Appendix I

Air Quality Modelling for Heathrow Airport 2008/9: Methodology. Report by AEA Energy & Environment on behalf of BAA, July 2010. AEAT/ENV/R/2915/Issue 1

Heathrow
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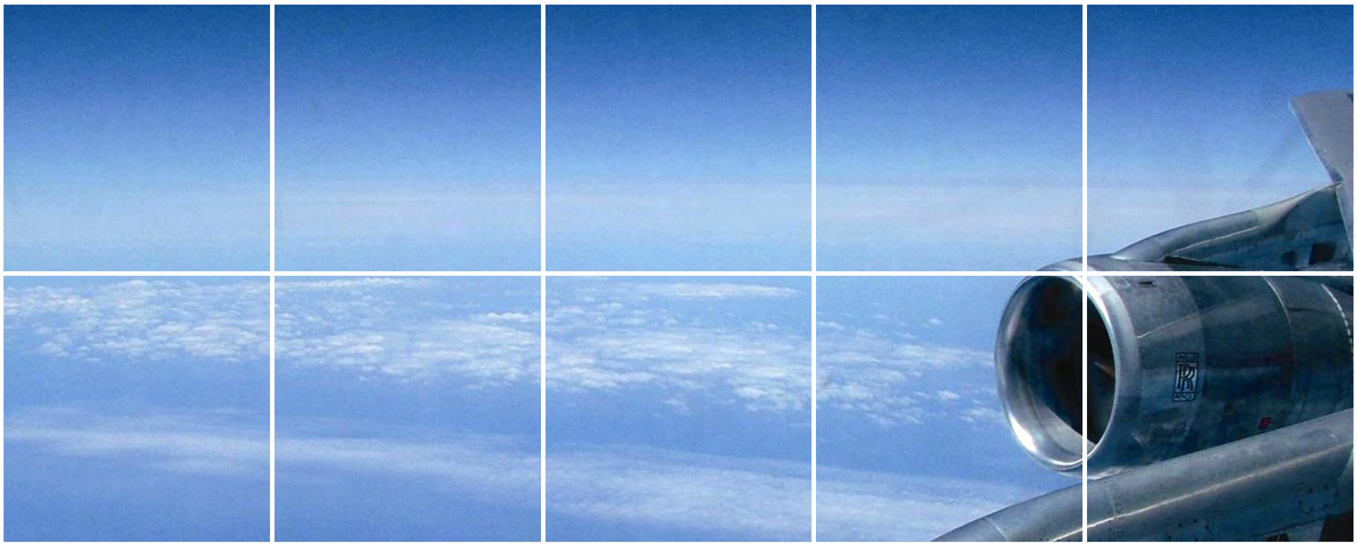

Air Quality Modelling for Heathrow Airport 2008/9: Methodology

Report to BAA

AEAT/ENV/R/2915/Issue 1
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Summary

S.1 In 2009, BAA commissioned AEA to carry out an air quality study for Heathrow with three components:

(a) to compile an inventory of atmospheric emissions arising from Heathrow Airport operations for the 12-month period from 1st April 2008 to 31st March 2009, including the pollutants NO_x (oxides of nitrogen), PM_{10} (particulate matter with an aerodynamic diameter less than 10 microns) and $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 microns);
(b) to carry out a dispersion-modelling study to quantify the contributions to airborne concentrations in residential areas close to Heathrow Airport arising from airport sources and from road-vehicle emissions on the major road network around the airport; to combine these contributions with the estimated contribution from all other sources to give a view of total airborne concentrations around Heathrow in 2008/9;
(c) to evaluate the performance of the model using monitoring data collected around Heathrow in 2008/9.

S.2 This report describes the methodology used for the dispersion modelling study (including the estimation of the contribution from sources not included explicitly via dispersion modelling). Separate reports are available covering the compilation of the airport emission inventory and the model evaluation study, with the latter report also presenting the results of the dispersion-modelling study.

S.3 The air quality around Heathrow is of continuing concern. The annual mean NO_2 concentration in some residential areas near the airport is close to or above the national objective (40 $\mu g/m^3$), which should have been met by 2005. Thus, there is a vital interest in understanding how much airport operations contribute to pollutant concentrations in the vicinity of the airport. Although monitoring provides spot checks on the situation at specific locations, modelling is required to give a fuller appreciation of the spatial variation in airborne concentrations. It is also needed to allow the relative contributions to the concentration at key locations from various sources on the airport to be identified and to provide a basis for forecasting the air quality impact of operational changes on the airport.

S.4 The area over which sources have been modelled explicitly in the dispersion modelling study includes the whole of the area covered by the London Atmospheric Emissions inventory (LAEI), principally to the east of Heathrow, and part of the National Atmospheric Emissions Inventory (NAEI) out to a distance of around 25 km west of the airport. The contribution from sources outside these areas (other than from large point sources such as power stations) was estimated from rural monitoring data collected at Rochester Stoke, to the east of London, and at Harwell, situated west of the modelled area.

S.5 Thus, total period-mean NO_x, PM_{10} and $PM_{2.5}$ concentrations around Heathrow have been modelled as the sum of contributions from the following source categories: (a) airport sources (taken from the Heathrow 2008/9 emission inventory); (b) road vehicle emissions on the major road network around Heathrow also (taken from the Heathrow 2008/9 inventory); (c) LAEI emissions (after removing the airport and road vehicle emissions already counted in (a) and (b)); (d) NAEI emissions in the specified area (excluding emissions already counted in (b)); (e) large point sources; and (f) background. The approach to setting the boundary between explicitly-modelled sources and ‘background’ is similar to that used in the modelling work undertaken in the Project for the Sustainable Development of Heathrow (PSDH).

S.6 In relation to dispersion modelling, the PSDH expert panels recommended the use of ADMS-Airport for the modelling work underpinning the government’s ‘Adding Capacity at Heathrow’ consultation, and ADMS-Airport has been used for the Heathrow 2008/9 modelling study reported here. A key development in the modelling of aircraft sources in ADMS-Airport is a module for treating the near-field dispersion of aircraft engine exhaust plumes (emitted with

significant fluxes of heat and momentum) from moving aircraft, and a major task in the 2008/9 dispersion modelling study was to devise an appropriate representation of aircraft sources (from the 2008/9 airport emission inventory) within the ADMS-Airport framework.

S.7 First, this requires the estimation of the efflux parameters (exhaust temperature and velocity) for the principal range of engine types currently contributing to emissions at Heathrow. Given that much of the relevant detailed engine data is proprietary, methods have been devised to derive the relevant parameters from openly published data sources, guided by information presented in the ADMS-Airport User Guide. Following on from this, the wide range of aircraft type/engine combinations has been partitioned into a number of categories termed MCATs (Modelling CATegories), with all the emissions in a given MCAT assigned a representative set of efflux parameters. The number of categories and the boundaries between them was based on a series of test runs of ADMS-Airport, using a simplified aircraft source configuration, leading to a separate set of categories for low-thrust and high thrust phases of the landing and take-off cycle.

