Projecting and mapping benzene concentrations in support of the Air Quality Strategy review

A report produced for the Department for Environment, Food and Rural Affairs, the Scottish Executive, the National Assembly for Wales and the Department of the Environment in Northern Ireland

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Executive Summary

The Air Quality Strategy for England, Wales, Scotland and Northern Ireland (AQS, DETR et al 2000) sets a specific objective for benzene:

Running annual mean of 16.25 mgm^{-3} (5 ppb) to be achieved by the end 2003

The Strategy also identifies as a long-term policy aim to be met as far as practicable in all locations:

Running annual mean of 3.24 mgm^{-3} (1 ppb) to be achieved *as far as practicable for 2005*

A review of the AQS is underway, aimed at reassessing the objectives set, in the light of new technical information and recent Government and European policies and Directives.

The recently adopted second European Daughter Directive on air quality, European Directive 2000/69/EC relating to limit values for benzene and carbon monoxide (AQDD2) prescribes the following limit value for benzene to be achieved by 2005:

Annual mean of 5 mgm^{-3} (1.54 ppb), to be achieved by 2010

Site-specific analysis techniques and high resolution mapping approaches have been used to assess concentrations for a recent and future years. Approaches have been updated with the latest pollutant models and information from the National Atmospheric Emissions Inventory (NAEI), incorporating the 10-Year Plan for Transport (DETR, 2000a) in pollutant projections. Projections to 2010 have been made using both the current baseline emissions inventory and by way of a sensitivity analysis, an alternative emissions scenario which provides more optimistic estimates for benzene emissions reductions by taking into account the impact of lower benzene content in fuels upon emissions from non-catalyst vehicles.

Site-specific projections of roadside and urban background annual mean benzene concentrations for a number of sites in the Automatic Urban Network (AUN) have been performed for two base years, representing adverse and normal meteorological conditions (1997 and 1999 respectively). Estimates for sites for which this analysis was carried out indicate that, benzene concentrations are likely to be below the AQDD2 limit value by the end of 2010 for both emissions scenarios. For the Marylebone Road roadside location, (currently the site with the highest measurements), concentrations are expected to meet the AQDD2 limit value by approximately 2006 for the baseline emissions scenario and by 2002 for the alternative scenario.

Results from the high resolution mapping analysis, using 1999 as a base year and baseline emissions scenario, indicate that highest modelled urban background and roadside annual mean benzene concentrations in 1999 were estimated to be 4.4 and 20.7 μgm^{-3} respectively. Road links with benzene concentrations greater than 5 μgm^{-3} in 1999 are found throughout the UK, although proportionally greater numbers are to be found in London. Exceedences of the Lower Assessment Threshold, Upper Assessment Threshold and long-term objective are widespread.

Projecting these concentrations forward to 2010 using the baseline emissions scenario, it is estimated that 9 road links in London and 1 in Leeds will exceed the AQDD2 limit value. Exceedences of the Upper Assessment Threshold (UAT) in the Daughter Directive and 3.24 μgm^{-3} long-term policy aim are estimated to be found throughout London and the Rest of England. Projections using the alternative emissions scenario show that the AQDD2 limit value for 2010 will be met in all locations. The UAT and long-term objective will also be met in all parts of the UK with the exception of London and parts of England.

From the mapping analysis, the highest roadside annual mean benzene concentration in 1999 has been identified (20.7 μgm^{-3}). Projecting this modelled concentration for 1999 forwards using the baseline emissions scenario, the concentration the in 2010 is estimated to be 5.7 μgm^{-3}, indicating that road links with the highest estimated annual mean benzene concentrations in 1999 are likely to meet or be close to meeting the AQDD2 limit value in 2010.

Contents

1 Introduction

This report describes the modelling methods that have been used to predict benzene concentrations across the UK. The work forms part of a review of the Air Quality Strategy for England, Wales, Scotland and Northern Ireland (AQS, DETR et al 2000) by Department for Environment, Food and Rural Affairs, The Scottish Executive, The National Assembly for Wales and The Department of the Environment Northern Ireland. The review is aimed at reassessing the objectives laid out in the Air Quality Strategy (AQS) in the light of new technical information and recent Government and European policies and Directives.

The current AQS gives the following objective for benzene

- Running annual mean of 16.25 μgm^{-3} (5 ppb) to be achieved by the end 2003

The Strategy also identifies as a long-term policy aim:

- Running annual mean of 3.24 μgm^{-3} (1 ppb) for 2005 (to be achieved at all locations as far as practicable)

The recently adopted second European Daughter Directive on air quality, European Directive 2000/69/EC relating to limit values for benzene and carbon monoxide (AQDD2) prescribes the following limit value for benzene to be achieved by 2010:

- annual mean of 5 μgm^{-3} (1.54 ppb)

The following sections outline the methods used in the site-specific analysis of benzene concentrations and high resolution mapping techniques used to assess concentrations for recent and futures years. Site-specific modelling and mapping approaches have been updated with the latest pollutant models and information from the National Atmospheric Emissions Inventory (NAEI), incorporating the 10-Year Plan for Transport (DETR, 2000a) in future pollutant projections.

2 Baseline emissions inventory

2.1 BASELINE

Emission inventory maps for 1998 at a 1 km x 1 km resolution from the NAEI have been used throughout the work presented here (Goodwin et al, 2000). Maps of area emissions for the following sectors have been calculated:

- Domestic
- Industry

- Road Transport
- Other

Emissions maps for 1999 and 2010 have been calculated by scaling the sector maps from the 1998 NAEI with the changes in the UK sectors totals from the 1998 NAEI (for the years 1990-1999) and emissions projections (2000 onwards) from the 1998 NAEI. As the dominant source of benzene in the urban areas of the UK is road transport, accounting for 71% of total emissions in the UK (DEFRA et al, 2001), the emissions and projections for this sector have been recalculated based on the approaches to be used in the 1999 NAEI.

In applying the effects of the 10-Year Plan for Transport to projected road transport emissions, the impact of the plan upon emissions has been applied to the specific area types identified in the plan. The following approach was used for projecting road transport emissions.

- Traffic activity data by vehicle type and UK area type were used in the form of vehicle kilometres per type of vehicle and road/area type in the UK.
- Speed data were used to calculate average emission factors from the speed-emission functions.
- Annual vehicle kilometre figures for years up to 1999 are taken from the traffic census of the national road network (Stationery Office, 2000).
- Growth in vehicle kilometres are forecast from 1999 for each vehicle, road and urban area type. Vehicle kilometres in each road/area type are forecast separately for traffic in England, Scotland, Wales and N Ireland, as follows:

England:
Traffic growth was based on a combination of vehicle kilometre (vkm) figures by area type from the 10 Year Transport Plan and the 1997 National Road Traffic Forecast (NRTF). It was assumed that traffic growth continues at the rate defined by the NRTF from the base year (1999) to 2005, then linearly approaches the vehicle kilometre figures given in the 10-Year Plan for 2010. After 2010, traffic was assumed to continue to grow at a rate defined by the NRTF from this year.

Scotland:
Traffic growth was based on a combination of base 1996 vehicle kilometre (vkm) figures for different road types in Scotland given by DETR and the rate of traffic growth from 1997 to 2011 defined by the Central Scotland Transport Model (CSTM3). It was assumed that traffic growth continued at the rate defined by the NRTF from the base year to 2005, then linearly approaches the vehicle kilometre figures given in the CSTM3 for 2011. After 2011, traffic was assumed to grow at a rate defined by the NRTF from this year.

Wales:
The 10-Year Plan was assumed to apply in Wales on the same area-type basis as in England.

Northern Ireland:
In the absence of other information, it was assumed that traffic growth in these regions was identical to that defined by the 1997 NRTF from base 1996 vehicle km figures.

Average traffic speeds on different urban area and road types, rural roads and motorways are used based on an analysis of data from a number of different DETR publications referring to results from different traffic speed surveys. It is assumed that average speeds on the road network do not change in the future.

For England and Wales the network model in the NRTF framework divides the country into 11 different 'area types' listed in Table 1. Traffic data for road links in Scotland were also assigned to area types 4 to 11. In addition to projections of UK total emissions the NAEI can also provide projections of emissions for each individual area type in England, Scotland and Wales and these have been incorporated into the road link and area emissions maps for 2010.

Table 1 National Road Traffic Forecast area types for the Ten Year Plan for Tansport

Area Type	Description
1	Central London
2	Inner London
3	Outer London
4	Inner Conurbations
5	Outer Conurbations
6	Other urban areas > 25 km^2 area
7	Urban areas 15 - 25 km^2 area
8	Urban areas 10 - 15 km^2 area
9	Urban areas 5 - 10 km^2 area
10	Urban areas < 5 km^2 area
11	Rural areas

A breakdown of emissions from the road transport sector shows that the overwhelming the majority of emissions are from petrol vehicles and is illustrated by the UK urban road transport benzene emissions projections presented in Table 2.

Table 2 UK projection of benzene emissions from urban road transport 1995-2025

		1995	2000	2005	2010	2015	2020	2025
Cars	Petrol	19.72	10.90	6.13	4.41	3.92	3.99	4.12
	DERV	0.04	0.04	0.03	0.02	0.02	0.03	0.03
	All Cars	19.76	10.93	6.16	4.43	3.94	4.01	4.15
LGV	Petrol	1.45	0.57	0.12	0.04	0.04	0.04	0.04
	DERV	0.09	0.10	0.09	0.06	0.06	0.06	0.07
	All LGV	1.54	0.66	0.21	0.11	0.10	0.10	0.11
ALL HGV		0.01	0.01	0.00	0.00	0.00	0.00	0.00
Buses		0.01	0.00	0.00	0.00	0.00	0.00	0.00
Motorcycles		0.79	0.71	0.74	0.78	0.82	0.86	0.90
All DERV		0.15	0.14	0.13	0.09	0.09	0.09	0.10
All Petrol		21.97	12.18	6.98	5.23	4.77	4.88	5.07
All Vehicles		**22.12**	**12.32**	**7.11**	**5.32**	**4.86**	**4.97**	**5.17**

2.2 ALTERNATIVE EMISSIONS SCENARIO FOR BENZENE FROM ROAD TRANSPORT

The baseline emission projections for benzene take account of the reduction in emissions from vehicles with catalysts arising from the lower benzene content in unleaded petrol. According to UK Petroleum Industry Association (UKPIA, 2000), the average benzene content of unleaded petrol in the UK fell from 2.2% v/v (average over period 1992-1998) to 0.6% v/v by early 2000, a reduction of 73%. This reduction was driven by the European Fuel Quality Directive 98/70/EC, which took effect from 1 January 2000 putting a ceiling on the benzene content limit value of 1%.

