Crown copyright with the title and source of the publication specified.

Further copies of the publication are available from:

Defra Publications

Admail 6000

London SW1A 2XX

Telephone: 08459 556000

This document is also available on the AQEG website at:

<http://www.defra.gov.uk/environment/airquality/aqeg>

Published by the Department for the Environment, Food and Rural Affairs.  
Printed in April 2005 on material containing 80% post-consumer waste and 20% elemental chlorine-free pulp.

Product code PB10580 ISBN 0-85521-143-1

The picture of TEOMs is reproduced with kind permission from Dr Paul Quincey. The pictures of the dust cart and breaking waves are reproduced with kind permission from Mr David Carslaw.

The map is reproduced with kind permission from Mr John Stedman.

When referencing this document, please use the following phrasing:  
*AQEG (2005) Particulate Matter in the UK*. Defra, London.

# Terms of reference

The Air Quality Expert Group was set-up in 2001 to provide independent scientific advice on air quality, in particular the air pollutants contained in the Air Quality Strategy (AQS) for England, Scotland, Wales and Northern Ireland and those covered by the EU Directive on ambient air quality assessment and management (the Air Quality Framework Directive). AQEG replaces the Airborne Particles Expert Group, who published their report on Source apportionment of airborne particulate matter in the UK in January 1999.

AQEG reports to the Secretary of State for Environment, Food and Rural Affairs, Scottish Ministers, the National Assembly for Wales and the Department of the Environment in Northern Ireland (the Government and Devolved Administrations). AQEG is an advisory non-departmental public body in England, Wales and Northern Ireland. In terms of the Scotland Act 1998, the Group is a jointly established body.

AQEG's main functions are:

- to give advice to ministers on levels, sources and characteristics of air pollutants in the UK;
- to assess the extent of exceedences of Air Quality Strategy objectives and proposed objectives, EU limit values and proposed or possible objectives and limit values, where monitoring data are not available;
- to analyse trends in pollutant concentrations;
- to assess current and future ambient concentrations of air pollutants in the UK; and
- to suggest potential priority areas for future research aimed at providing a better understanding of the issues that need to be addressed in setting air quality objectives.

The Group will not give approval for products or equipment.

Further information on AQEG can be found on the Group's website at:  
<http://www.defra.gov.uk/environment/airquality/aqeg/index.htm>

Information on these pages includes the dates, agendas, and minutes of meetings as they become available, a list of the members, the Register of Interests and draft and final reports as they become available.

# Air Quality Expert Group membership

## Chair

### **Professor Mike Pilling**

School of Chemistry, University of Leeds

## Members

### **Professor Helen ApSimon**

Department of Environmental Science and Technology, Imperial College London

### **Dr David Carruthers**

Cambridge Environmental Research Consultants (CERC)

### **David Carslaw**

Institute for Transport Studies, University of Leeds

### **Dr Roy Colvile**

Department of Environmental Science and Technology, Imperial College London

### **Professor Dick Derwent OBE**

rdscientific

### **Dr Steve Dorling**

School of Environmental Sciences, University of East Anglia (UEA)

### **Professor Bernard Fisher**

National Centre for Risk Assessment and Options Appraisal, Environment Agency

### **Professor Roy Harrison OBE**

Division of Environmental Health and Risk Management, University of Birmingham

### **Dr Mathew Heal**

Department of Chemistry, University of Edinburgh

### **Professor Duncan Laxen**

Air Quality Consultants Ltd

### **Dr Sarah Lindley**

School of Geography, University of Manchester

### **Dr Ian McCrae**

Environment Group, TRL Limited (Transport Research Laboratory)

### **John Stedman**

Netcen, a part of AEA Technology plc

## *Ad-hoc members*

### **Professor Mike Ashmore**

University of Bradford

### **Dr Mike Jenkin**

Department of Environmental Science and Technology, Imperial College London

### **Dr Peter Woods**

Analytical Science Group, National Physical Laboratory

## *Ex Officio members*

Central Management and Control Unit of the automatic urban and rural networks: **Stephen Moorcroft**, Air Quality Consultants Ltd (representing Casella Stanger)

National Atmospheric Emissions Inventory: **Dr Tim Murrells**, Netcen, a part of AEA Technology plc

Hydrocarbon monitoring networks: **Dr Paul Quincey**, Analytical Science Group, National Physical Laboratory

Quality Assurance and Quality Control of the automatic urban network and the Non-automatic monitoring networks: **Ken Stevenson**, Netcen, a part of AEA Technology plc

## *Assessors and observers*

### **Dr Antje Branding** (to September 2004)

Scottish Executive

### **Joan Forteath** (from September 2004)

Scottish Executive

### **Dan Kennedy**

Department of the Environment in Northern Ireland

### **Professor Bob Maynard**

Department of Health

### **Dr Havard Prosser**

Welsh Assembly Government

## *Secretariat*

### **Dr Janet Dixon**

Air and Environment Quality Division, Defra

### **Dr Sarah Honour** (to September 2004)

Air and Environment Quality Division, Defra

### **Ingrid Holmes** (from September 2004)

Air and Environment Quality Division, Defra

### **John Rea**

Air and Environment Quality Division, Defra

# Acknowledgments

The Group would like to acknowledge the following individuals and organisations for their help in the preparation of this report.