S.8 In implementing the jet/plume modelling, ADMS-Airport represents line sources as a discrete set of plumes, each having a specified set of efflux parameters and aircraft speed. The distance between the discrete plumes is under user control, with the intention that a spacing is chosen that reduces the discretisation error to a tolerable level for the relevant spatial disposition of sources and receptors (albeit guided by values in the ADMS-Airport User Guide). The spacing used in the 2008/9 study was based on the experience gained from previous studies using ADMS-Airport, leading to a spacing of up to 100 m for ground-level aircraft sources.

S.9 For take-off roll, the PSDH recommendations lead to non-uniform acceleration on the runway, in contrast to the uniform acceleration assumed in earlier methodologies. The PSDH methodology takes account of the initial phase of the take-off roll when the engines have not yet reached the selected take-off thrust (spool-up), and also allows for the influence of aircraft motion on engine thrust. Similarly, the influence of aircraft forward speed on pollutant emission rates is also taken into account. Forward-speed effects are also included for elevated flight phases (for example initial climb), albeit in an approximate manner consistent with their lower impact on ground-level concentrations.

S.10 Although ADMS-Airport has the capability to accept road traffic data (flows, speeds and traffic composition) - and then use the data to calculate both the vehicle emissions and the traffic-related turbulence parameters – the model also allows the input of externally-calculated emissions. For the 2008/9 modelling study, road vehicle emissions in an 11 km square ‘road network area’ around Heathrow were taken from the 2008/9 Heathrow emission inventory. This separation between the inventory calculations and the dispersion modelling allowed greater flexibility in associating emission-factor datasets with the particular traffic data available for the 2008/9 inventory. Nevertheless, traffic data were still input to the model to allow traffic-induced turbulence parameters to be calculated.

S.11 As explained in the 2008/9 inventory report, road-traffic flows and speeds were made available for the inventory separately for a number of vehicle categories for each hour of an average weekday and each hour of the weekend (72 representative ‘traffic’ hours in total), so the temporal profile of total emissions of a given pollutant over a week varies in principle from link to link. In order to allow a reasonable representation of both traffic and emission temporal variations, each of the 72 traffic hours was modelled separately, with each run using the sub-set of hourly meteorological data appropriate to the particular traffic hour. The results from the 72 traffic hours were combined externally, taking account of the difference between the number of instances of a weekday hour and a weekend hour over the course of a year. The assumption was made that the traffic flows and speeds were the same in each instance of a given traffic hour during the year.

S.12 Concentrations were calculated at a set of locations, including a number of ‘specific’ receptors, chosen for their intrinsic importance. Principally, these are the monitoring sites within the study area, together with sites chosen to facilitate comparisons with the results of the PSDH work. In addition, a grid of receptors points was set up covering the selected study area, to enable concentration contours to be plotted, with the grid spacing chosen to reflect the expected concentrations gradients. First, a basic regular grid of receptor points was specified to cover the 9 km square study area at a grid spacing of 100 m. Receptor points were then added close to the road-vehicle and aircraft sources, using the 'intelligent gridding' option available in ADMS-Airport. For emissions on the road network, the total network was split into 9 approximately equal segments to take account of the upper limit on the total number of 'intelligent' grid points.

S.13 Emissions in the LAEI area were based on the LAEI 2006 inventory, the latest published version at the time of the assessment, together with the associated projections to 2010, using linear interpolation for sources other than road vehicles. For road-vehicle emissions, 2006 values were retained for 2008/9 on the grounds that interpolation using the 2010 projections would likely underestimate 2008/9 emissions, given the assumptions in the forecasts regarding the Congestion Charging Scheme and the London Low Emission Zone phasing. It is accepted, that the 2006 emissions may be overestimates for 2008/9.

S.14 The LAEI emissions on the section of the Great Western railway line within the 11 km square near-Heathrow area were modelled separately as a line source, given that it represents a source of relatively high emission density close to residential areas. All other sources from the LAEI, other than major point sources, were modelled as 1 km area sources, bearing in mind that road-vehicle emissions on the major road network around the airport were taken from the 2008/9 airport inventory and modelled separately as line sources, so were removed from the LAEI.

S.15 The starting point for estimating the contribution from emissions taken from the NAEI was the 2007 inventory, the latest version published at the time of this assessment. Road vehicle emissions for the 2007 inventory were quantified by the NAEI team using an interim set of emission factors, which were close to - but not identical to - the final set of factors released by the DfT in 2009.

S.16 NO_x emissions for 2008/9 were obtained by linear interpolation between published 2007 NAEI values and projections for 2010, assuming the relative spatial distribution of emissions (at 1 km resolution) for a given source category remains the same in 2010 as in 2007. Projected 2010 UK NO_x totals were taken from published sources. For PM_{10} and $PM_{2.5}$, equivalent published national projections were not available, but recent national inventories and previous forecasts indicated a much slower rate of decrease per year than for NO_x. Thus PM_{10} and $PM_{2.5}$ emissions from the NAEI were taken to be the same in 2008/9 as in 2007.

S.17 The overall modelling process described above directly yields annual mean NO_x concentrations, whereas the key air quality metric of interest from a human health viewpoint is annual mean NO_2 concentration. The derivation of annual mean NO_2 concentrations from annual mean NO_x concentrations in the 2008/9 study was based on the 'Jenkin' approach, which recognises the coupling between NO, NO_2 and O_3 concentrations resulting from gas-phase reactions. A recent refinement of this approach categorises sites according to the inter-quartile ratio of hourly NO_x concentration during the year (i.e. the ratio of the 75th and 25th percentile values), with the Jenkin category then determining what fraction of the total oxidant concentration (the sum of NO_2 and O_3 concentrations) is actually in the form of NO_2, as a function of total NO_x concentration. Arguments are put forward for expecting Jenkin Category II to be reasonably applicable in 2008/9 throughout the area around Heathrow.

S.18 To implement the Jenkin approach, it is necessary to assign to each source a 'primary NO_2' fraction (i.e. the fraction of the NO_x from the source that is emitted as NO_2). Primary NO_2 fractions for aircraft sources were taken from the PSDH work, whereas for road vehicles the fraction (as a function of vehicle type) was taken from the latest national set of road-vehicle emission factors. For LAEI emissions, primary NO_2 emissions from road vehicles are provided on the same footing as for other pollutants. For other LAEI source types, primary NO_2 ratios were taken from the NAEI.

S.19 The approach adopted to allow modelled concentrations to be compared against the short-period NO_2 limit (that the hourly-average NO_2 concentrations should not exceed 200 $\mu g/m^3$ on more than 18 occasions in a calendar year) is to use a surrogate annual mean value of

60 $\mu g/m^3$, as recommended in technical guidance for local authority air quality review and assessment. Similarly, it is proposed that tests of the 24-hour limit for PM_{10} concentrations (that the 24-hour mean concentration should not exceed 50 $\mu g/m^3$ for more than 35 days of the year) are carried out using a surrogate annual mean value of 31.5 $\mu g/m^3$.