Equations relating emissions to fuel quality given by the European Auto-Oil Research Programme (EPEFE) are used in the NAEI projections, taking account of the sulphur, benzene and aromatic content of fuels, as well as a range of other fuel properties. According to EPEFE, exhaust emissions of benzene from cars with three-way catalysts decrease with decreasing benzene content of the fuel, but the effect is not linear. No information is available on the effect of benzene content on emissions from cars without catalysts (or catalysts which have failed), so this is not included in the baseline inventory.

Between October 1999 and January 2000, sharp reductions in ambient benzene concentrations were observed at several urban monitoring locations in the UK. We consider that a contribution of the observed reductions may be explained by a reduction in benzene emissions from non-catalyst vehicles. The observed reduction in monthly mean benzene concentrations were around 45% at sites where vehicle emissions were expected to be the dominant emission source, and were not matched by any significant reduction in other vehicle related hydrocarbons, such as 1,3-butadiene or toluene. This indicates that the reductions were likely to result from changes in the benzene content of the fuel over this period.

Observed reductions in ambient benzene concentrations over this period can be explained by assuming that benzene exhaust emissions from cars without catalysts were reduced by the same amount as the benzene content of the fuel (i.e. 73%). A linear relationship between exhaust emissions was supported by chemical kinetic modelling of fuel combustion in engine conditions, which suggests that benzene exhaust emissions arise from unburned fuel released from the cylinder.

Table 3 illustrates the effect of including this hypothesis in the baseline projections. It shows a more optimistic reduction in benzene emissions for the alternative emissions scenario. Ambient benzene concentrations were modelled from the baseline emission projections both with and without the hypothesis that emissions are reduced from non-catalyst (and failing catalyst) cars by the same amount that the benzene content of petrol is reduced. Ideally, this hypothesis should be backed up by vehicle emission tests, but in the absence of these, it is felt that the hypothesis should be adopted in the inventory projections, once ratified ambient benzene data have been used to verify it for a full 12 month period from 1999-2000. In particular, the fall in the ratio of concentrations of benzene/1,3-butadiene should be used to verify the hypothesis, since 1,3-butadiene is not expected to be effected by the benzene content and the ratio also cancels out dispersion effects.

Table 3 Comparison benzene emissions projections from the current baseline emissions scenario and an alternative emissions scenario

		Benzene emission in ktonnes						
		1995	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**
Baseline scenario	Petrol	19.72	10.90	6.13	4.41	3.92	3.99	4.12
	Petrol LGV	1.45	0.57	0.12	0.04	0.04	0.04	0.04
	Motorcycles	0.79	0.71	0.74	0.78	0.82	0.86	0.90
	All Vehicles	21.97	12.18	6.98	5.23	4.77	4.88	5.07
Alternative scenario	Petrol cars	19.72	5.73	4.52	3.38	2.84	2.86	2.97
	Petrol LGV	1.45	0.20	0.07	0.04	0.04	0.04	0.04
	Motorcycles	0.79	0.20	0.20	0.21	0.22	0.23	0.25
	All Vehicles	21.97	6.13	4.80	3.63	3.10	3.14	3.25

Site specific projections and mapping analyses have been carried out using the baseline emissions projections and in addition, as a sensitivity analysis, the alternative emission projection scenario.

3 Site-specific projections of benzene concentrations

3.1 METHOD

The method used to calculate site-specific projections of annual mean benzene concentrations was first implemented for the calculation of NO_2 and PM10 projections and is described in the AQS (DETR et al, 2000) and in some detail by Stedman et al (1998a) and Stedman (1999). The method has subsequently been revised and updated for benzene to incorporate:

1. More up-to-date monitoring information.
2. More detailed emission inventory using:

- *1990-1999 historical data from the 1999 NAEI* for traffic
- *1990-1998 historical data from the 1998 NAEI for stationary sources*
- *Projections to 2025 from the 1998 NAEI*
- *Road transport historical emissions and projections updated to the 1999 NAEI methodology*

The projections are based on measurements carried out at sites within the national automatic monitoring networks (see www.aeat.co.uk/netcen/airqual for details of the site locations and an archive of monitoring results). The following steps were required to project measured concentrations, and are carried out using the current baseline and alternative emissions scenario:

1. The measured benzene concentrations were divided into component parts. A map of rural benzene concentrations was derived from the 1998 rural NO_x concentration field using a NO_x:benzene ratio of 0.0424 (the measured ratio at the Harwell rural site) to scale the data.

The local source contribution to annual mean benzene was derived by subtracting the rural benzene map value at the location of the monitoring site from the measured benzene concentration. Emission inventory maps (Goodwin et al, 2000) for 1998 were used to split the local source contribution into emissions sectors. Local sources were summed within a 35 km x 35 km area centred on the monitoring site location. An ADMS based dispersion matrix was applied to weight emissions from individual grid cells according to distance and direction from the site location. This dispersion matrix approach was also used to calculate the maps and is described in sections 4.

2. An additional contribution from emissions on the road adjacent to the monitoring site was included for roadside monitoring sites. An annual mean background concentration for each roadside site was derived from the maps described in section 4.
3. Each component was then projected forwards from the measurement year through to 2025 according to the projected change in emissions from each sector. Each sector was then summed to give an estimate of annual mean benzene concentrations for 2010. Rural concentrations were projected on the basis of changes in UK total benzene emissions.

Figures 1 to 8 present illustrative examples of site-specific projections of benzene concentrations for years between 1990 and 2025 for both baseline and alternative emissions scenarios. Projection have been calculated from measured concentrations in a number of base years in order to show the effect of varying dispersion characteristics upon projected concentrations. Nominally, the base years selected were 1997, representing poor dispersion characteristics and 1999, representing normal dispersion characteristics. In cases where monitoring data for these years are unavailable, alternative years have been selected. There is good agreement between the projections for the years in the mid 1990s and the measured concentrations, giving confidence in the emissions sector split and emissions estimates.

3.1.1 Relationship between modelled annual mean and running annual mean statistics

Both the site specific analyses and high resolution mapping techniques (see section 4) produce benzene concentration estimates based on the annual average. Concentration estimates derived from these tools are directly comparable with the EU limit values for benzene, but not directly comparable with the running annual mean AQS objective and long-term.

To facilitate the identification of exceedence of the long-term objective as a running annual mean, an analysis of the relationship between the benzene annual mean and running annual mean statistics was carried out for sites in the national automatic network with data between 1994 and 1999. This analysis identified that on average the running annual mean was approximately 11.3% higher than the annual mean. This relationship was used to identify an annual mean equivalent for the running annual mean of 2.87 $\mu g\ m^{-3}$ (0.87 ppb) to enable estimation of exceedence of the long-term objective.

Figure 1 Projected annual mean benzene concentrations at Edinburgh based on 1997 and 1999 monitoring data – baseline emissions scenario

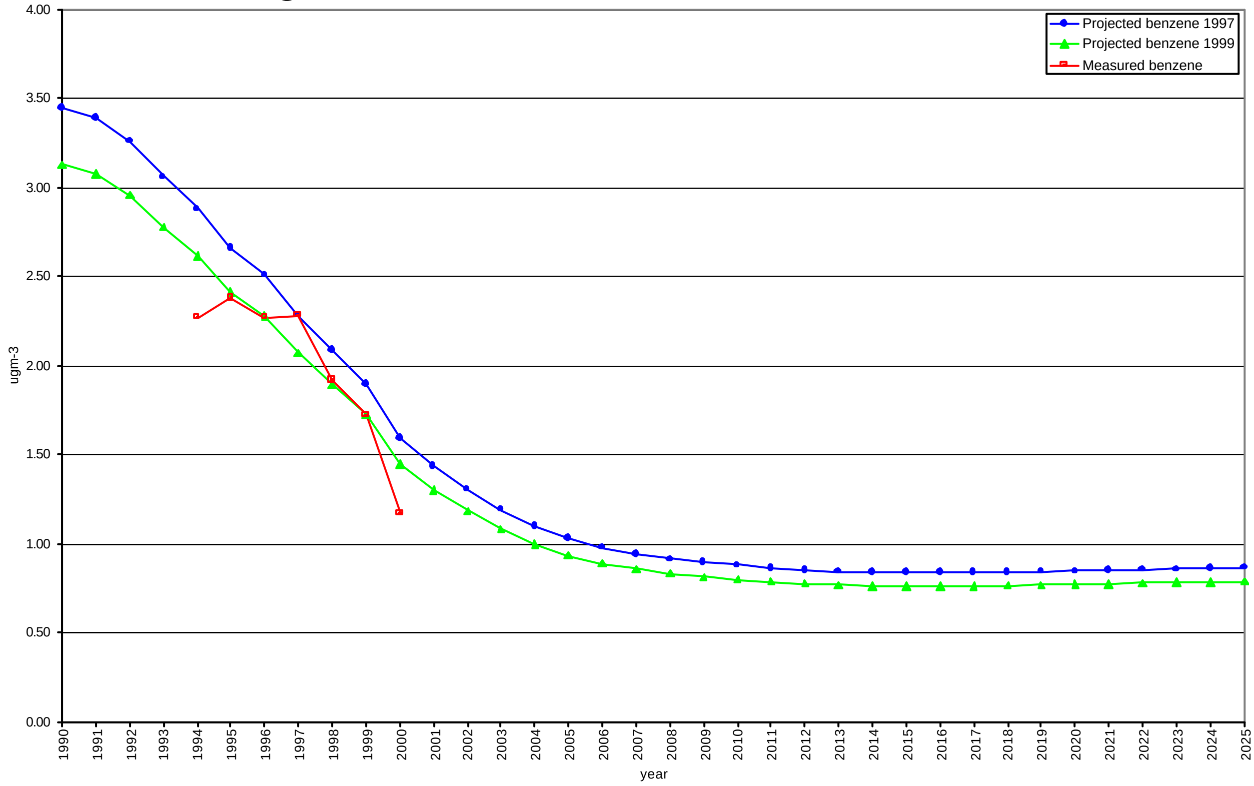


Figure 2 Projected annual mean benzene concentrations at Edinburgh based on 1997 and 1999 monitoring – alternative emissions scenario