- Dr Wenche Aas, NILU, Norway for provision of elemental and organic carbon data.
- Bob Appleby (Birmingham City Council), Alan Webb (Innogy), Kevin Brown (Powergen), Carrie Harris (Heathrow Airport Limited) and various local authorities participating in the Netcen Calibration Club for providing the Group with data for the pro forma. Bob Appleby also provided long-term trend data for PM<sub>10</sub> and PM<sub>2.5</sub>.
- Dr Paul Boulter of TRL for his contribution in the area on non-exhaust particulate emissions from road transport.
- Dr Aurelie Charron, Dr Alan Jones and Mr Salah S. Abdalmogith of the University of Birmingham for provision of data and data analyses.
- Gary Fuller, David Green and Ben Barratt at ERG, King's College London for their help in compiling, processing and interpreting air pollution data.
- Dr Mark Gibson of the University of Strathclyde for the provision of particulate matter compositional data for Glasgow.
- Kate Johnson and Amy Stidworthy of CERC for provision of ADMS model output for Chapter 8.
- Dr Richard Maggs, Ms Yvonne Brown and Dr David Harrison at Casella Stanger who processed some of the data used in Chapter 5 and contributed to the report.
- Neil Passant, Melanie Hobson, Chris Dore, Rob Stewart, Martin Adams and Kate Haigh at Netcen for their contributions to Chapter 4 and Andrew Kent, Susannah Grice, Jaume Targa, Paul Cumine, Jeff Lampert also at Netcen for their contributions to other parts of the report, particularly areas focusing on air quality trends.
- Dr Alison Redington of the Met Office for provision of NAME model results used in Chapter 8 and Mr Derrick Ryall of the Met Office for analyses of the air mass origins of the Saharan dust and Russian forest fires particle episodes used in Chapter 6.
- CEH Edinburgh, EMEP and the University of Edinburgh for provision of modelling data.
- The Highways Agency for access to those data from their network of roadside air pollution monitoring stations.
- All local authorities for use of their air quality data.

# Table of contents

<b>Executive summary</b>	<b>1</b>	
<b>Chapter 1: Introduction</b>	<b>6</b>	
1.1	Particulate matter	6
1.2	Health effects of particulate matter	7
1.3	Emissions	7
1.4	Measurements of particulate matter	8
1.5	Modelling	9
1.6	Policy background	9
	1.6.1 International legislation and agreements	9
	1.6.2 National framework	11
1.7	Structure of the report	13
<b>Chapter 2: What is particulate matter?</b>	<b>16</b>	
	Key points	16
2.1	Introduction	16
2.2	Key physical characteristics of airborne particles	18
	2.2.1 Nucleation mode	19
	2.2.2 Accumulation mode	19
	2.2.3 Coarse particle mode	19
	2.2.4 Number, surface area and volume size distributions	20
	2.2.5 Semi-volatile components	21
2.3	Chemical composition of airborne particles	23
	2.3.1 Major components	23
	2.3.2 Minor components	24
2.4	Mass closure of airborne PM	25
2.5	Source apportionment	26
	2.5.1 Dispersion modelling	27
	2.5.2 Receptor modelling	27
<b>Chapter 3: What is causing the health effects of particles?</b>	<b>29</b>	
	Key points	29
3.1	Introduction	30
3.2	The health impact of particles in the UK	31
3.3	Evidence for adverse health effects from specific physical/chemical components of PM <sub>10</sub>	32
	3.3.1 Fine particles (PM <sub>2.5</sub> )	32
	3.3.2 Ultrafine particles (PM <sub>0.1</sub> )	33
	3.3.3 Coarse particles (PM <sub>coarse</sub> )	33
	3.3.4 Total surface area of particles	34
	3.3.5 Chemical constituents of particles	34
	3.3.5.1 Sulphate, acidity and other major inorganic ions	34
	3.3.5.2 Trace metals	34
	3.3.5.3 Organic components	35
	3.3.6 Interactions between physicochemical properties of particles	36
	3.3.7 Particle source	36
3.4	Summary of current understanding	37



<b>Chapter 4: Sources of particles in the UK</b>	<b>40</b>
Key points	40
4.1 Introduction	42
4.1.1 Scope	42
4.1.2 Legislation and regulatory framework controlling emissions	43
4.1.2.1 Control of industrial sources of particles	43
4.1.2.2 Control of emissions from road vehicles	44
4.1.2.3 Control of emissions from other transport and machinery	45
4.1.2.4 Control of emissions from other sources	46
4.1.2.5 National emissions ceilings	46
4.2 Sources of primary emissions	47
4.2.1 Estimation of emissions	47
4.2.2 Transport	47
4.2.2.1 Particle formation mechanisms and definitions	47
4.2.2.2 The regulatory test for exhaust emissions of PM	49
4.2.2.3 Particle size and number emissions by vehicle and fuel type and legislation class	50
4.2.2.4 Estimating emissions from road transport	51
4.2.2.5 Exhaust emission factors for PM	53
4.2.2.6 Road transport activity data	54
4.2.2.7 Cold start emissions	54
4.2.2.8 Non-exhaust road transport PM	55
4.2.2.9 Road vehicle tyre wear	55
4.2.2.10 Road vehicle brake wear	56
4.2.2.11 Estimation of tyre and brake wear emissions	56
4.2.2.12 Road vehicle resuspension	56
4.2.2.13 Other non-exhaust road vehicular emissions	58
4.2.2.14 Emission factors for other transport	58
4.2.2.15 Rail	59
4.2.2.16 Aircraft	59
4.2.2.17 Shipping	59
4.2.2.18 Non-road mobile machinery	59
4.2.2.19 Chemical composition of PM emissions from transport sources	60
4.2.3 Stationary sources	60
4.2.3.1 Overview of stationary sources	60
4.2.3.2 Derivation of emission estimates	61
4.2.3.3 Power stations	63
4.2.3.4 Industrial and commercial combustion processes	64
4.2.3.5 Domestic combustion	65
4.2.3.6 Coke and SSF manufacture	65
4.2.3.7 Cement and lime processes	66
4.2.3.8 Iron and steel industry	66
4.2.3.9 Aluminium production	67
4.2.3.10 Chemical processes	67
4.2.3.11 Bricks, tiles, refractories and ceramics	68
4.2.3.12 Other processes	68
4.2.3.13 Mining and quarrying	69
4.2.3.14 Construction	70
4.2.3.15 Waste incineration	70
4.2.3.16 Agriculture	70