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Abbreviations

ADMS	Atmospheric Dispersion Modelling System
AEA	A business name of AEA Technology plc
APU	Auxiliary Power Unit
AQEG	Air Quality Expert Group
AQMA	Air Quality Management Area
AQS	The Air Quality Strategy for England, Scotland, Wales and Northern Ireland
AQSR	Air Quality Standards Regulations
ATWP	Air Transport White Paper
AURN	Automatic Urban and Rural Network (of monitoring sites)
B	Initial buoyancy flux ($m^4\ s^{-3}$)
BPR	By-Pass Ratio
CAA	(UK) Civil Aviation Authority
CERC	Cambridge Environmental Research Consultants
CHP	Combined Heat and Power
Defra	Department for the Environment, Food and Rural Affairs
DfT	Department for Transport
EU	European Union
HDV	Heavy Duty Vehicles (HGV and buses)
HGV	Heavy Goods Vehicle
ICAO	International Civil Aviation Organisation
LAEI	London Atmospheric Emissions Inventory
LDV	Light Duty Vehicles (cars and LGV)
LGV	Light Goods Vehicle
LHR	London Heathrow Airport
LTO	Landing and Take-Off
MCAT	Modelling Category
mppa	million passengers per annum
NAEI	National Atmospheric Emission Inventory
NO_x	Nitrogen Oxides ($NO+NO_2$)
OPR	Overall Pressure Ratio
PAH	Polycyclic Aromatic Hydrocarbons
PCM	Pollution Climate Mapping
PM	Particulate Matter
PM_{10}	Particulate Matter with aerodynamic diameter less than 10 µm*
$PM_{2.5}$	Particulate Matter with aerodynamic diameter less than 2.5 µm*
PSDH	Project for the Sustainable Development of Heathrow
TEOM	Tapered Element Oscillating Microbalance
UKMO	United Kingdom Meteorological Office

* PM_{10} ($PM_{2.5}$) refers to particles that pass through the selective size inlet of a specified measuring instrument with 50% efficiency at 10 (2.5) µm aerodynamic diameter, where the 'aerodynamic diameter' of a particle is the diameter of a spherical particle of unit relative density that would have the same gravitational settling velocity as the particle of interest.

1 Introduction

Background

1.1 London Heathrow Airport (Heathrow) is the world's busiest international airport, serving around 65 million passengers in 2008, and is a key component of the UK's transport infrastructure. The airport lies close to residential areas, however, and the off-site air quality impacts of its operations are kept under review by both the airport operator, BAA, and by the local authorities in the administrative areas surrounding the airport. This review process draws on measurements made at a number of automatic monitoring sites around the airport, and also includes the periodic updating of an airport emission inventory accompanied by a dispersion modelling study. These aim to inform airport stakeholders of the evolving contribution of the airport to local airborne pollutant concentrations.

1.2 In 2009, BAA commissioned AEA to carry out an air quality study for Heathrow with three components:

(a) to compile an inventory of atmospheric emissions arising from airport operations for the 12-month period from 1st April 2008 to 31st March 2009, including the pollutants NO_x (oxides of nitrogen), PM_{10} (particulate matter with an aerodynamic diameter less than 10 microns) and $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 microns);
(b) to carry out a dispersion-modelling study to quantify the contributions to airborne concentrations in residential areas close to Heathrow Airport arising from airport sources and from road-vehicle emissions on the major road network around Heathrow; to combine these contributions with the estimated contribution from all other sources to give a view of total airborne concentrations around Heathrow in 2008/9;
(c) to evaluate the performance of the model using monitoring data collected around Heathrow in 2008/9.

1.3 This report describes the methodology used for the dispersion modelling study (including the estimation of the contribution from sources not included explicitly via dispersion modelling). Separate reports are available covering the compilation of the airport emission inventory[1] and the model evaluation study[2], with the latter report also presenting the results of the dispersion-modelling study. Below, the former report will be referred to as 'the 2008/9 inventory report' and the latter as the '2008/9 model evaluation report'.

1.4 The air quality around Heathrow is of continuing concern. The annual mean NO_2 concentration in some residential areas near the airport is close to or above the national objective (40 µg/m^3), which should have been met by 2005. The air quality modelling work underpinning the government consultation 'Adding Capacity at Heathrow' forecast that there would be exceedences of the EU limit value (40 µg/m^3) in 2010 (the date when compliance with the limit becomes mandatory). Although widespread exceedences of the limit value in London in 2010 are expected[3] – for which the government is likely to seek a time extension from the European Commission – the latest Mayor's draft air quality[3] strategy notes that the limit has been met consistently since 1999 at non-roadside monitoring locations in outer London, except around Heathrow airport. The boroughs around Heathrow* have all declared an AQMA for NO_2.

1.5 Similarly, in its *'Future of Air Transport'* White Paper (ATWP)[4] the government's support of a third runway at Heathrow was provisional on it being confident that air quality limits (as well as a noise condition) could be met, which led to the setting up of the Project for the Sustainable Development of Heathrow to examine the technical basis for developing the required confidence. After consulting on the evidence base relating to the environmental conditions[5], the Secretary of State announced his support for a third runway[6], again emphasising in the decision document the need to meet air quality limits.

* London Borough of Harlington, London Borough of Hounslow, Spelthorne Borough Council, Slough Borough Council

1.6 In light of the above, there is a vital interest in understanding how much airport operations contribute to pollutant concentrations in the vicinity of the airport. Although monitoring provides spot checks on the situation at specific locations, modelling is required to give a fuller appreciation of the spatial variation in airborne concentrations. It is also needed to identify the relative contributions from various sources to the concentration at key locations and to provide a basis for forecasting the air quality impact of operational changes on the airport.

1.7 In July 2006, the PSDH published its report of the work of the air quality technical panels[7], which contained a number of recommendations for the methodologies and data to be used in quantifying the impact of airport operations on local air quality. In relation to emissions quantification, the PSDH recommendations have been followed in compiling the 2008/9 Heathrow inventory, as detailed in the 2008/9 inventory report. In relation to dispersion modelling, the work of the panels led to a recommendation that the ADMS-Airport[8] software be used for the modelling work in support of the 'Adding Capacity at Heathrow' Consultation[5], based on a comparative evaluation of a number of potential modelling approaches. ADMS-Airport has been used in the 2008/9 modelling study, and a principal focus in the present report is an explanation of how the 2008/9 emission inventory has been represented within the ADMS-Airport framework.

1.8 Around Heathrow, however, a large contribution to annual mean NO_x (and PM) concentrations derives from the major road network close to the airport and from sources distant from the airport (for example, the Greater London conurbation). Thus, the modelling methodology must encompass all major contributions if it is to provide a basis for understanding how the total concentrations may change in the future in response to initiatives aimed at one or other of the contributions. The present report, therefore, also includes a description of how off-airport contributions are modelled for 2008/9.

1.9 It is a key requirement that air quality models be evaluated by comparison with monitoring data in order to quantify their limitations. As noted earlier, the evaluation of the modelling methodology described here is presented in a separate report.