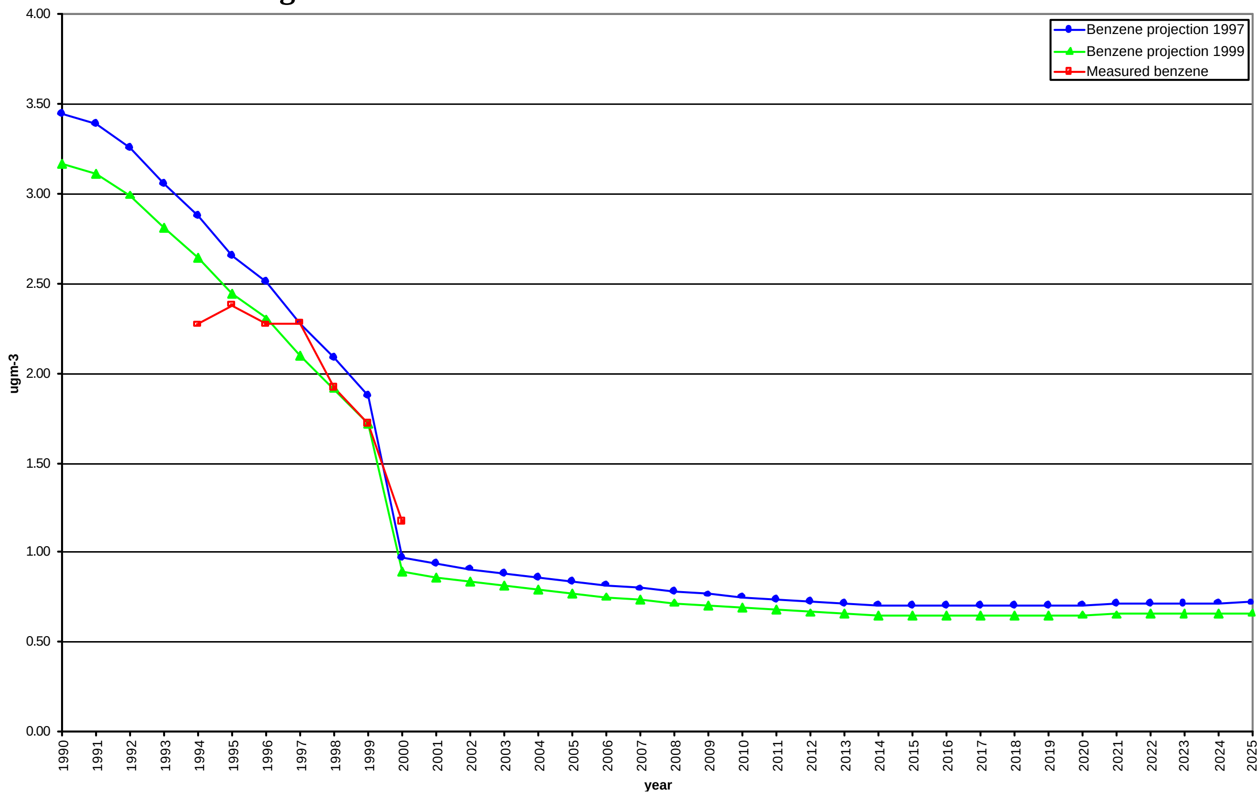


Figure 3 Projected annual mean benzene concentrations at Middlesbrough based on 1997 and 1999 monitoring – baseline emissions scenario

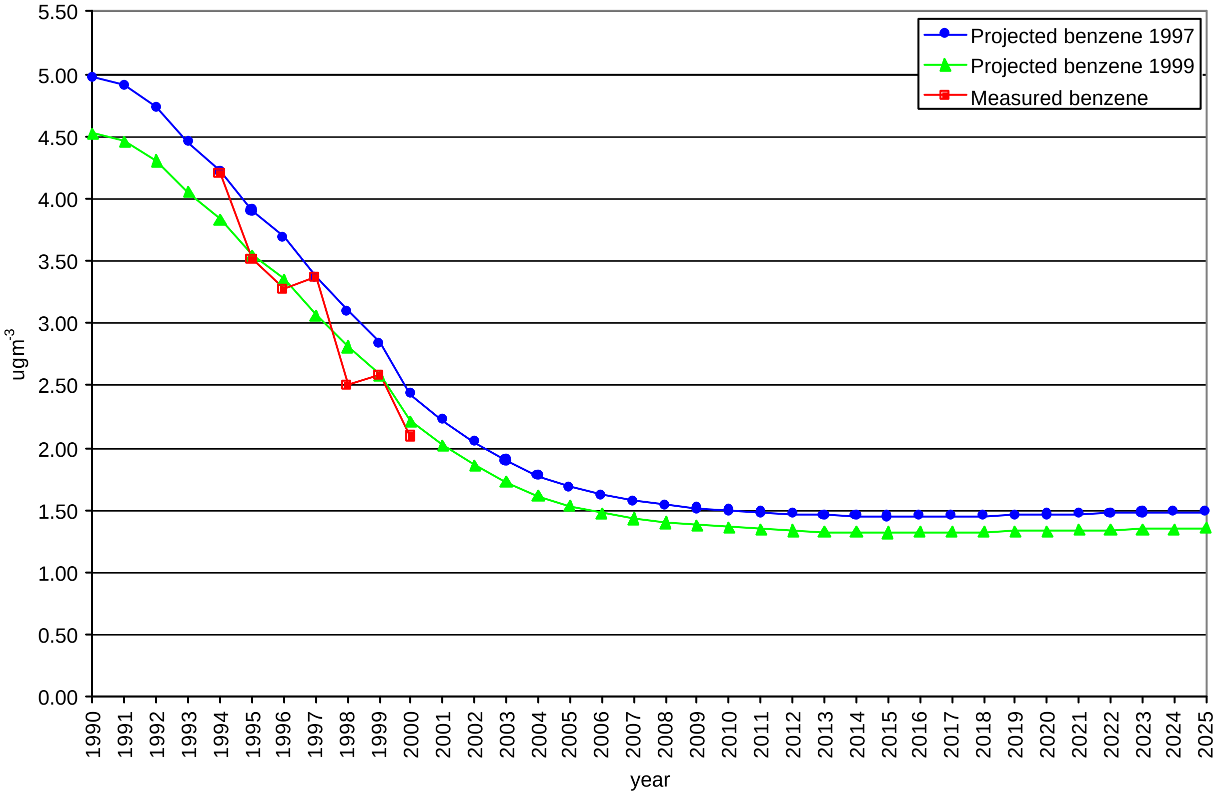


Figure 4 Projected annual mean benzene concentrations at Middlesbrough based on 1997 and 1999 monitoring – alternative emissions scenario

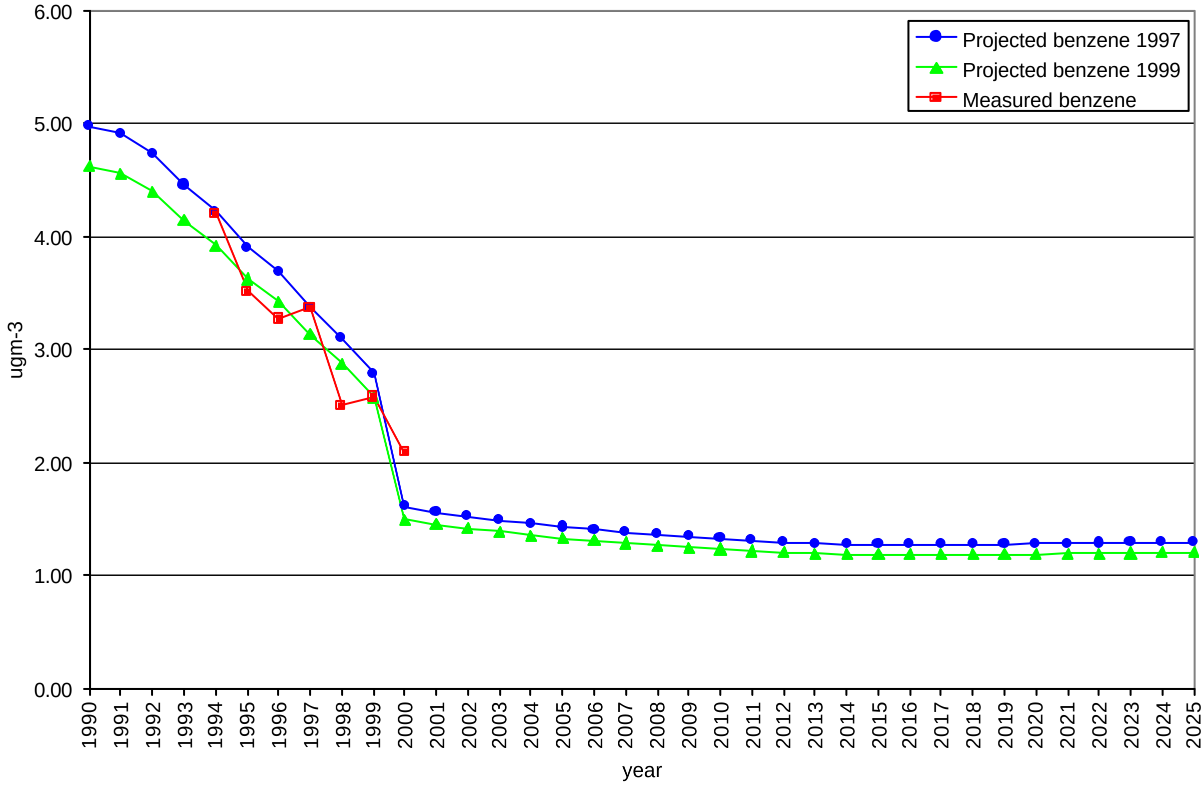


Figure 5 Projected annual mean benzene concentrations at Marylebone Road based on 1998 and 1999 monitoring data - baseline emissions scenario