	4.2.3.17	Foot and mouth pyres	71
	4.2.3.18	Chemical composition of PM emissions from stationary sources	72
	4.2.4	A recent review of particulate matter emission factors for industrial processes and combustion	72
	4.2.4.1	Review of industry processes	72
	4.2.4.2	Review of emissions from the combustion of natural gas	74
	4.2.4.3	Review of emissions from mining, quarrying and construction	74
	4.2.5	Fireworks and associated fires	74
4.3		Secondary particle precursors	75
	4.3.1	Origin of secondary particles	75
	4.3.2	Sulphate	75
	4.3.3	Nitrate	76
	4.3.4	Ammonium	78
	4.3.5	Organics	78
4.4		Emission estimates by source type	80
	4.4.1	Directly estimated primary emissions	80
	4.4.2	Emissions of PM <sub>2.5</sub> and fine PM	82
	4.4.3	Emissions of particle precursors	83
	4.4.3.1	NO <sub>x</sub> emissions	83
	4.4.3.2	SO <sub>2</sub> emissions	84
	4.4.3.3	NMVOC emissions	85
	4.4.3.4	NH <sub>3</sub> emissions	85
	4.4.4	Biogenic emissions	85
	4.4.5	Local emissions inventories	86
	4.4.6	Changes in the 2002 NAEI	88
	4.4.7	Uncertainty in national emissions estimates	90
	4.4.7.1	Quantification of uncertainties in emission estimates for sources covered in the inventory	90
	4.4.7.2	Sources omitted in the inventory	92
	4.4.7.3	Local emissions in critical areas and ratio of NO <sub>x</sub>	93
4.5		Time series of emissions	94
	4.5.1	UK emissions	94
	4.5.1.1	Stationary fuel combustion	94
	4.5.1.2	Production processes	95
	4.5.1.3	Road transport	95
	4.5.2	Emission trends by particle size: the 2001 NAEI time series	96
	4.5.3	Emissions by fuel type	96
	4.5.3.1	Public power	96
	4.5.3.2	Commercial, residential and institutional combustion	98
	4.5.4	Trends in PM <sub>10</sub> – PM <sub>2.5</sub> emissions	98
	4.5.5	Trends in UK precursor emissions	100
	4.5.5.1	Temporal trends of NO <sub>x</sub> emissions	100
	4.5.5.2	Temporal trends of SO <sub>2</sub> emissions	101
	4.5.5.3	Temporal trends of NMVOC emissions	101
	4.5.5.4	Temporal trends of NH <sub>3</sub> emissions	102
	4.5.6	Trends in the PM <sub>10</sub> to NO <sub>x</sub> ratio	102
	4.5.7	Emissions of primary particulates in Europe	103
	4.5.8	Emissions of PM precursor gases in Europe	105

4.5.9	UK emission projections	107
4.5.9.1	Assumptions for non-road transport sources	109
4.5.9.2	Assumptions for road transport sources	109
4.5.9.3	Baseline PM emission projections for urban UK road transport	111
4.5.10	Baseline PM emission projections for all UK sources	112
4.5.11	Baseline emission projections for PM precursor pollutants from all UK sources	112
4.5.11.1	SO <sub>2</sub>	112
4.5.11.2	NO <sub>x</sub>	113
4.5.11.3	NMVOCs	113
4.5.11.4	NH <sub>3</sub>	114
4.6	Emissions controls and abatement technologies	115
4.6.1	Abatement of industrial emissions of particles	115
4.6.2	Abatement of emissions from road vehicles	117
4.7	Impact of policies on particle emissions	119
4.7.1	The impact of increased diesel car penetration	119
4.7.2	An evaluation of policies and regulations affecting emissions from the road transport sector in the UK	120
4.7.3	Low emission zones	122
4.7.4	London congestion charging scheme (CCS)	123
<b>Chapter 5: Methods for monitoring particulate concentrations</b>		<b>125</b>
	Key points	125
5.1	Introduction	126
5.2	Overview of PM monitoring methods	126
5.2.1	Introduction	126
5.2.2	Size-selective inlet heads	128
5.3	PM <sub>10</sub> monitoring methods	128
5.3.1	Filter-based gravimetric samplers	128
5.3.2	TEOM analysers	129
5.3.3	β-attenuation analysers	131
5.3.4	Optical analysers	133
5.3.5	Black smoke method	134
5.3.6	Personal samplers	134
5.4	Comparison of PM <sub>10</sub> monitoring methods	135
5.4.1	Introduction	135
5.4.2	EU Working Group paper on equivalence	135
5.4.2.1	Background	135
5.4.2.2	The equivalence procedure for PM <sub>10</sub> in EN 12341	136
5.4.2.3	The equivalence procedure for PM <sub>10</sub> in the draft EC Guidance Document	136
5.4.3	The UK PM <sub>10</sub> intercomparison exercise	137
5.5	Measurement of PM <sub>2.5</sub> (and PM <sub>1</sub> ) concentrations	139
5.5.1	Methods of measurement	139
5.5.2	Development of CEN reference method for PM <sub>2.5</sub>	141
5.6	Measurement of nuisance dusts	141
5.7	Measurement of ultrafine particles	142
5.7.1	Particle number measurements	142
5.7.2	Measurement of particle surface area	142