Pollutants Included

1.10 Ambient air quality in the UK is managed by reference to the Air Quality Strategy (AQS) for England, Scotland, Wales and Northern Ireland[9], which sets objectives for airborne concentrations of specified pollutants*, together with target dates for their achievement. In addition, air quality limit values and associated introduction dates set by EU Directives have been taken into English law† through the Air Quality Standards Regulations[10](AQSR). Although there is considerable overlap between the AQS and AQSR, there are some differences in detail, particularly in relation to dates of applicability.

1.11 Of the key pollutants of interest from a human health standpoint, this study focuses on NO_2, PM_{10} and $PM_{2.5}$. The justification for this choice is given in the 2008/9 inventory report and will not be repeated here. The objectives and limit values for the pollutants of interest are shown in Table 1.1.

Outline of the Approach

1.12 The methodology is aimed at predicting annual mean‡ concentrations for the relevant pollutants. Some air quality objectives and limit values relate directly to the annual mean value, whereas others also refer to shorter-period averages. The approach adopted here is that shorter-period metrics, where required, will be derived from annual mean concentrations using empirical relationships.

* Sulphur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter (PM_{10} and $PM_{2.5}$), benzene, 1,3-butadiene, ozone, carbon monoxide (CO), lead and polycyclic aromatic hydrocarbons (PAHs)
† The $PM_{2.5}$ limit value has not yet been taken into UK law.
‡ The term 'annual mean' is generally reserved for averages over a calendar year, and the term 'period-mean' will be used to refer to averages over the specific 2008/9 period of the study. However, in a generic description of the methodology it is not necessary to make the distinction.

1.13 The annual mean concentration of a given pollutant is considered to have two contributions:

(a) the contribution from explicitly-modelled sources;
(b) the contribution from all other sources, termed the ‘background’.

1.14 For (a), the methodology has the following steps for each source type:

(i) quantification of the total annual emissions;
(ii) specification of the spatial distribution of the emissions, at an appropriate level of detail;
(iii) specification of the temporal variation of the emissions, for example in terms of the diurnal and monthly profiles of emissions;
(iv) dispersion modelling to generate the contribution to annual mean concentration at a set of receptors throughout the study area.

1.15 For emissions from the airport and from road vehicles on the near-Heathrow major road network, the first three steps have already been carried out in generating the 2008/9 inventory, and the present report focuses on step (iv). Although the spatial and temporal distribution of emissions were considered in the inventory report, some of the details are intrinsic to the modelling approach and are treated here.

1.16 For the 2008/9 modelling, a decision was taken to include in the explicit dispersion modelling the emissions in the area covered by the LAEI (London Atmospheric Emissions Inventory), together with emissions from the NAEI (National Atmospheric Emissions Inventory) over an area stretching about 25 km to the west of the airport. The (background) contribution from more distant sources was then included by reference to measurements taken at relevant rural monitoring sites. This split between explicitly-modelled sources and background is similar to that used (by Cambridge Environmental Research Consultants) in the modelling underpinning the ‘Adding Capacity at Heathrow’ Consultation, and further details are given in Section 2.

Structure of the Report

1.17 Section 2 describes the overall strategy adopted for the modelling study, in particular explaining the approach to modelling non-airport sources.

1.18 Section 3 describes general features of the dispersion modelling that apply to all explicitly-modelled sources.

1.19 Section 4 details how aircraft sources have been represented within ADMS-Airport, whereas Section 5 explains how the non-aircraft sources (including LAEI and NAEI sources) have been modelled.

1.20 Section 6 explains how period-mean NO_2 concentrations were derived from period-mean NO_x concentrations, and discusses the primary NO_2 fractions assigned to each source type.

2 Modelling Strategy

Explicitly-Modelled versus Background

2.1 Air quality objectives and limits apply to total concentrations from all sources, so the modelling approach must account for sources at a range of distances from Heathrow, even sources far from the airport if, cumulatively, they contribute significantly to airborne concentrations near the airport. Given that the spatial distribution of emission sources is highly non-uniform, it is not clear *a priori* out to what distance it is necessary to extend the modelling in any particular direction. A complicating factor is that the dispersion models appropriate to the local scale may not be valid at longer scales. Straight-line plume models (such as ADMS – see below) are commonly considered appropriate out to distance scales of tens (but not hundreds) of kilometres.

2.2 A pragmatic solution to this problem is to model sources explicitly within a defined spatial region centred on the location of interest, and to derive the contribution from more distant sources using a semi-empirical approach based on monitoring data.

PCM Approach

2.3 A version of this approach is commonly used in local authority air quality review and assessment (R&A) in fulfilment of obligations under Part IV of the Environment Act 1995, which requires local authorities to understand the extent to which local sources are contributing to local air quality issues. In calculating the concentration close to a local source of concern (a section of road, for example), the contribution from the source itself is modelled explicitly and the contribution from all other sources is taken from national maps of background* concentration generated using the Pollution Climate Mapping (PCM) methodology[11], developed originally for air quality policy studies carried out by Defra and updated on an annual basis. This strategy has the clear advantage of not having to model spatially extensive source regions in the context of a local study; a subsidiary advantage is that it affords a measure of consistency in how the background contribution is quantified from one local study to another. In addition, the performance of the background modelling has already been separately evaluated against monitoring data on a national scale.

2.4 The use of the PCM maps (which in principal include all sources) to get the background contribution involves an element of double-counting, but if the local sources contribute little to the overall PCM background the approximation is not significant. Alternatively, if the sources under investigation contribute significantly to the PCM background, steps can be taken to exclude them when deriving the background contribution. This type of approach has been used by AEA in a number of previous airport air quality studies[12].

2.5 For NO_x, the PCM model derives the background concentration at any location in the country as the sum of contributions from point sources (such as power stations), from area sources (such as emissions from domestic/commercial combustion) and from distant sources, with the latter estimated from rural monitoring data†. The contributions from point and area sources are derived using the ADMS dispersion model, albeit making a number of approximations in the dispersion modelling, but the strategy is to 'calibrate' the model by introduce a scaling factor multiplying the area-source contribution. This factor is then adjusted to get the best fit to national monitoring data at background sites (which may lie in polluted areas but must not be close to individual sources). Scaling factors greater than 1 are usually necessary, typically (but not always) in the range 1-2 for NO_x. The calibrated model can then be tested against additional monitoring data that were not included in the calibration process.

* 'Background' in this context means not close to any specific source, in particular not close enough to a road to receive a major contribution from the road links(s) closest to the receptor.
† For PM, more types of contribution are recognised explicitly, but the basic principles of the method are similar.

2.6 A single scaling factor cannot give a perfect fit at all national monitoring sites, but discrepancies within a given range are tolerated as modelling uncertainties, with the acceptable range set by the purpose for which the model is used. In this sense, what may be tolerable from an overall national perspective may prove too large in a local context, implying that the performance of the background modelling may need separate evaluation in a local study.

2.7 Bearing in mind the truncation of area sources at 16.5 km from the point of interest, it is expected that locations near the edge of major conurbations that stretch for many tens of km – as is the case for Heathrow - may prove challenging for the PCM approach, given that the emission density may increase strongly with distance from the source in some directions.