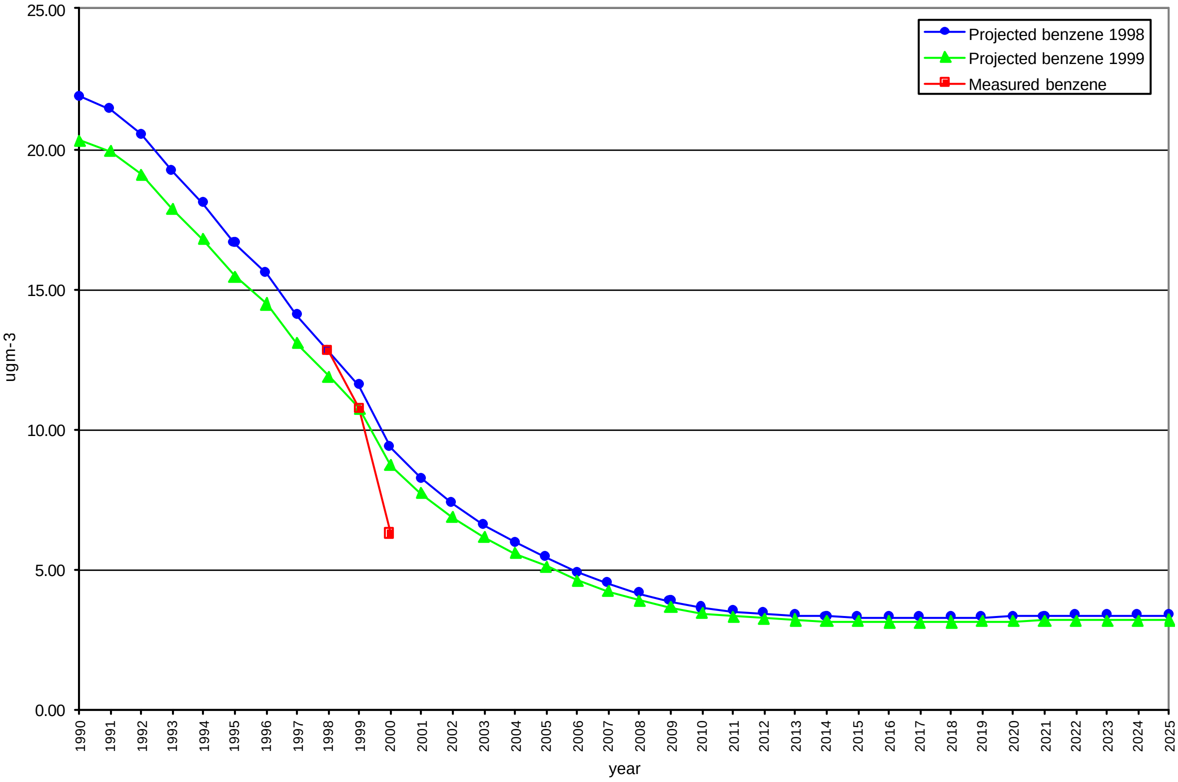


Figure 6 Projected annual mean benzene concentrations at Marylebone Road based on 1998 and 1999 monitoring data - alternative emissions scenario

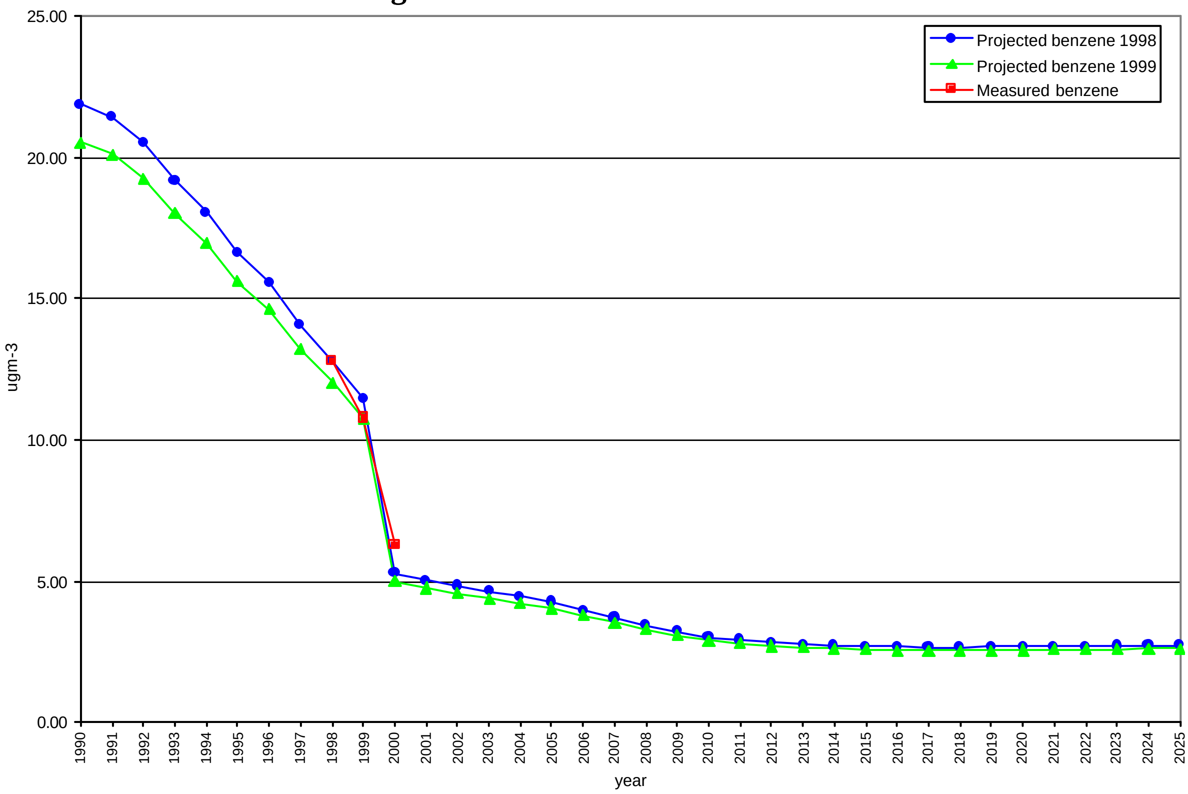


Figure 7 Projected annual mean benzene concentrations at UCL based on 1997 and 1999 monitoring data – baseline emissions scenario

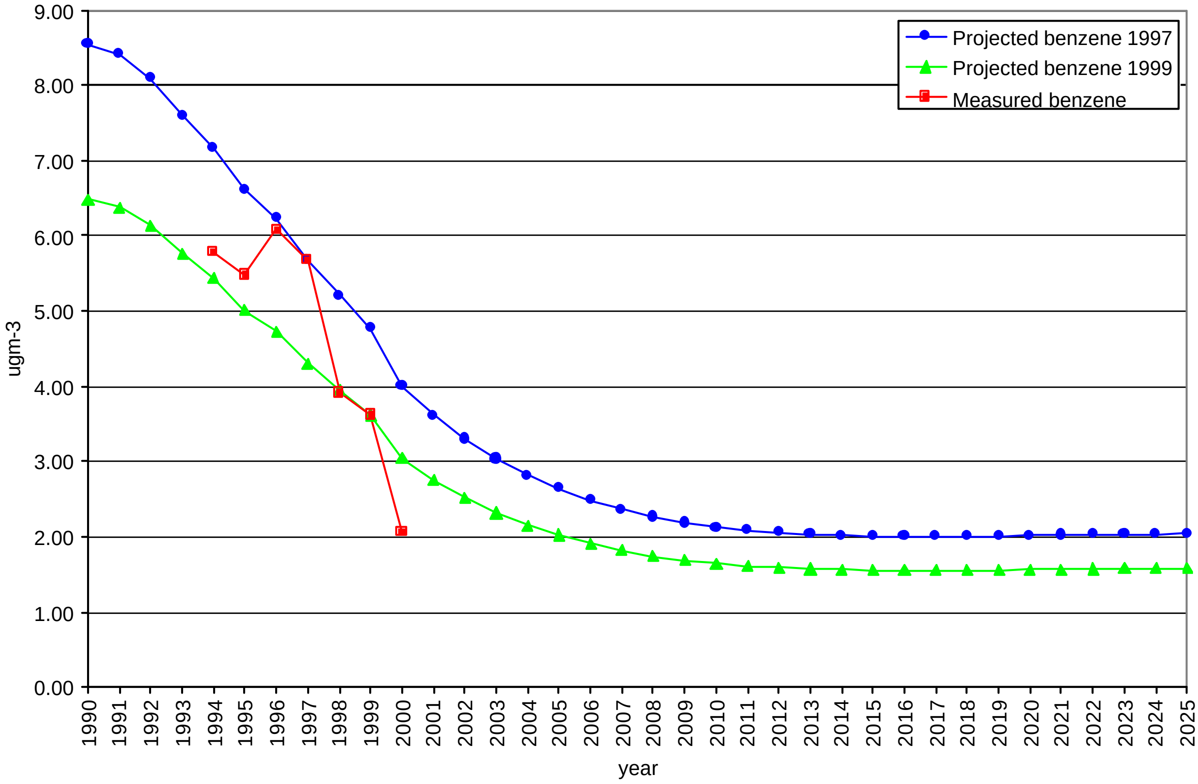
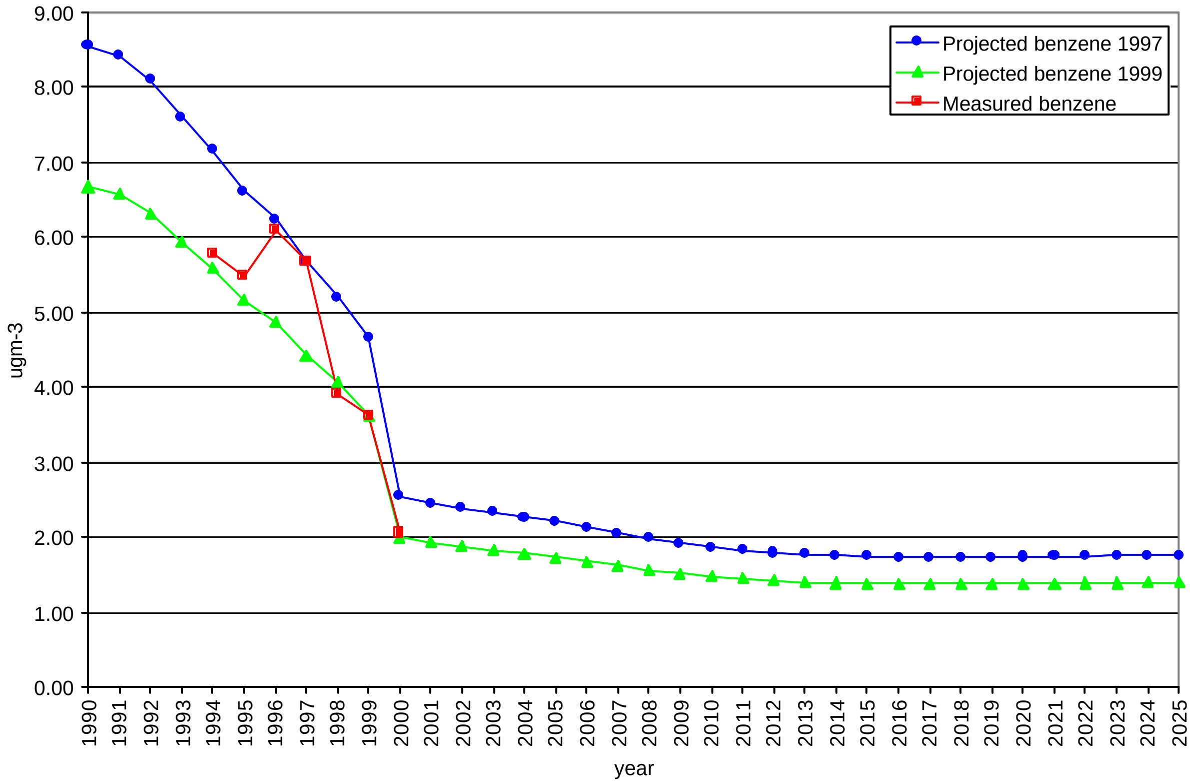