5.8	Measurement of metals, PAH and major ions	143
5.8.1	Metals	143
5.8.2	PAH	143
5.8.3	Major ions	143
5.9	Continuous monitoring of speciated PM	143
5.10	The UK monitoring networks	144
5.10.1	Monitoring networks for PM <sub>10</sub> and PM <sub>2.5</sub>	144
5.10.1.1	UK networks	144
5.10.1.2	Regional networks	147
5.10.1.3	Other networks	148
5.10.1.4	PM <sub>2.5</sub> monitoring networks	149
5.10.2	Black smoke monitoring network	150
5.10.3	PAH monitoring network	151
5.10.4	Heavy metals monitoring networks	151
5.10.5	Major ions and elemental and organic carbon in PM	152
5.10.6	Ultrafine particles	154
5.11	Measurement uncertainty and quality assurance and control	154
<b>Chapter 6: What do the measurements tell us?</b>		<b>155</b>
	Key points	155
6.1	Overview of PM mass concentration data	158
6.1.1	Introduction	158
6.1.2	Relationships of PM metrics	160
6.1.3	Relationship between PM <sub>2.5</sub> and PM <sub>10</sub>	160
6.1.4	Specific components of airborne particles	163
6.1.4.1	Metals: network data	163
6.1.4.2	Metals: other data	163
6.1.4.3	PAHs	166
6.1.4.4	Black smoke	169
6.1.4.5	Elemental and organic carbon	170
6.1.4.6	Airborne chloride measurements at inland sites	176
6.1.5	Mass closure model for airborne particulate at roadside and background sites	177
6.1.6	Chemical composition of roadside and urban background particles and the roadside increment	181
6.1.7	Apportionment of urban background PM <sub>10</sub> in Glasgow using mass-closure model	182
6.2	Spatial distribution of PM	183
6.2.1	Spatial distribution of PM <sub>10</sub> within and between Edinburgh and Glasgow	183
6.2.2	Regional distribution of PM <sub>10</sub> and PM <sub>2.5</sub> concentrations across London	184
6.2.3	Background concentration surfaces of PM <sub>10</sub> in London	187
6.2.3.1	Annual mean background concentrations in London	187
6.2.3.2	Spatial distributions of PM <sub>10</sub> in London under episode conditions	191
6.2.4	Roadside concentration distribution	195
6.2.5	Roadside increments of PM <sub>10</sub> , PM <sub>2.5</sub> and PM <sub>coarse</sub>	196
6.2.6	Spatial distribution of secondary constituents across the UK	199

6.3	Episodicity of particle concentrations	202
6.3.1	Monthly exceedences of air quality objective concentrations	202
6.3.2	Episodicity of specific components	203
6.3.3	Saharan dust episodes	204
6.3.4	Sea salt aerosol	206
6.3.5	Biomass-burning fires as a source of particles	209
6.3.6	PM from construction activities	214
6.4	Use of correlations, concentrations or chemistry to elucidate particle sources	219
6.4.1	Comparison of PM concentrations with measurements of other pollutants	219
6.4.2	Weekday/weekend differences at traffic-influenced sites	226
6.4.3	Influence of air mass back trajectory and weather type on PM concentrations	228
6.4.4	Analysis of trends in PM concentrations by wind direction	229
6.4.5	Coarse particles at Marylebone Road: sources and concentrations	235
6.4.5.1	Concentrations measured at Marylebone Road	235
6.4.5.2	Local sources of PM <sub>coarse</sub> at Marylebone Road	238
6.4.5.2.1	Traffic	238
6.4.5.2.2	Construction and demolition activities	239
6.4.6	Estimation of the resuspension emission rate at Marylebone Road	239
6.4.7	Particle resuspension at the Manor Road site, London	242
6.4.8	Contribution to ambient particle concentrations from power stations	243
6.4.9	Industrial sources: Port Talbot case study	244
6.5	Particle number: concentrations and size distributions	249
6.5.1	Particle number concentrations	249
6.5.2	Particle number size distributions at a rural (Harwell), urban (Bloomsbury) and roadside (Marylebone Road) sites	252
6.5.3	Particle formation from vehicle emissions at Marylebone Road	254
6.5.4	NanoSMPS data at Marylebone Road	257
6.5.5	Homogenous nucleation events at Harwell	258
<b>Chapter 7: What are the main trends in particulate matter in the UK?</b>		<b>261</b>
	Key points	261
7.1	Historical setting	263
7.2	Trends during the 1990s and onwards	265
7.2.1	Black smoke trends	265
7.2.2	Particulate sulphate trends	266
7.2.3	PM <sub>10</sub> trends	268
7.2.4	PM <sub>2.5</sub> trends	272
7.2.5	PM <sub>coarse</sub> trends	273
7.2.6	Ultrafine particle number trends	273
7.2.7	Normalised monthly mean PM <sub>10</sub> trends within the LAQN	274
7.2.8	Trends at sites close to motorways	275
7.2.9	Trends at the multi-element sites	275