Revised Approach

2.8 For this reason, an alternative approach was adopted for estimating the non-airport contribution for the 2008/9 study, in which emissions in the whole of Greater London were included in the explicitly-modelled sources – in fact emissions in all directions out to a distance such that contribution from residual sources could reasonably be derived from rural monitoring data alone.

2.9 This type of approach was used by CERC in the air quality modelling underpinning the DfT consultation on 'Adding Capacity at Heathrow'. In its idealised form, rural monitoring sites in a ring surrounding the location of interest are identified, with all sources within the ring modelled explicitly. The contribution from sources outside the ring in a given hour is taken to equal the concentration at the rural monitor that is closest to being upwind of the location of interest according to the meteorological data in that hour for the area of interest. This approach draws the line between explicitly-modelled sources and 'background' much further from the local area of interest than when the PCM is used.

2.10 There is an approximation inherent in this revised approach in that the concentration contribution from sources outside the ring will be different at the ring monitors from that at the location of interest, but if the principal contributors are far out from the ring (as expected for rural monitors) the approximation will be small.

2.11 Quantifying the contribution from sources other than the local sources using the above approach foregoes the separate 'calibration' and validation of the 'background' contribution that is implicit in the use of the PCM model, so has implications for model evaluation. These are taken up in the companion 2008/9 model evaluation report[2], which considers the performance of the modelling for airport sources separately from its performance for non-airport sources.

2.12 The particulars of the implementation of the above approach to the 2008/9 modelling study are given below.

Implementation of the Revised Approach

2.13 Sources that are included explicitly in the dispersion modelling can be categorised as follows:

(a) 'airport' sources – a shorthand for sources within the airport perimeter (aircraft on the ground, airside vehicles, etc) plus elevated aircraft emissions* - with emissions taken from the 2008/9 Heathrow emissions inventory;
(b) road vehicle emissions on the near-Heathrow major road network, defined within an 11 km square centred on the airport, having its SW corner at OS (502000,171000), with emissions taken from the 2008/9 Heathrow emissions inventory;
(c) sources in the LAEI inventory area;
(d) sources within an area defined as a 40 km square centred on Heathrow, with SW corner

* The contribution from elevated aircraft sources to ground-level concentrations decreases rapidly with increasing emission height, so that sources above a few hundred metres height can be ignored.

at OS (480000, 150000, but excluding the area already covered by the LAEI;
(e) large UK point sources.

2.14 The relevant areas for (a)-(d) are marked on Fig 2.1. For (a) and (b), the spatial distribution of the emissions is represented in detail in the dispersion modelling, given that the area of interest lies close to these sources; details are given in the 2008/9 emission inventory report and in Section 4 of the present report. For (c) and (d), sources are represented at a 1 km spatial resolution, with the emissions based on the London Atmospheric Emissions Inventory (LAEI) for the area within (and including) the M25 and based on the National Atmospheric Emissions Inventory (NAEI) outside the M25, as explained in Section 5. To avoid double-counting, road vehicle emissions in the LAEI and NAEI within the 11 km square road-network area were removed from the relevant squares of the LAEI/NAEI sources; similarly Heathrow airport sources and large point sources were removed from the relevant LAEI 1 km squares.

2.15 Leaving aside large point sources for the moment, the contribution from sources outside the area marked on Fig 2.1 is derived from the measurements taken at the rural monitoring stations Rochester Stoke (for all hours with a wind vector having an easterly component) and Harwell (for all hours with a wind vector having a westerly component). The justification for using Rochester Stoke for easterlies is that there are few sources immediately to the east of it, given the site's location close to the Thames estuary (although shipping emissions in the estuary may contribute), which is approximately equivalent to the situation at Heathrow after removal of the LAEI sources (which are modelled separately).

2.16 To the west, the strategy is to model explicitly the major source areas immediately west of Heathrow out to a distance beyond which the spatial density of emissions (broadly speaking, the size and spacing of towns and villages) is much the same as that west of Harwell. This sets the 20 km distance scale for the westerly extent of the explicitly-modelled area, which includes the towns of Slough, Windsor and Maidenhead. There may a minor element of 'double-counting' implicit in the approach, in that Harwell has some sources immediately to the west of it whereas Heathrow has the contribution from sources out to 20 km west already taken into account explicitly. However, the total westerly background contribution to annual mean concentrations at Heathrow in 2008/9 (using Harwell data) is only around 6 $\mu g/m^3$, so the degree of approximation is expected to be small.

2.17 The background concentrations derived from the rural monitors are given in Section 6.

2.18 Separate consideration was given to large point sources (power stations and major industrial plant) that generally need to be treated as stack releases. In principle, the contribution from such major facilities may only become negligible at large distance from the plant, and it is possible that their impact in the area of interest may be quite different to that at the 'background' rural monitors. For this reason, large* point sources are given separate treatment in the PCM modelling[11], with each plant modelled individually using plant-specific specific efflux parameters.

2.19 In the present work, all large point sources were modelled individually, adopting the 2008 emissions and efflux parameters used in the national Pollution Climate Modelling modelling, but applying 2008/9 meteorology. For NO_x, 166 large point sources were modelled; for PM_{10} and $PM_{2.5}$, 55 large point sources were modelled. The 2008 version of the PCM report was awaiting publication at the time of this analysis, but the essential methodology has been described in earlier reports, for example the 2007 version[11].The PCM stack database has been developed over a period of time under the PCM contract and is updated annually as required. Data sources for this database include a survey of Part A authorisation notices held by the Environment Agency and previously collated datasets on emission release parameters from large SO_2 point sources. Defra gave permission for the PCM stack data to be used in the Heathrow 2008/9 assessment.

* 'Large' is given a pollutant-specific interpretation (> 500 tonnes per year for NO_x, > 200 tonnes per year for PM_{10} and $PM_{2.5}$).

2.20 The contribution from large point sources at the rural monitors (for the pertinent range of angles) was small* (less than 1 $\mu g/m^3$) , so no correction to avoid double-counting was necessary. There is one large point source within the 11 km near-Heathrow area, in Hayes (the Nestle plant), and care was taken to use the most accurate efflux parameters available for this plant. Emissions for the plant were taken from the Environment Agency 2007 database[13], which gives 510 tonnes NO_x per year (with no reported value for PM_{10}).

2.21 Large point sources other than this plant contribute around 1.2 $\mu g/m^3$ to 2008/9 period-mean concentrations in the near-Heathrow area.

* Didcot power station is close to Harwell, but downwind for the westerly wind directions; similarly, Kingsnorth power station is west of Rochester Stoke.

3 Dispersion Modelling: General Features

3.1 Model Description

ADMS-Airport

3.1.1 The dispersion model used for the study was ADMS-Airport[8], version 2.3, licensed to AEA by Cambridge Environmental Research Consultants (CERC). ADMS-Airport is a recent addition to the ADMS family of dispersion models, developed to include specific features of emission sources at airports. It shares with other members of the family the underlying description of atmospheric dispersion governed by atmospheric turbulence, which exploits advances made over the last few decades in understanding the transport and diffusion of pollutants in the lower levels of the atmosphere. The performance of its representation of basic atmospheric dispersion has been evaluated extensively against field trial data, and results can be found on the CERC website www.cerc.co.uk.