Figure 8 Projected annual mean benzene concentrations at UCL based on 1997 and 1999 monitoring data – alternative emissions scenario



3.2 MEASURED CONCENTRATIONS 1997 AND 1999

Measured annual mean benzene concentrations for the 1997 and 1999 base years are listed in Table 4 for the sites for which site-specific projections have been calculated. Measurement data for 1997 and 1999 are presented to illustrate the effects of adverse (1997) and normal (1999) meteorological conditions upon benzene concentrations. Blank entries in the table indicate the absence of monitoring data for that year.

Table 4 Measured annual mean benzene concentrations 1997 and 1999 (mgm^{-3})

	Measured annual mean benzene (µgm^{-3})	
	1997	1999
Harwell	1.17	0.88
Birmingham East	3.29	2.41
Southampton	5.82	4.25
Middlesbrough	3.37	2.58
Edinburgh	2.28	1.72
Cardiff	3.91	3.23
Eltham	3.38	2.52
Belfast	2.97	2.14
Bristol	4.56	3.03
Leeds	3.65	2.91
Liverpool	3.02	2.39
UCL	5.67	3.62
Marylebone Road		10.77

Table 4 shows that the measured annual mean benzene concentration at urban background location is generally below 5 µgm^{-3} in 1997 and 1999 with exceptions of the Southampton and University College London (UCL) locations in 1997. Measurements at the Marylebone Road roadside location in 1999 were significantly higher than 5 µgm^{-3}.

3.3 PROJECTIONS FOR 2010

Projected benzene concentrations for 2010 (using 1997 and 1999 base years) are presented in Table 5 for both baseline and alternative emissions scenarios. A blank entry in the tables indicates that projections could not be performed owing to the absence of monitoring data for that year.

Table 5 Annual mean benzene projections to 2010 based upon 1997 and 1999 base years for baseline and alternative emissions scenarios

	Baseline scenario Estimated annual mean benzene 2010 (μgm^{-3})		Alternative scenario Estimated annual mean benzene 2010 (μgm^{-3})	
	1997 base year	1999 base year	1997 base year	1999 base year
Harwell	0.53	0.49	0.46	0.46
Birmingham East	1.28	1.13	1.12	1.02
Southampton	2.31	2.04	1.99	1.79
Middlesbrough	1.50	1.36	1.33	1.23
Edinburgh	0.88	0.80	0.75	0.69
Cardiff	1.64	1.63	1.44	1.45
Eltham	1.29	1.15	1.12	1.04
Belfast	1.54	1.28	1.40	1.29
Bristol	1.74	1.40	1.49	1.20
Leeds	1.36	1.31	1.17	1.16
Liverpool	1.18	1.12	1.02	1.00
UCL	2.12	1.64	1.86	1.48
Marylebone Road		3.36		2.79

Table 5 indicates that by 2010, annual mean benzene concentrations for both emissions scenarios will be substantially lower than the AQDD2 limit value even at heavily trafficked roadside locations and applying projections from a base year with adverse dispersion characteristics for all sites where monitoring data is available. The long-term objective of 3.24 ugm^{-3} as a running annual mean (2.87 ugm^{-3} as an annual mean equivalent) is only likely to be exceeded at the heavily trafficked Marylebone Road location under the baseline scenario.

4 Maps of benzene concentrations

4.1 METHOD FOR MAPS OF BACKGROUND CONCENTRATIONS

The methods used to calculate maps of background benzene concentrations have been developed over a number of years and are described in detail in a number of reports and papers including Stedman et al (1997), Stedman (1998), Stedman et al (2001a), Stedman (1999b), Stedman and Dore (1998) and Stedman and Bush (2000). These methods have been continually revised and updated to incorporate more up-to-date monitoring data, emission inventory data and projection information. This section briefly summarises the methods used.

Measured annual mean background benzene concentrations have been assumed to consist of two parts:

- A contribution from relatively distant major point and area sources such as refineries or large conurbations. Benzene measurements from monitoring sites well away from local sources are not well represented in the UK and hence, rural NO_x has been used as a surrogate, scaled to benzene using a NO_x:benzene ratio of 0.0424 derived from an analysis measurement data from the Harwell site between 1994 and 1999.

- A contribution from more local emissions.

The difference, *diff*, between measured ambient benzene and the underlying rural concentration field is calculated at automatic monitoring site locations.

diff = measured annual mean urban benzene concentration - mapped rural benzene concentration

A regression analysis is then performed to find the coefficient, k_b, for the relationship between *diff* and estimated benzene emissions in the vicinity of the monitoring sites taken from the NAEI (Goodwin et al 2000):

$$diff = k_b.emissions$$

This coefficient, which is the equivalent of an empirical box model coefficient, can then be used to derive a map of annual mean concentrations from a combination of rural mapped concentrations and emissions inventory estimates. Thus, automatic monitoring data are used to calibrate the relationship between ambient air quality and emissions inventories.

In earlier work on the estimation of air pollutant concentrations from emission related parameters (Stedman et al, 1997) we have studied the spatial scale at which local emissions seem to influence ambient air quality. We found that estimates of emissions in an area of 25 km^2 centred on a background monitoring site provide the most robust relationships. In subsequent work incorporating improved spatially resolved emission inventories and more extensive monitoring data it became clear that contributions from outside the 25 km^2 area should be included. This is particularly important for large urban areas such as London, where an empirically derived ‘out of square’ contribution was added for inner London (Stedman et al, 2001a, Stedman and Bush 2000).

This has been addressed in the current work by including contributions to ambient concentrations from emissions in an area of 1225 km^2, with the contribution weighted by distance and direction from the central receptor. We have adapted an ADMS based approach described by Abbott and Vincent (1999) and others. The ADMS dispersion model was used to calculate the contribution to concentrations at a receptor point from a 35 x 35 km hypothetical grid of 1 x 1 km cells of unit emissions, grouped into blocks of 5 x 5 km. This level of spatial resolution was chosen to retain consistency with earlier work and avoid discontinuities in predicted concentrations at the borders of 1 x 1 km cells. Long period average meteorological data from Heathrow was used. The weighted sum of emissions around each monitoring site location was calculated and compared with *diff* to derived the empirical dispersion coefficient k_b.

$$\text{estimated background benzene concentration } (mgm^{-3}) = \text{rural benzene map } (mgm^{-3}) + \\ k_b.\ \text{emissions (Tonnes benzene per year, weighted by distance and direction)}$$

This revised method therefore, implicitly includes a contribution from ‘out of square’ emissions but the calibration of dispersion coefficients by automatic monitoring data is retained.

Area emissions maps were calculated for 1999 as described in section 2. Empirical dispersion coefficients were calculated for 1999 by comparing emissions with automatic monitoring results. The meteorological conditions of the base year are, therefore, included in the dispersion coefficients.

Owing to the relative paucity of benzene monitoring locations available for inclusion in the regression analysis to define the dispersion coefficient k_b, NO_x relationships have been used (Stedman et al, 2001b). Coefficients are listed in Table 6. Monitoring sites were found to fall into two groups: those in the large urban centres of Greater London, the West Midlands and Greater Manchester and those in the rest of the UK. The empirical dispersion coefficients were found to be lower in the large urban areas, presumably due to a combination of urban influences on local meteorology. This observation has been confirmed by dispersion modelling studies in London recently carried out by Abbott and Vincent (2001).

Table 6 Coefficients used to calculate background annual mean benzene maps 1999 (sm^{-1})

	Coefficient
Large urban areas	3.89
Elsewhere in the UK	7.18

4.2 METHOD FOR MAPS OF ROADSIDE CONCENTRATIONS

We have considered that the annual mean concentration of benzene at a roadside location is made up of two parts: the background concentration (as described above) and a roadside increment (Stedman and Dore 1998).

roadside concentration = background concentration + roadside increment

As for the relationship between emissions and measured benzene at urban background locations, the scarcity of roadside benzene measurements has necessitated the use of roadside NO_x:emissions coefficients as a surrogated for benzene.

roadside increment of annual mean benzene (mgm^{-3}) = k_r.benzene emission from road link (kg benzene km^{-1} y^{-1})

The values of k_r for the different base years are listed in Table 7.

Table 7 Coefficients used to calculate the roadside increment of annual mean benzene concentration (sm^{-2})

	1999
Coefficient	0.233

As for NO_x it has been assumed that roadside benzene monitoring sites at locations with a more open aspect, such as roads in rural areas, do not conform to this relationship. The benzene emissions from vehicles travelling on open aspect roads are generally more effectively dispersed than the emissions on built-up urban roads. We have therefore restricted our mapping to built-up major roads where the relationship is reliable (7,180 A-road and motorway road links). Built-up motorway road links with speed limits of less than 70 mph were treated in the same as other built-up major road links. Built-up motorway road links with speed limits of 70 mph were treated separately and the roadside increment was set to 0.225 of the value for other built-up major road links. This factor is based on the analysis of the limited monitoring data from sites close to motorways with fast moving traffic, which indicates considerably enhanced dispersion in comparison with other roads in the urban environment.