<b>Chapter 8: Modelling of particulate matter</b>	<b>278</b>
Key points	278
8.1 Introduction	279
8.2 Current modelling and mapping methods	280
8.2.1 National models – Receptor and Mapping	280
8.2.1.1 Site-specific source apportionment using the APEG receptor model	280
8.2.1.2 Netcen mapping model	281
8.2.1.2.1 Contribution from point sources	282
8.2.1.2.2 Contribution from area sources	282
8.2.1.2.3 Secondary particle contributions	283
8.2.1.2.4 Coarse and other particles not included explicitly in the modelling	283
8.2.1.2.5 Roadside concentrations	283
8.2.1.2.6 Verification of the mapped values	284
8.2.1.2.7 PM <sub>2.5</sub> maps	285
8.2.2 Urban models	286
8.2.2.1 ERG PM <sub>10</sub> model and predictions	286
8.2.2.2 ADMS-Urban	289
8.2.3 Regional models	292
8.2.3.1 The EMEP model	292
8.2.3.2 The FRAME model	292
8.2.3.2.1 Model domain	293
8.2.3.2.2 Emissions	293
8.2.3.2.3 Chemistry	293
8.2.3.2.4 Wet deposition	293
8.2.3.2.5 Dry deposition	294
8.2.3.2.6 Meteorology	294
8.2.3.3 The NAME model	294
8.2.4 Other models	298
8.2.4.1 Models for sources of PM due to wind generation, non-exhaust traffic emissions	298
8.2.4.2 Advanced transport models including aerosol dynamics	298
8.3 Comparison of model features	300
8.3.1 Netcen, ERG and ADMS-Urban models	301
8.3.2 Air pollution models for road traffic	305
8.4 Model outputs and comparisons	307
8.4.1 High resolution models up to national scale	308
8.4.1.1 Site-specific source apportionment	308
8.4.1.2 Mapped concentrations of PM <sub>10</sub>	315
8.4.1.3 Site-specific projections at monitoring sites	323
8.4.1.4 Mapped concentrations for PM <sub>2.5</sub>	326
8.4.2 Regional models	332
8.4.2.1 Comparison of modelled sulphate, nitrate and ammonium concentrations for the UK	332
8.4.2.2 Europe-wide calculations	336
8.5 Uncertainty in modelling PM	346
8.5.1 Methods for quantification of uncertainty and error	346
8.5.2 Results of uncertainty analysis	347
8.5.2.1 Annual average past concentrations of PM <sub>10</sub>	347
8.5.2.2 Future projections	349

8.5.2.3	Other metrics of PM concentration	349
8.5.2.3.1	90 <sup>th</sup> percentile	349
8.5.2.3.2	Higher percentile	350
8.5.2.3.3	PM <sub>2.5</sub>	350
8.5.2.3.4	Finer particle size fractions and particle number	350
8.5.2.4	Sensitivity of air quality management outcome to model uncertainty	351
8.6	Conclusions and recommendations	352
<b>Chapter 9: Discussion</b>		<b>354</b>
9.1	Introduction	354
9.2	Answers to questions	355
9.3	Are the current assessment methods (emissions inventories, measurements and modelling) fit for purpose? How could they be improved?	356
9.3.1	Answer	356
9.3.1.1	Emissions inventories	356
9.3.1.2	Measurements	356
9.3.1.3	Modelling	357
9.3.2	Rationale	357
9.3.2.1	Emissions inventories	357
9.3.2.1.1	Uncertainty of annual emissions inventories	357
9.3.2.1.2	Local and episodic emissions	358
9.3.2.1.3	Improvements to the annual emissions inventories	358
9.3.2.1.4	Emissions in future years	358
9.3.2.2	Measurements	359
9.3.2.2.1	Relationships between episode days and annual means	359
9.3.2.2.2	Spatial representation	359
9.3.2.2.3	Measurements of PM <sub>2.5</sub>	360
9.3.2.2.4	Chemical composition and source apportionment	360
9.3.2.3	Modelling	361
9.3.2.3.1	Secondary inorganic compound	361
9.3.2.3.2	Primary PM	361
9.3.2.3.3	Residual component	361
9.3.2.3.4	Air pollution episodes and daily limit values and objectives	362
9.3.2.3.5	Links between modelling and measurements	362
9.3.2.3.6	Inter-annual variation and extrapolation of trends	363
9.3.2.3.7	Other uncertainties when assessing exceedence of limits	363
9.4	Are there sources missing from (a) UK emissions inventories and (b) other European inventories	363
9.4.1	Answer	363
9.4.2	Rationale	364



9.5	Is the UK likely to achieve, with current abatement measures and technologies (a) the Stage I and indicative Stage II annual and daily mean PM <sub>10</sub> limit values in the First Air Quality Directive and (b) the Air Quality Strategy objectives for PM <sub>10</sub> ? If not, why not? What levels of PM <sub>10</sub> are likely to be achieved by current measures and policies?	365
9.5.1	Answer	365
9.5.2	Rationale	365
9.5.2.1	AQMAs and exceedences away from roads	366
9.5.2.2	Achievement of Stage II limit values and provisional air quality objectives	366
9.5.2.3	Site-specific projections	367
9.5.2.4	GIS-based modelling results	368
9.6	Will the UK be able to meet the range of targets for PM <sub>2.5</sub> as proposed in the draft CAFE Position Paper on Particulate Matter? If not, why not? What levels of PM <sub>2.5</sub> are likely to be achieved by current measures and policies?	370
9.6.1	Answer	370
9.6.2	Rationale	371
9.7	What are the practical maximum feasible reductions of PM <sub>10</sub> and PM <sub>2.5</sub> concentrations at (a) hotspots and (b) urban background, for example central London locations?	371
9.7.1	Answer	371
9.8	Where and what are the main source contributors to current and future concentrations of PM <sub>10</sub> and PM <sub>2.5</sub> ? What are the contributions of different sources to forecast exceedences of the EU limit values and UK objectives?	373
9.8.1	Answer	373
9.8.2	Rationale	374
9.9	What are the potential sources of abatement and types of measures to reduce particle concentrations at (a) hotspots, such as near busy roads, (b) at urban background, central London and (c) across the whole country? What role can local/national/EU-wide measures play in meeting targets? These measures should be defined as technical (for example, vehicle standards); non-technical (for example, traffic management systems); and international (for example, controlling European/ hemispheric emissions). Are there alternatives to emissions reduction?	374
9.9.1	Answer	374
9.9.2	Rationale	376
9.10	A number of recent studies (that is, the WHO report) have highlighted the health effects of certain components of PM (fines, ultrafines, particle number, metals and elemental/organic carbon). Where further abatement techniques are known, how might they specifically affect reduction of the different PM metrics (for example PM <sub>10</sub> , PM <sub>2.5</sub> , PM <sub>1</sub> and particle numbers) and chemical components?	381
9.10.1	Answer	381
9.10.2	Rationale	381