3.1.2 Specialised versions of ADMS also take into account source-induced effects on dispersion, with ADMS-Airport in particular including additional modelling to account for the influence of the momentum and heat flux accompanying aircraft exhaust gases. The momentum flux creates additional dispersion via the shear between the exhaust flow and the ambient air; the heat flux, besides also adding to plume spreading, leads to plume rise (i.e. raises the centre-of-gravity of the plume), thereby lowering the maximum ground-level concentrations due to emissions from aircraft on the ground. A particular feature of the ADMS-Airport modelling for this effect is that it takes account of the motion of the aircraft – for example during take-off roll - which leads to lower plume rise than for a stationary aircraft with the same heat release rate.

3.1.3 Early versions of ADMS-Airport were evaluated in the Project for the Sustainable Development of Heathrow[7] (PSDH) alongside a number of other models, with all models using the 2002 Heathrow emission inventory (as revised following PSDH recommendations). Model predictions were compared with extensive pollutant monitoring data for the relevant year, and ADMS-Airport was found to perform better than earlier models. The comparisons were detailed enough to be able to attribute much of the improvement to the increased realism in representing the near-field dispersion of plumes from moving aircraft.

3.1.4 In relation to the modelling of vehicle emissions on the road network, ADMS-Airport shares with ADMS Urban and ADMS Roads the representation of traffic-induced turbulence, which leads to reduced concentrations close to the road (typically within tens of metres of the road) compared to values calculated assuming the action of atmospheric turbulence alone. In the model, the velocity scales associated with this source of turbulence depend on traffic flows (and speeds), so the concentration reduction close to the road increases with traffic volume. This aspect of ADMS Urban/Roads modelling has been tested in a number of urban and isolated-road environments, as reported on the CERC website, and has been found to give a realistic representation of near-road concentrations for plausible values of the pertinent model coefficients.

Annual-Mean Modelling for NO_2 Concentrations

3.1.5 The ADMS family of models includes a module for calculating the production of NO_2 from gas-phase reactions in the atmosphere following the release of NO_x (which is mainly in the form of NO initially). The method relies on an approximation to enable the impact of non-linear chemical reactions to be expressed within a Lagrangian framework. Using ADMS in this way to calculate NO_2 concentrations requires that all sources of NO_x be included in the same code run, which can be unwieldy and lead to long run times if concentrations are required on an extensive grid of receptors.

3.1.6 Alternative approximate methods of deriving annual-mean NO_2 concentrations are available and the 'Jenkin' method, as discussed in Section 6, was applied in the current work. This method has practical advantages - although this is not the sole reason for its choice - in that it allows the ADMS-Airport runs to be carried out separately for sub-sets of the NO_x sources, with the results then added together at the annual-mean level before calculating NO_2 concentrations. This brings flexibility to the modelling study, and keeps the run-time of individual ADMS-Airport runs at a manageable level.

Model Options

3.1.7 ADMS-Airport has various model options that can be used singly or in combination to represent particular features of the dispersion situation. Besides the decision not to use the chemistry module for NO_x-to-NO_2 conversion discussed above, other specific modelling choices made for this study are listed below:

• No building wakes. ADMS-Airport has provision to calculate the near-field concentration in the wake of an individual building (or combinations of buildings), but this level of detail in the modelling was deemed unnecessary for the majority of sources on the airport. The presence of buildings on the airport has been taken into account in setting an effective roughness length (see below) for the airport as a whole, but this relates to dispersion once plumes have grown beyond the size of individual building wakes. Given that the interest lies in off-airport concentrations, the direct effect of airport building wakes will be small, although concentrations in the immediate vicinity of specific buildings will be sensitive to near-field modelling. An exception was made for heating-plant stack emissions, where it may be optimistic to ignore the potential for building downwash. The provisions made for modelling heating-plant emissions are discussed separately later.

• No coastal or topographical effects on dispersion are included other than through their influence, if any, on the meteorological data used for the airport. The topography around Heathrow airport does not warrant the use of the complex-topography module.

• No deposition. The dry deposition velocities and scavenging coefficients appropriate to the pollutants considered are small enough that attenuation of the airborne plume due to both dry and wet deposition can be ignored over the distance scales relevant to the current study.

Concentration Differences as a Function of Wind Direction and Speed

3.1.8 A key aim of the 2008/9 air quality study is to test the performance of the modelling approach using comparisons with monitoring data in the immediate vicinity of the airport. Given that total NO_x and PM concentrations near the airport include a large contribution from non-airport sources, a strategy for enhancing the airport-specific 'signal' is to analyse the hourly concentration differences between monitors close to but on opposite sides of the airport as a function of wind direction. For wind directions that blow from one monitor to the other, the concentration contribution from more distant sources will be much the same at both monitors whereas the contribution from sources between the monitors will contribute to one monitor and not the other. This more detailed type of analysis of modelled and measured concentrations facilitates a separate assessment of model performance for on-airport sources, which is a major interest from the perspective of source attribution. Examination of concentration differences as a function of wind speed may yield further insights into model performance.

3.1.9 Thus, although annual-mean concentration is the focus of attention in relation to air quality limits and objectives, for model evaluation purposes ADMS-Airport outputs were retained on an hourly basis for the whole year. Given the computational overheads associated with the more detailed output, hourly information was generated only for the 'specific' receptors (in particular the monitoring points) to be used in the model-measurement comparisons, not for the full set of grid points (see later for a discussion of receptor points for model output).

3.1.10 For emission categories treated as 1 km area source, the smearing over 1 km creates an angular imprecision in the modelled concentration contribution at the monitoring points, which is larger the closer the source is to the monitor, so is of particular relevance within the 11 km inner area. However, the residual sources treated at this spatial resolution (for example, domestic combustion and minor road sources) – after removing the airport, road network, rail line and large point sources – tend not to be highly focused spatially.

3.2 Source-Independent Input Parameters

3.2.1 In terms of input parameters, a division is made between inputs that are source specific – discussed in later sections - and those that are not, discussed here.

3.2.2 There are a number of ADMS-Airport input parameters that relate to the basic dispersion modelling processes or to the methodology used by the ADMS-Airport meteorological pre-processor to predict the vertical profiles of wind speed and turbulence within the atmospheric boundary layer from routine surface meteorological observations. The values selected are discussed below.

Aerodynamic Roughness Length

3.2.3 This is a length scale related to the height, shape and packing density of projections from the surface (crops, hedges, buildings etc), and governs the variation of wind speed with height above the surface (in the absence of thermal gradients) at heights above the ‘canopy’ created by the surface projections. On the airport, this parameter influences the dispersion of pollutants once they escape from the near-field influences of aircraft, vehicles and buildings.