4.3 MAPS OF CONCENTRATIONS 1999

Maps of estimated annual mean benzene concentrations for 1999 at urban background and built-up major road links are shown in Figures 9 and 10 at the end of this section. Highest estimated concentrations are in the centres of the large cities. As a result of the limited availability of benzene measurement data from the national network sites, modelled roadside benzene concentrations have been compared with diffusion tube measurement data made available by a number of local authorities throughout the UK. Summary statistics for the comparison of mapped and measured roadside concentrations are listed in Table 8. There is generally good agreement between the averaged mapped and measured concentrations of benzene. The linear correlation coefficient (R^2) shows a poor degree of correlation, although it is expected that the degree of scatter in the diffusion tube measurements carried out by a number of independent local authorities and laboratories might contribute to this. Also presented in Table 8, is the comparison of modelled and measured benzene at the Marylebone Road site, which indicates that a reasonable comparison is achieved at this site.

Table 8 Summary statistics for comparison of estimated and measured maximum annual mean benzene concentration at roadside sites

	Mean of measurements (mgm^{-3})	*Mean of model estimates (mgm^{-3})*	*r^2*	*Number of sites*
Diffusion tube comparison	6.3	5.7	0.03	37
Marylebone Road comparison	10.8	11.8	n/a	1

Highest background concentrations of benzene are to be found in inner London where the highest annual mean benzene concentration is estimated to be 4.4 μgm^{-3}. Highest roadside concentrations were also found in inner London where concentrations are estimated at 20.7 μgm^{-3} on the A4207.

Table 9 presents the number of road links with estimated annual mean benzene concentrations in 1999 greater than the 5 μgm^{-3} AQDD2 limit value. The numbers of roads exceeding a selection of lower concentration thresholds are also presented. The relevance of these thresholds is listed below.

5 mgm^{-3}: AQDD2 Limit Value for 2010
3.5 mgm^{-3}: AQDD2 Upper Assessment Threshold
2.87 μgm^{-3}: annual mean equivalent for the 1 ppb long-term AQS objective
2 mgm^{-3}: AQDD2 Lower Assessment Threshold

Table 9 Number of built-up major road links with estimated annual mean benzene concentration greater than or equal to different assessment criteria, 1999

	No. road links with annual mean benzene ≥				Total road links in region
	2 μgm^{-3}	2.87 μgm^{-3}	3.5 μgm^{-3}	5 μgm^{-3}	
Scotland	307	178	107	22	548
Wales	119	53	33	13	282
Northern Ireland	43	19	9	3	101
Inner London	760	760	760	721	760
Outer London	787	786	775	528	789
Rest of England	4220	3382	2495	838	4700
TOTAL	6236	5178	4179	2185	7180

Table 9 shows that during 1999, there are exceedences, throughout the UK, of the AQDD2 limit value for 2010 and all other thresholds and objectives below 5 μgm^{-3}

4.4 PROJECTED CONCENTRATIONS 2010 – BASELINE EMISSIONS SCENARIO

Maps of estimated annual mean benzene concentrations for 2010 at urban background and built-up major road links are presented in Figures 11 and 12. By 2010, it is estimated that the highest urban background annual mean benzene concentration will continue to be found in London (2.2 μgm^{-3}). At the roadside, highest concentrations are estimated to be on the A4202 where annual mean benzene is estimated to be 5.9 μgm^{-3}. Table 10 lists the number of road links with estimated annual mean benzene concentrations in 2010 greater than the AQDD2 limit value of 5 μgm^{-3}, based on the baseline emissions scenario. The table also shows the number of road links at which concentrations are projected to be greater than annual mean equivalent for the long-term policy aim.

Table 10 Number of built-up major road links with estimated annual mean benzene concentration greater than or equal to different assessment criteria, baseline projections 2010

	No. road links with annual mean benzene ≥				Total road links in region
	2 μgm^{-3}	2.87 μgm^{-3}	3.5 μgm^{-3}	5 μgm^{-3}	
Scotland	16	0	0	0	548
Wales	10	1	0	0	282
Northern Ireland	5	1	0	0	101
Inner London	742	287	84	5	760
Outer London	611	99	27	4	789
Rest of England	761	90	18	1	4700
TOTAL	2145	478	129	10	7180

Table 10 shows that estimates of the number of road links with concentrations greater than the UAT and LAT will be significantly reduced. Exceedence of the AQDD2 Limit Value is estimated to be limited to 9 road links in inner and outer London and 1 road link in the central Leeds area.

4.5 PROJECTED CONCENTRATIONS 2010 - ALTERNATIVE EMISSIONS SCENARIO

Maps of estimated annual mean benzene concentrations for 2010 at urban background and built-up major road links were also calculated for the alternative emissions scenario, although they are not presented in this report. By way of a sensitivity analysis, the number of road links with estimated annual mean benzene concentrations greater than 5 μgm^{-3} and other assessment thresholds were calculated and are presented in Table 11.

Table 11 Number of built-up major road links with estimated annual mean benzene concentration greater than or equal to 5 mgm^{-3}, alternative emissions scenario projection 2010

	No. road links with annual mean benzene ≥				Total road links in region
	2 μgm^{-3}	2.87 μgm^{-3}	3.5 μgm^{-3}	5 μgm^{-3}	
Scotland	5	0	0	0	548
Wales	3	0	0	0	282
Northern Ireland	1	0	0	0	101
Inner London	588	87	28	0	760
Outer London	248	22	9	0	789
Rest of England	271	16	2	0	4700
TOTAL	1116	125	39	0	7180

Table 11 indicates that under the alternative emissions scenario for benzene, it is estimated that roadside benzene concentrations will have been reduced to below the 5 μgm^{-3} AQDD2 limit value by 2010. Exceedence o f the UAT and 1 ppb long-term objective by this date will largely have been limited to London and England.

Figure 9 Estimated annual mean benzene concentrations at background and built-up major roads 1999 (μgm^{-3}). Ref. NETCEN 18/04/2001, ~/naqs3tb/aq_objective/uk1benz19991, rbenz19991uk

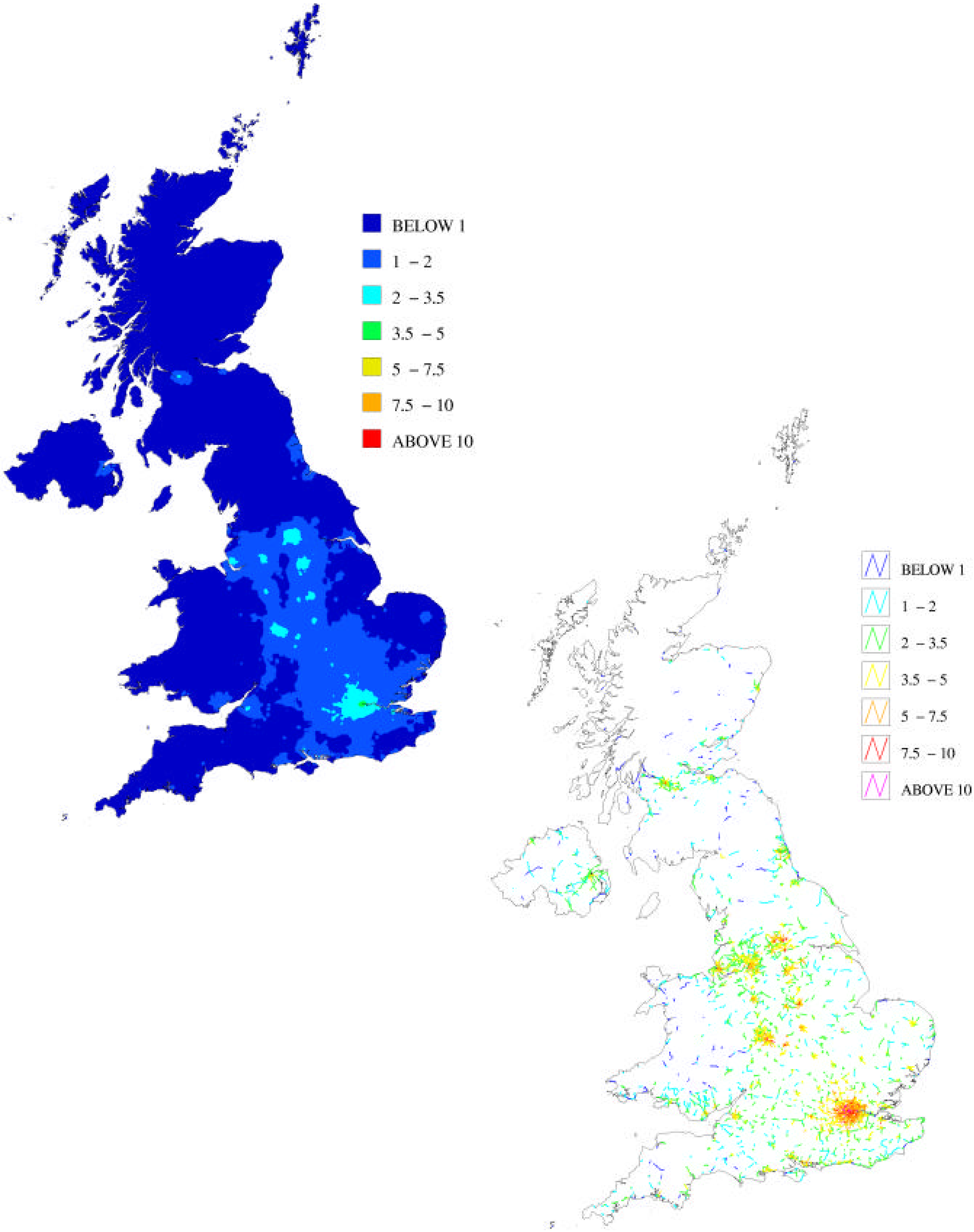


Figure 10 Estimated annual mean benzene concentrations at background and built-up major roads in London, 1999 (µgm^{-3}). Ref. NETCEN 18/04/2001, ~/naqs3tb/aq_objective/uk1benz19991, rbenz19991uk