9.11	Ultrafines – what have we learned from the measured data, including source apportionment? Are the observed trends real? What fraction of ultrafine particles volatilise?	382
9.11.1	Answer	382
9.11.2	Rationale	382
9.12	Source apportionment – how does the UK source apportionment for PM <sub>10</sub> , PM <sub>2.5</sub> and other metrics compare with other modelling in Europe? Is road traffic more important than current models show? How is the coarser fraction between 2.5 and 10 µm accounted for?	382
9.12.1	Answer	382
9.12.2	Rationale	383
9.13	Can we explain the trends in measured PM <sub>10</sub> , sulphur and black smoke since 1992?	384
9.13.1	Answer	384
9.13.2	Rationale	385
9.14	What are the differences between strategies that address hotspots of exceedence and those that aim to reduce population exposure? Should policy evaluation consider impacts on population exposure as well as concentrations at specific locations?	385
9.14.1	Answer	385
9.14.2	Rationale	386
<b>Chapter 10: Conclusions and recommendations</b>		<b>387</b>
10.1	Particulate sulphate	387
10.2	Particulate nitrate	388
10.3	Elemental or black carbon	388
10.4	Organic carbon	389
10.5	PM <sub>10</sub>	389
10.6	PM <sub>2.5</sub>	390
10.7	Ultrafine particles	390
10.8	Particulate iron	390
10.9	Natural PM sources	391
10.10	Other manmade sources	391
10.11	Ozone and PM air quality	391
10.12	Projected exceedences of future air quality targets based on the Site-specific Receptor and Projections Model	392
10.13	Projected exceedences of future air quality targets based on dispersion modelling	392
10.14	Local air quality management	393
10.15	Future PM policy development	393
10.16	Summary of research recommendations	394
10.17	Summary	395
<b>Abbreviations and glossary</b>		<b>397</b>
Abbreviations		397
Glossary		401

<b>References</b>	<b>405</b>
<b>Bibliography</b>	<b>415</b>
<b>Annex 1: Regulation of the major industrial sources of particles in England and Wales</b>	<b>417</b>
<b>Annex 2: Emission limit values for different vehicle types in Europe</b>	<b>418</b>
<b>Annex 3: The regulatory test method, in-service emissions testing, the measurement of exhaust particles and particles research</b>	<b>420</b>
A3.1 Limitations of the regulatory test method	420
A3.2 In-service emissions testing	420
A3.3 Issues relating to the measurement of exhaust particles	421
A3.4 Particle research programmes	422
<b>Annex 4: Summary of PM<sub>10</sub> and PM<sub>2.5</sub> monitoring methods in Europe</b>	<b>424</b>
<b>Annex 5: Performance of unheated <math>\beta</math>-attenuation analysers</b>	<b>426</b>
<b>Annex 6: Potential implications of the internal TEOM offset</b>	<b>432</b>
A6.1 Comparison of TEOM with gravimetric measurements	432
A6.2 Effect on PM <sub>10</sub> and PM <sub>2.5</sub> trends	433
A6.3 Effect on PM <sub>10</sub> to PM <sub>2.5</sub> ratios	434
A6.4 Effect on measured concentrations	434
<b>Annex 7: Source apportionment calculations for PM and status of roadside monitoring sites</b>	<b>436</b>
<b>Annex 8: Sensitivity analysis of Netcen and ERG models</b>	<b>441</b>
<b>Annex 9: The estimated effect of the London congestion charging scheme on PM<sub>10</sub> concentrations</b>	<b>444</b>

# Executive summary

When commissioning this report, Defra and the Devolved Administrations asked the Air Quality Expert Group (AQEG) a number of questions that are shown, in abbreviated form, in Figure 1. AQEG's answers to these questions, together with a rationale for each answer, are provided in Chapter 9. This executive summary provides a less detailed overview of the report and does not attempt to answer the questions explicitly.

**Figure 1.** Questions on particulate matter set by Defra and the Devolved Administrations for AQEG.

- Are the current assessment methods fit for purpose? How could they be improved?
- Are there sources missing from UK other European emissions inventories?
- Is the UK likely to achieve, with current abatement measures and technologies, the European Union limit values and the Air Quality Strategy objectives for PM<sub>10</sub>? If not, why not? What levels of PM<sub>10</sub> are likely to be achieved by current measures and policies?
- Will the UK be able to meet the range of targets for PM<sub>2.5</sub> as proposed in the draft CAFE Position Paper on Particulate Matter?
- What are the practical maximum feasible reductions of PM<sub>10</sub> and PM<sub>2.5</sub> concentrations at hotspots and urban background, for example central London locations.
- Where and what are the main source contributors to current and future concentrations of PM<sub>10</sub> and PM<sub>2.5</sub>? What are the contributions of different sources to forecast exceedences of the EU limit values and UK objectives?
- What are the potential sources of abatement and types of measures to reduce particle concentrations at hotspots, at urban background, central London and across the whole country? What role can local/national/EU-wide measures play in meeting targets? Are there alternatives to emissions reduction?
- A number of recent studies have highlighted the health effects of certain components of particulate matter. Where further abatement techniques are known, how might they specifically affect reduction of the different particulate matter metrics and chemical components?
- What have we learned from the measured data on ultrafines, including source apportionment? Are the observed trends real? What fraction of ultrafine particles volatilise?
- How does the UK source apportionment for PM<sub>10</sub>, PM<sub>2.5</sub> and other metrics compare with other modelling in Europe? Is road traffic more important than current models show? How is the coarser fraction accounted for?