3.2.4 The concept of aerodynamic roughness length applies, in principle, when the vertical wind-speed profile has come into equilibrium with an underlying surface of fairly homogeneous surface cover. The area on and around Heathrow airport is heterogeneous, and the wind speed and turbulence profiles will generally be in transition, so the use of a single roughness length represents an idealisation. For extended, homogeneous surfaces, values of roughness length greater than 1 m are considered appropriate to dense urban areas whereas values around 0.1 m are appropriate to surfaces with low vegetation.

3.2.5 Although the airport itself has large areas of grass and concrete, it also has a complex of buildings in the terminal areas. Also, upwind of Heathrow along many wind directions there are extensive built-up areas Thus, an approximate representative value of roughness length for modelling the dispersion of sources on, or close to, the airport is expected to be around 0.5 m, with an uncertainty of around 0.2 m; the value of 0.5 was used in the modelling for all sources sources within the 11 km road-network area and other sources west of the M25. For the dispersion modelling of area sources within the Greater London, area a roughness length of 1 m was used, reflecting the increased height and packing density of buildings, although it is an approximation to have a sharp boundary between two areas of different surface roughness.

3.2.6 In the context of the model inter-comparison study carried out for the PSDH, a test was carried out on the sensitivity of the AEA model results for airport sources to a change in roughness length. This indicated that increasing the roughness length from 0.2 m to 0.5 m typically decreased modelled concentrations from ground-level sources by around 15-20% in the relevant distance range from the source.

Lower Limit on Monin-Obukhov Length

3.2.7 The basic ADMS dispersion modelling can account for the fact that in a built-up area the waste heat per unit plan area is sufficient to affect the thermal structure of the lower levels of the atmosphere and consequently the dispersion of pollutants. Thus, the ADMS user can set a constraint on how 'stable' the atmosphere can become (where stable conditions inhibit the vigour of the turbulence responsible for atmospheric diffusion), and this is represented in terms of setting a lower limit on positive values of the Monin-Obukhov length (which is the distance scale from the surface at which buoyancy effects and shear effects become comparable).

3.2.8 In principle, this parameter applies to an equilibrium atmospheric boundary layer and not to the transient situation where the boundary layer is disturbed by local influences. Thus it is difficult to judge an effective value of the parameter for the area around a large airport, which acts as a local source of heat and additional turbulence, but the value is expected to lie within the range 10 m (the value recommended by ADMS for small towns) and 30 m (for urban/industrial complexes). A value of 20 m was chosen for 11 km square near-Heathrow area, and also applied to all sources west of the M25.

3.2.9 For sources within Greater London, it is recognised that there may be a more significant 'heat island' effect, indicating a higher value of the Monin-Obukhov cut-off length is appropriate. It has been suggested[14] that values in the range 30 m to 100 m are appropriate for London, and a value of 50 m was chosen for the 2008/9 work. It is an approximation from a modelling perspective to have a sharp boundary between two regions of different effective cut-off length, but this is considered acceptable given the uncertainty assigning an appropriate value. In fact, it would be justifiable to treat the cut-off length as an adjustable parameter (within its acceptable range), choosing a value to improve the fit between monitoring and modelling within the study area, but the 2008/9 model evaluation did not indicate any need for significant adjustment.

Other

3.2.10 The *Priestley-Taylor* parameter reflects the balance between sensible and latent heat fluxes at the surface. The ADMS default value of 1.0 was retained, appropriate to moist grassland.

3.2.11 The *surface albedo* determines the fraction of incoming solar radiation that is reflected from the surface. The ADMS default value of 0.23 was retained.

3.3 Meteorological Data

3.3.1 The ADMS-Airport model was run using hourly sequential wind speed and direction data from the Heathrow site for the period 1st April 2008 to 31st March 2009, obtained under licence from the UK Meteorological Office.

3.3.2 Fig 3.1 shows the wind rose for the period, and Table 3.1 gives some statistical information on the met data. The data capture (fraction of hours in the year with valid data for parameters used by ADMS) was 97%. As seen from Fig 3.1, the wind blows predominantly from the SW, particularly at higher wind speeds, which is commonly the case in the UK in the absence of specific mesoscale effects. This explains the greater frequency of usage of runways 27L and 27R (westerly operation) compared to runways 09L and 09R (easterly operation). For the period of interest, the westerly/easterly split was 71.7%/28.3%.

3.3.3 Fig 3.2 shows the frequency distribution of wind speed, irrespective of wind direction, in the period, giving a mean wind speed of 4.1 m/s. Hours in which the recorded wind speed was zero ('calms') – accounting for 0.13% of all hours in the year (Table 3.1) - were handled internally in ADMS-Airport (by assigning a wind speed of 0.75 m/s and the wind direction of the previous hour).

3.3.4 The ADMS met pre-processor (which uses routine meteorological observations to derive the boundary-layer parameters needed by the dispersion model) requires cloud cover data in addition to wind data. The Heathrow met station includes an automatic device for estimating cloud cover. Although in the past there have been some reservations about the use of automatic cloud-cover data for dispersion-modelling purposes, the latest government guidance for local authority air quality review and assessment[15] states that the additional uncertainties deriving from the use of automatic cloud cover are not significant compared to other uncertainties in air quality modelling.

3.3.5 The nearest met station to Heathrow with manual cloud cover data is Northolt (OS 510,185), around 9 km north of Heathrow. Previous UKMO information about Northolt was that it has manual observations during the hours of 0600 to 2000 (which covers the period when most airport emissions arise), with automatic measurements at other time. However, more recent communications raise the possibility that the automatic instrument may be used during non-flying periods at other times of the day. For the present study, the full hourly sequence of cloud cover for 2008/9 was obtained for both Heathrow and Northolt to allow a sensitivity test to be carried out.

3.3.6 In a test run for airside vehicle sources distributed over the airport, the period mean concentration using the Heathrow automatic cloud data was typically around 1% higher than that using the Northolt data. Thus, the automatic cloud cover data have been used for the main assessment.

3.4 Receptors

3.4.1 The concentration contribution from on-airport sources falls off rapidly with distance from the airport boundary, so that airport contribution to annual mean NO_x concentrations drops to only a few percent of the total on a distance scale of a few kilometres from the key airport sources. This sets the spatial scale of the area over which direct airport-related impacts on local air quality need to be assessed. Consequently, a 'study area' was defined, representing the area over which concentration contours were calculated, including concentrations close to modelled roads. This was chosen to be a rectangular area 9 km E-W by 9 km N-S, with SW corner at OS grid reference (503000, 172000), as marked on Fig 3.3.

3.4.2 Within this study area, near-road concentrations were calculated using data from the Heathrow-specific traffic modelling described in the inventory report. Of course, in principle there can be road links much further from the airport where airport-related traffic may contribute to air quality issues close to roads, but it is assumed that these would need to be investigated separately within the context of the relevant local authority air quality review and assessment process.

3.4.3 ADMS-Airport calculates concentrations at a set of locations (termed receptors) input by the user. In the current modelling study, two sets of receptors were distinguished. First, the modelling was carried out for a number of 'specific' receptors, chosen for their intrinsic importance. Principally, these are the monitoring sites within the study area and sites chosen to facilitate comparisons with the results of the PSDH work. Site details are given in the 2008/9 model evaluation report.