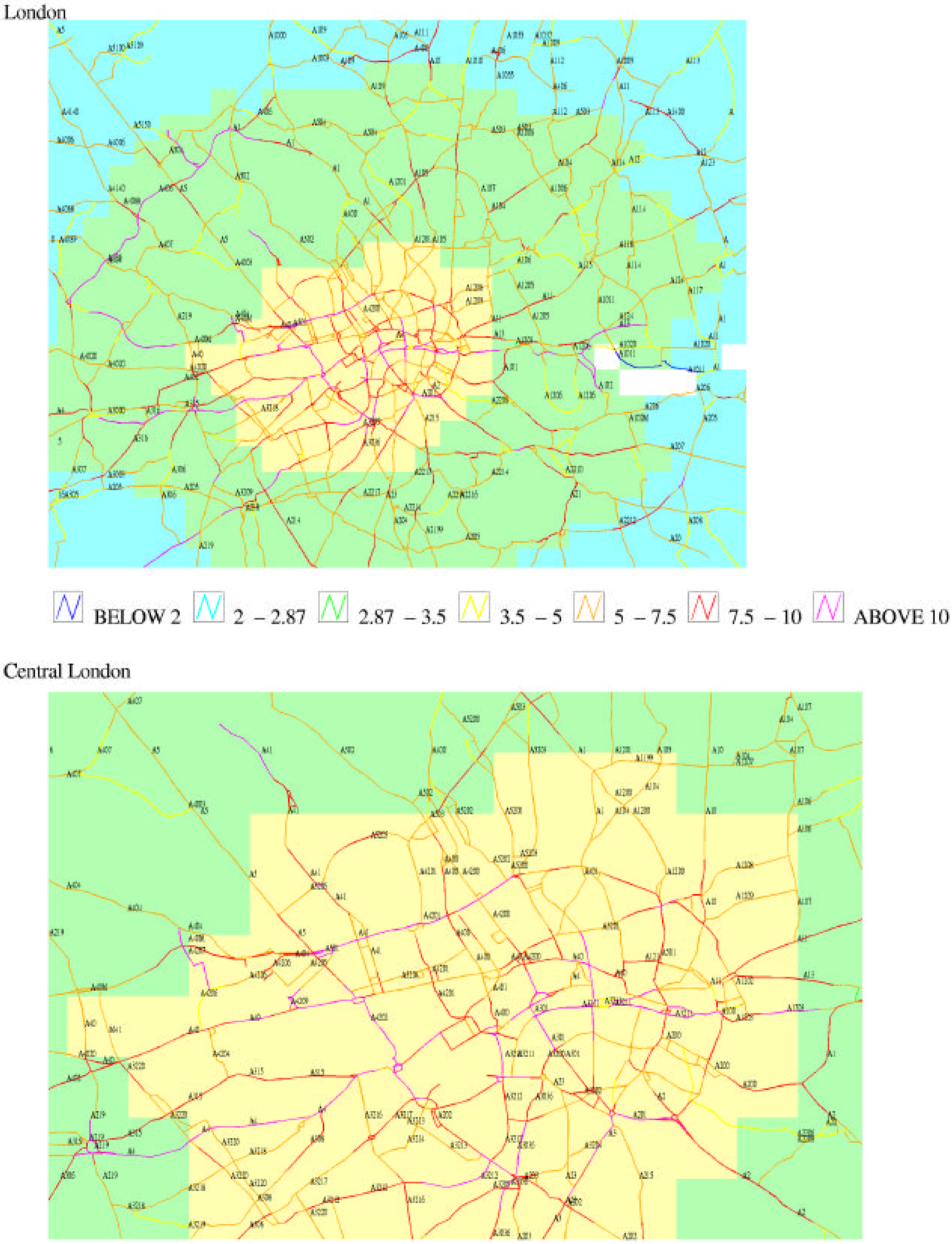


Figure 11 Estimated annual mean benzene concentrations at background and built-up major roads 2010 (μgm^{-3}). Ref. NETCEN 18/04/2001, ~/naqs3tb/aq_objective/uk1benz20101, rcom8h20051uk

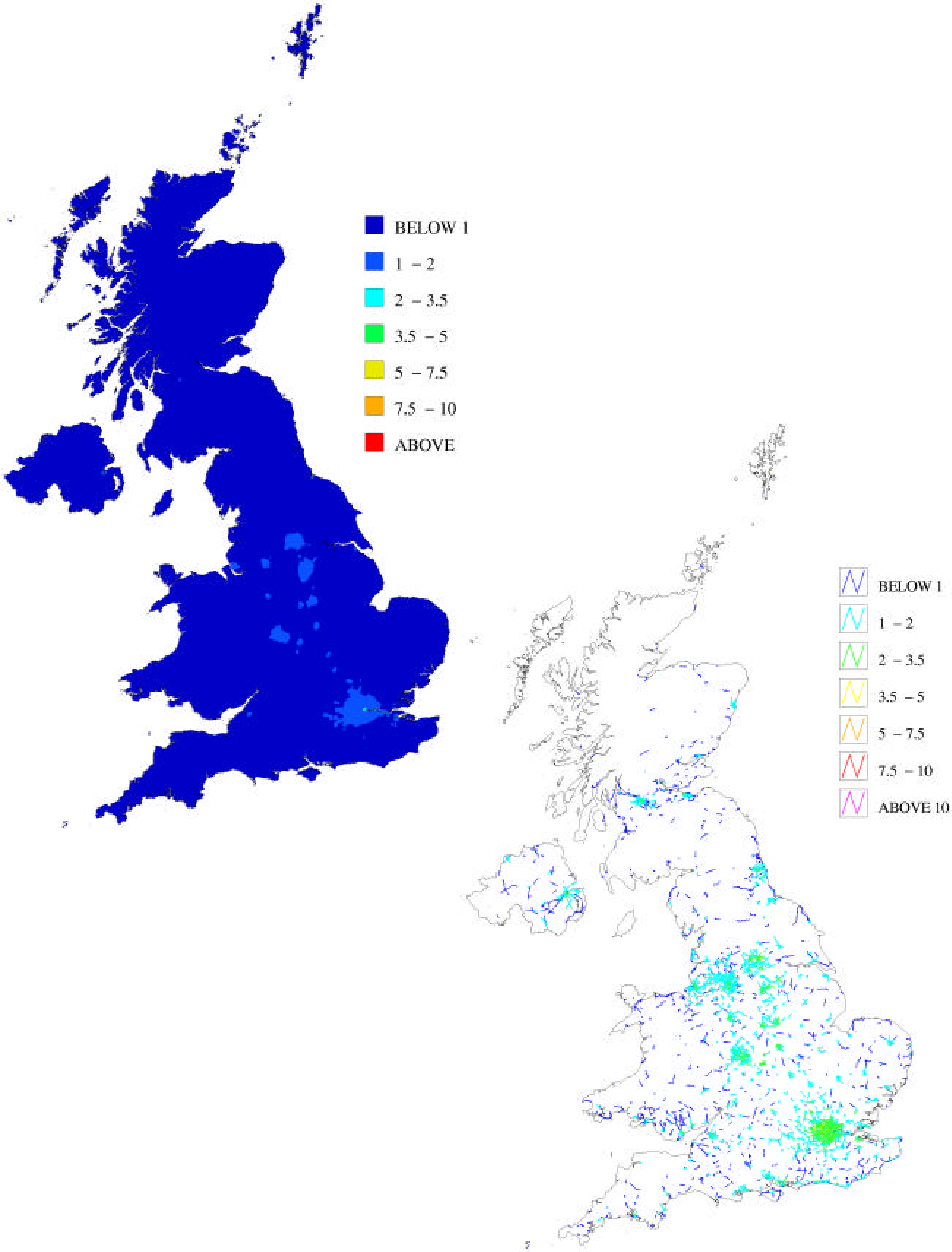
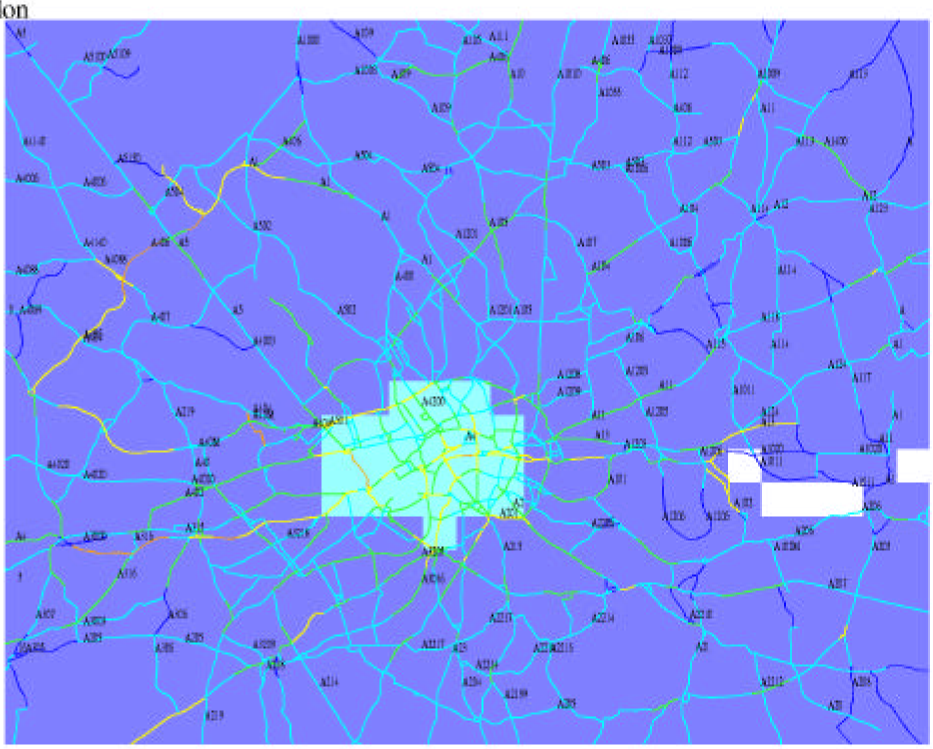