- Can we explain the trends in measured PM<sub>10</sub>, sulphur and black smoke since 1992?
- What are the differences between strategies that address hotspots of exceedence and those that aim to reduce population exposure? Should policy evaluation consider impacts on population exposure as well as concentrations at specific locations?

## Properties of particulate matter

Atmospheric particulate matter consists of solid or liquid matter in sizes that range from a few nanometres (nm) in diameter to around 100 micrometres (100 µm). Its chemical composition includes sulphates, nitrates, ammonium, sodium chloride, elemental and organic carbon and a range of minerals. It contains both primary components, emitted directly into the atmosphere, and secondary components formed in the atmosphere by chemical reactions. The metric generally employed for particles in the UK is PM<sub>10</sub>, which, to a good approximation, describes the mass of particles with a size of less than 10 µm diameter; similarly PM<sub>2.5</sub> describes the mass of particles with a size of less than 2.5 µm diameter. An older, but still useful, metric measures the blackness of particulate matter and is termed black smoke.

The balance of evidence currently available suggests that it is combustion-derived components of which PM<sub>10</sub> that are primarily responsible for the harmful effects on human health. These components are comprised predominantly of fine (less than 2.5 µm) and ultrafine (less than 100 nm) carbon-containing particles and may be enriched with trace metals or specific organic compounds. There is generally less evidence to connect secondary inorganic particulate matter and coarse particles with adverse health effects. However the latter, in particular, cannot be ruled out since certain sources of these particles may be enriched with components of putative high risk (for example, soluble trace metals). The coarse fraction also contains biological material such as pollen and may be proportionally enriched with endotoxin, both of which factors can lead to adverse health effects.

## Objectives and limit values for concentrations of particulate matter

The Air Quality Strategy objectives for particulate matter are based on the health effects, which can result from both short-term and long-term exposure, and are linked mainly to respiratory and cardiovascular effects. The European Union limit value for PM<sub>10</sub> that came into force on 1 January 2005 is 50 µg m<sup>-3</sup> per 24-h period, with up to 35 exceedences per year allowed. The annual limit value that also came into force on 1 January 2005 is 40 µg m<sup>-3</sup>. The European Union has proposed an indicative limit value that should be met by 1 January 2010. It is also 50 µg m<sup>-3</sup> per 24-h period, but the number of allowed exceedences is reduced to seven per year and the annual limit value is halved to 20 µg m<sup>-3</sup>. The Air Quality Strategy adopted the 2005 values as objectives and the 2010 values as provisional objectives but modified them to make the annual objective more stringent (18 µg m<sup>-3</sup>) in Scotland and less stringent (23 µg m<sup>-3</sup>) in London. The 2010 limit values will be reviewed by the EC in the light of further experience and information and currently have no legal standing.

## Sources of particulate matter and trends in emissions

Particulate matter derives from both human-made and natural sources. Road transport gives rise to primary particles from engine emissions, from tyre and brake wear and from other non-exhaust traffic emissions. Other primary sources include stationary combustion processes (industrial, commercial and domestic), quarrying, construction and non-road mobile sources; natural sources include sea spray and Saharan dust. Secondary particulate matter is formed from emissions of ammonia ( $\text{NH}_3$ ), sulphur dioxide ( $\text{SO}_2$ ) and nitrogen oxides as well as emissions of organic compounds both from combustion sources and vegetation.

There have been substantial reductions in emissions in recent decades. Primary UK  $\text{PM}_{10}$  emissions fell from 570 kt in 1970 to 200 kt in 2000. A further fall of 28% is expected between 2000 and 2010 and predicted reductions in UK emissions of secondary precursors over this period range from 52% ( $\text{SO}_2$ ) to 10% ( $\text{NH}_3$ ). It is clear, however, that reductions will level off and total UK  $\text{PM}_{10}$  emissions are expected to change little between 2010 and 2020 with current measures. The Department for Transport now expects greater market penetration of diesel cars in the UK than it had previously forecast and had been assumed in the earlier versions of the National Atmospheric Emissions Inventory used in the air quality models that are discussed in this report. This will lead to slightly higher  $\text{PM}_{10}$  emissions than were originally predicted.

## Monitoring of particulate matter

UK monitoring networks primarily use the tapered element oscillating microbalance (TEOM) analyser. This provides real-time data with a short time resolution that is essential for the delivery of up-to-date public information. The TEOM uses a heated inlet, which leads to losses of semi-volatile compounds. The European reference method uses an unheated, filter-based gravimetric method. This method provides 24-h concentrations some days after the measurement. The differences in sampling lead to some inconsistency in results. Currently, as an interim measure, TEOM values are scaled by a factor of 1.3 to account for the losses of semi-volatile components. This is not ideal, as the real factor is highly variable from day to day and place to place. It would therefore be advantageous to identify a continuous method of quantifying the semi-volatile components.

The Clean Air for Europe (CAFE) programme is currently considering the introduction of targets for  $\text{PM}_{2.5}$ . Only a small number of sites (15) in the UK have co-located monitoring of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ . Although current evidence in this report indicates a strong correlation between daily  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  concentrations, AQEG views this number as inadequate and recommends an increase in the number of sites measuring both.