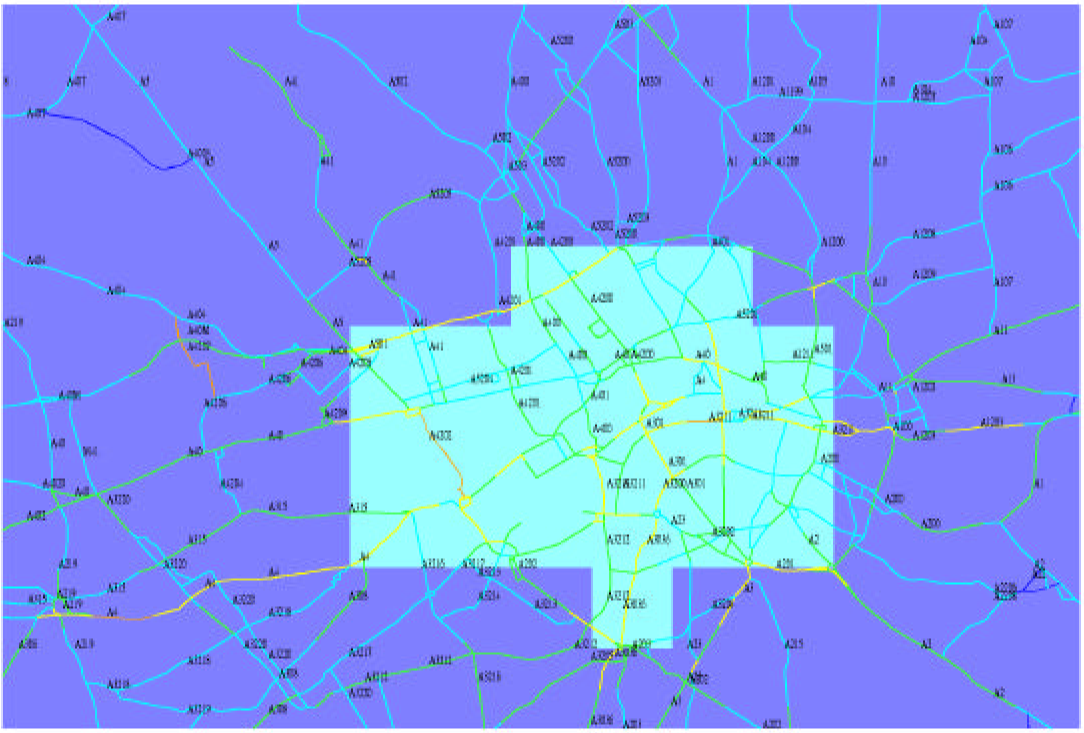
Figure 12 Estimated annual mean benzene concentrations at background and built-up major roads in London, 2010 (μgm^{-3}). Ref. NETCEN 18/04/2001, ~/naqs3tb/aq_objective/uk1benz20101, rcom8h20051uk

London



BELOW 2 | 2 – 2.87 | 2.87 – 3.5 | 3.5 – 5 | 5 – 7.5 | 7.5 – 10 | ABOVE 10

Central London



5 Discussion

Present day and projected benzene concentrations for 2010 under the baseline emissions scenario are discussed in the following sections. Projections to 2010, based on an alternative emissions scenario are also discussed and have been undertaken as part of a sensitivity analysis to appraise the impact of low benzene fuel upon emissions from non-catalyst petrol vehicles and vehicles that have failed or failing catalysts.

An indication of the applicability of the alternative emissions scenario, relative to the baseline, is presented in Figures 1-8 by a comparison of the alternative projections for 2000 with the measured concentrations. The baseline scenario provides better agreement at Middlesbrough but the alternative scenario provides better agreement at Edinburgh Centre and Marylebone Road. The alternative scenario provides excellent agreement with measurements for 2000 at the University College London site.

5.1 PRESENT DAY BENZENE CONCENTRATIONS

The site specific analyses presented in Table 4 have shown that measured concentrations at the majority of urban background locations were consistently below the AQDD2 limit value for 2010 irrespective of prevailing atmospheric characteristics. Under unfavourable atmospheric conditions experienced in 1997, sites close to local emission sources, (Southampton and University College London) measured concentrations greater than 5μgm^{-3}. Concentrations at the Marylebone Road roadside site in 1999 were higher than the AQDD2 limit value (10.8 μgm^{-3}).

The high resolution pollutant mapping techniques have shown that the highest estimated urban background and roadside annual mean benzene concentrations in 1999 were 4.4 and 20.7 μgm^{-3} respectively. Road links with benzene concentrations greater than 5 μgm^{-3} in 1999 are found throughout the UK, although proportionally greater numbers were found in London. Exceedences of the LAT, UAT and 1 ppb long-term objective are widespread.

5.2 PROJECTED BACKGROUND BENZENE CONCENTRATIONS 2010

Estimated urban background benzene concentrations in 2010, projected using the site specific technique were presented in Table 5. These projections show that for both the current baseline emission scenario and the alternative scenario, projected concentrations are expected to be substantially below the AQDD2 limit value irrespective of the atmospheric dispersion characteristics applied in the analysis. The highest projected urban background concentrations using this technique were 2.04 and 1.79 μgm^{-3} at the Southampton site under the baseline and alternative emissions scenarios respectively.

Similarly, using the high resolution mapping technique, highest projected concentrations in 2010 under the baseline and alternative emissions scenarios were estimated to be 2.2 and 1.9 μgm^{-3} respectively.

5.3 PROJECTED ROADSIDE BENZENE CONCENTRATIONS 2010

Site specific projections for the Marylebone Road roadside location indicate that concentrations in 2010 will be below the AQDD2 limit value for both emissions scenarios. Concentrations for this site in 2010 are estimated to be 3.36 and 2.79 μgm^{-3} under the baseline and alternative emissions scenarios respectively.

Projected concentrations for 2010 derived from the high resolution mapping technique and the baseline emissions scenario, show that all road links except 9 in London and 1 in Leeds will meet the AQDD2 limit value. Exceedences of the UAT and 1 ppb long-term objective are estimated to be found throughout London and the Rest of England. Under the alternative emissions scenario the AQDD2 limit value for 2010 will be met in all locations. The UAT and long-term objective will also be met in all parts of the UK with the exception of London and parts of England.

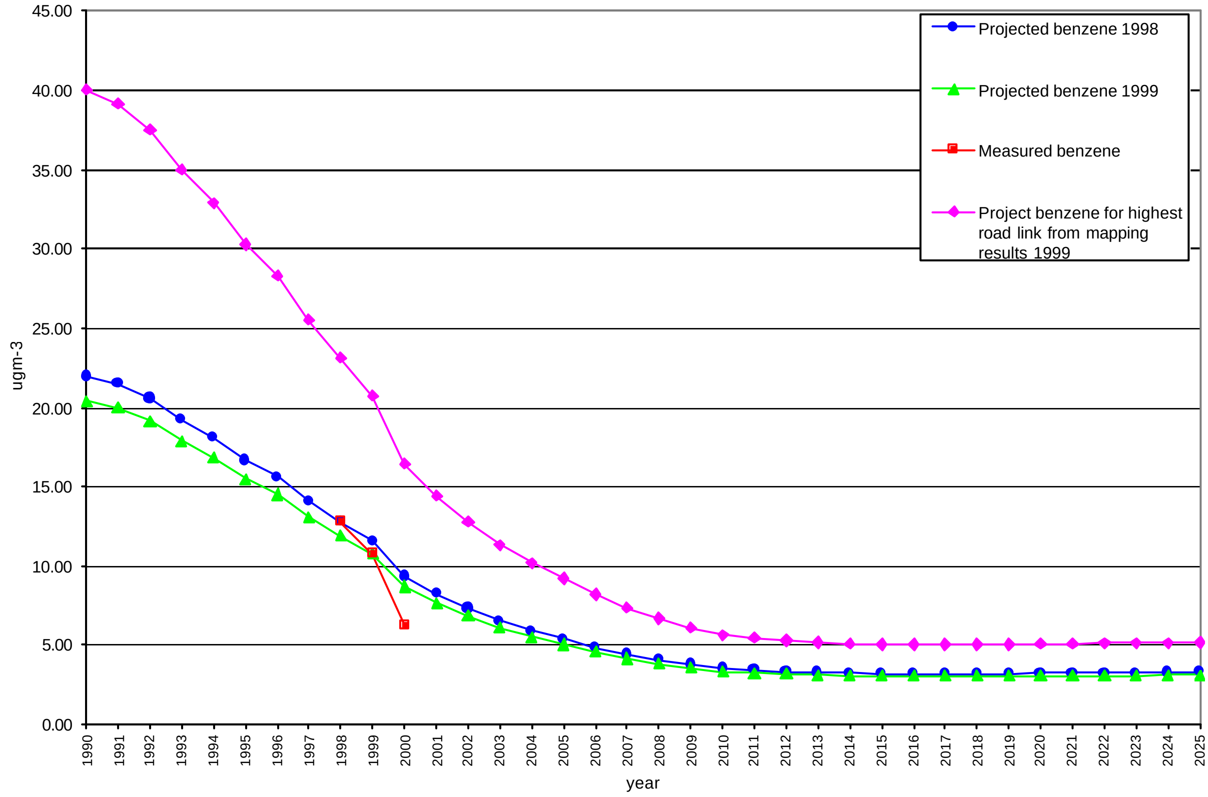
5.3.1 Early implementation of the AQDD2 limit value

From the site specific analyses presented in section 3.1, it has been shown that for the baseline emissions scenario, the AQDD2 limit value is likely to be met by 2010 at all locations included in these analyses. For the Marylebone Road roadside location Figures 5 and 6 indicate that concentrations should meet the AQDD2 limit value by approximately 2006 for the baseline emissions scenario and by 2002 for the alternative scenario.

From the mapping analysis, the road with the highest annual mean benzene concentration in 1999 has been identified (20.7 μgm^{-3}). Projecting this modelled concentration for 1999 forwards using the baseline scenario, the concentration for this road in 2010 is estimated to be 5.7 μgm^{-3} indicating that by 2010, road links with the highest estimated annual mean benzene concentrations in 1999 are likely to be close to meeting the AQDD2 limit value, but that some may exceed this concentration. Figure 11 presents projected annual mean benzene concentrations at the Marylebone Road location and road link with highest estimated concentration in 1999 using the baseline emissions scenario.

Taken together with the mapping analysis of the numbers of road links with concentrations in excess of 5 μgm^{-3} in 2010, it is unlikely that there is significant scope for achieving compliance with this limit value earlier than 2010 and local measures may be required at some sites to ensure the limit value is achieved.

Figure 11 Projected annual mean benzene concentration at Marylebone Road based on 1998 and 1999 monitoring data and at the highest modelled road link 1999, Baseline



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Kennet District Council
Leicester City Council
London Borough of Redbridge
Tameside Metropolitan District Council
Tandridge District Council
West Oxfordshire District Council
London Borough of Southwark
Stoke-on-Trent City Council

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