## Current measured concentrations and composition of particulate matter

The report collates measurements from 240 monitoring sites, including kerbside, roadside, urban background/centre, industrial and rural/remote locations. Data from these sites and from other measurements have been used to assess

sources, distributions and concentrations of particulate matter in the UK. Annual mean PM<sub>10</sub> concentrations are highest at roadside sites and lowest at rural sites, demonstrating the importance of road traffic as a source. There is evidence that the contribution of heavy duty vehicles is much greater than that of light duty vehicles. The concentration gradient between roadside, urban background and rural concentrations is much less pronounced than is found for nitrogen oxides and indicates a greater regional background contribution to PM<sub>10</sub>. This regional background contribution is a substantial fraction of the total even in London. There is a considerable variability, from month to month, in the number of exceedences of 24-h average concentrations of 50 µg m<sup>-3</sup>. This demonstrates episodicity in concentrations derived from a range of sources that contribute to PM<sub>10</sub>. Episodes of high secondary particulate matter also result from air masses arriving in the UK from European sources during anticyclones. Other episodic sources include sea salt, Saharan dust and biomass burning. Locally elevated particulate matter concentrations can result from construction activities, local roads, industries and domestic premises burning solid fuel.

## Observed and predicted trends in concentrations of particulate matter

Monitoring sites that have long enough records to establish trends show downward trends in PM<sub>10</sub> concentrations, but the steep decline observed over the period 1992–1999 has given way to a flattening out or even a slight increase over the period 2000–2003. It is unclear to what extent this change in behaviour arises from year-to-year variations in the weather. Black smoke records provide an 80-year record in London and show a decrease of a factor of about 50 over this period, largely as a result of the phase-out of coal burning. Measurements in London, though, show evidence of a slower decline in black smoke concentration over the last 10 years, related to emissions from diesel road traffic. Declines have also been seen in rural PM<sub>10</sub> measurements that can be related, in part, to reduced emissions of SO<sub>2</sub> and hence of production of secondary particulate sulphate. The overall reductions show, however, that other sources – primary or secondary – must also contribute to rural concentrations.

## Attainability of the Air Quality Strategy's objectives

Models incorporating assessments of future source strengths are used to predict future concentrations of particulate matter and likely exceedences of limit values and objectives in 2005 and 2010 as well as to develop mitigation policies. The models routinely used for national and local policy support in the UK include empirical components, based on monitoring data, and dispersion calculations. The diverse sources of particulate matter make predictions difficult and problems are encountered with: (i) the coarse fraction, which has a large range of sources, including road dust; (ii) the background concentrations and their dependence on both primary and secondary sources; and (iii) the increment in concentrations occurring at the road side. Calculations show the annual mean limit value set for 2005 being met nearly everywhere, but with some exceedences of the limit of 35 days with 24-hour averages above 50 µg m<sup>-3</sup>, especially in London. However, substantial exceedences both of the more stringent indicative annual mean limit values and of the smaller number of days above 50 µg m<sup>-3</sup> suggested for 2010 are likely throughout the UK. It is clear, given the substantial background particulate matter concentrations and the extent of the exceedences, that the

additional reductions required by 2010 to meet the Stage 2 indicative limit values cannot be met by control of primary emissions alone.

Local air quality management is able to identify local hotspots that are not necessarily identified through national studies. Air Quality Management Areas (AQMAs) have been established by 63 local authorities where exceedences of the 2005 limit values for  $PM_{10}$  are likely. The majority of these are for traffic sources, but there are also AQMAs for industrial, commercial and domestic sources of  $PM_{10}$ . The Action Plans being developed will help to ensure that concentrations are driven down in these areas, but will probably make only a marginal contribution to the wider reduction in particulate matter concentrations because of the substantial background contribution. The exception to this might be in London and other major conurbations, where many local authorities are working together to develop larger scale plans, for example, the low emission zone initiative being developed in London.

### Enhancement of policy assessment and improvement of air quality

The modelling of particulate matter concentrations is inherently more complex than for other common pollutants because of the need to combine the contributions from different sources, for example, long-range transport of secondary particulate matter, primary contributions from urban sources and very local contributions from individual roads. Models perform reasonably well for current years, but the complexity of particulate matter and the manner in which source contributions may change adds to the uncertainty in predicting future concentrations. Further work is required to improve and refine the models and to check their accuracy with respect to the different components and their sources. It is still not possible to relate all the observed  $PM_{10}$  mass to specific sources or to be certain about the relative contributions of different types of source, some of which remain obscure. Targeted improvements in the monitoring network, including enhanced monitoring of chemical components of the particulate mass, would help to clarify these questions and uncertainties. These improvements should include the deployment of monitors for particulate sulphate, nitrate, elemental and organic carbon and iron. It is also recommended that further rural  $PM_{10}$  and  $PM_{2.5}$  monitoring is undertaken to assess the background levels of particulate matter and hence determine the urban increment and to aid the understanding of particulate matter episodes. Co-location of particulate sulphate monitors with existing rural ozone, particulate nitrate,  $PM_{10}$  and  $PM_{2.5}$  measurements would contribute substantially to our understanding of the link between elevated regional particulate matter concentrations and the concentrations of individual components.

It is clear that while road traffic emissions are a major source of particulate matter near to roads, the regional background contribution, both rural and urban, is still dominant and must form a central component of mitigation strategies. AQEG recommends that consideration be given to additional forms of regulation to reduce mean population exposure, complementing concentration-based limit values, which tend to focus attention on local hotspots. The regional contribution and the links between the concentrations of different pollutants demonstrate the need for a more holistic approach to urban air quality management and its coupling to the control of acid rain, eutrophication and ground-level ozone.