3.4.4 In addition, a grid of receptors points was set up covering the selected study area[*], to enable the plotting of concentration contours. The prime requirement here is that the grid spacing should reflect the expected concentrations gradients. First, a basic regular grid of receptor points was specified to cover the study area at a grid spacing of 100 m. Receptor points were then added close to the road-vehicle and aircraft sources, using the 'intelligent gridding' option available in ADMS-Airport.

3.4.5 For road vehicle sources, this facility adds 4 lines of receptors parallel to each road link, at distances ±0.45 and ±2.0 times the road width from the road centre-line, with an along-road spacing determined by the number of links and the limit on the total number of additional points (5000). In addition, after the model run is finished, further receptors points are added between the intelligent-grid points, with the model values at this set of points determined by interpolation. It was found that the size of the near-Heathrow network in the 2008/9 study was too large for there to be a sufficient density of intelligent-grid points near all roads if the whole network and the whole receptor area are included in a single run.

3.4.6 One possible solution to this problem was to subdivide the output receptor area, so that intelligent gridding is only applied to a portion of the network (although all links of the network still have to be included in each run). An alternative strategy was adopted for the 2008/9 work, in which the network itself was subdivided into approximately nine equal areas (but with every link assigned to one sub-area or another, without splitting links). A run for a network sub-area was then given a 'customised' set of output receptors that included the

[*] Of course, the concentrations at the specific receptors could have been obtained from the grid results by interpolation, but the separate specific receptor run avoids interpolation errors at the key receptors used in the model evaluation. Also a more detailed breakdown of concentration by met condition was retained for the results at continuous-analyser locations.

intelligent grid points for the particular network segment together with an adapted base grid, with the latter having a grid spacing of 50 m within the network sub-area itself, relaxing to 100 m spacing then 200 m spacing with increasing distance from the sub-area. The results from all the network sub-areas were then combined using standard interpolating/contouring software. An example of the set of receptors for one of the network sub-areas is shown in Fig 3.4.

3.4.7 This strategy has the added advantage that the computer runtime for a single road-network run was kept within reasonable limits, with the modelling for each sub-area (itself composed of 72 sub-runs, one for each representative model hour) taking less than a day on a standard PC. This strategy takes advantage of the fact that the modelling is aimed at predicting annual-mean concentrations (of NO_x, PM_{10} and $PM_{2.5}$), for which contributions from sub-components can be simply added; in particular it relies on annual-mean NO_2 concentrations being derived from annual-mean NO_x concentrations in a post-processing step (see Section 7).

3.4.8 For aircraft sources included in the ADMS-Airport jet/plume modelling, 8 additional lines of receptors are added by the intelligent-gridding routine, at ±0.2, ±0.45, ±1.0 and ±2.0 times the maximum engine-to-engine spacing for the relevant aircraft. The minimum along-source spacing is constrained by the number of discrete runway sources, the size of the overall modelling domain and the maximum number of additional points available for aircraft sources (2000). Again, after the model run is finished, further receptors points may be added between the intelligent-grid points, with the model values at this set of points determined by interpolation.

4 Representation of Aircraft Emissions in ADMS-Airport

4.1 Efflux Parameters

4.1.1 ADMS-Airport characterises an aircraft exhaust plume in terms of efflux velocity (V_p), plume temperature (T_p) – for an assumed ambient temperature (T_a) of 15°C – and a plume diameter (D_p). Detailed engine manufacturer's data on efflux parameters are usually proprietary, so an alternative route to obtaining these parameters is required. The ADMS-Airport User Guide[8] provides a table of values for the representative aircraft/engine combinations that were used in the PSDH work, spanning the range of aircraft types in the Heathrow fleets used in that work. However, for other aircraft fleets it may be appropriate to use a different set of representative aircraft/engine combinations, so a procedure for estimating these parameters for other engines is desirable. The are several alternative starting points based on available information, some of which are suggested in the ADMS-Airport User Guide, and the line of approach used in the current work is described below.

4.1.2 Using data made available to them for the PSDH work, CERC found that the efflux velocity and plume temperature increment did not span a large range (less than a factor of two from smallest to largest) for the engines fitted to a wide range of common commercial jets. In addition, V_p and T_p were found to correlate strongly with engine by-pass ratio (BPR) (perhaps indicating that combustor core outlet conditions are less variable even than final outlet conditions). Thus, the ADMS-Airport User Guide provides linear regression relationships for V_p and T_p as a function of BPR, with the latter readily available for certificated engines in the ICAO engine databank with rating greater than 26.7 kN[16].

$$\begin{aligned} V_p &= m_v BPR + c_v \\ T_p &= m_T BPR + c_T \end{aligned} \tag{1}$$

4.1.3 These relationships are provided separately for the four standard representative thrust settings (100%, 85%, 30% and 7%), and the coefficients of the regression lines are shown in Table 4.1. Thus for aircraft/engine combinations not in the ADMS-Airport list, V_p and T_p were obtained from the regression relationships*.

4.1.4 Given values of V_p and T_p, the following procedure was used to derive the effective diameter of the exhaust plume. Equating engine thrust to momentum flux (for a stationary engine)†, i.e.

$$Th = \dot{m} V_p \tag{2}$$

where thrust (Th) is the engine rating (from the ICAO databank) times the relevant percentage, enables the mass flux $\dot{m}$ to be derived for a given thrust.

4.1.5 From $\dot{m}$ and T_p, an effective diameter D_p can be worked out from

$$\dot{m} = \frac{1}{4}\pi D_p^2 \rho_p V_p \tag{3}$$

where ρ_p is the density of the gas. Although in principle the composition of the exhaust gas

* If the required aircraft/engine combination happens to be on the ADMS-Airport list, the value given in the table is preferred to the value obtained from the regression relationship because there is some scatter about the best fit line. This was the case for four of the representative engines chosen using the procedure in Section 4.2

† This ignores the momentum of the incoming air, but this is insignificant for a stationary engine.

is needed to work out ρ_p, it is sufficient to assume that the gas is air, since aircraft engines have large air-to-fuel ratios even in the core and, in addition, have by-pass air mixed in. It is adequate to take a representative ambient pressure (101.3 kPa) when working out ρ_p for a given T_p. D_p is an effective diameter in that it assumes the exhaust gases are homogeneously mixed (and can be taken to be pure air).

4.1.6 The three parameters V_p, T_p and D_p provide ADMS-Airport with the information required to calculate near-field dispersion and plume rise.

4.1.7 It should be noted that this procedure yields slightly smaller (typically <5% smaller) diameters than the values in the ADMS-Airport table for the engines listed there. This stems from the fact that the values in the table were derived from the mass flow rates given in the data provided to CERC for the PSDH work, based on detailed engine modelling by QinetiQ. These mass flow rates are for a moving aircraft, taken at some intermediate point along the aircraft take-off roll. As an aircraft picks up speed, the thrust will fall for a given mass flow rate because of the momentum associated with the incoming air. In practice, the engine management system may make adjustments to compensate for this effect to some degree (by increasing the mass flow rate), so there is no requirement that the product of mass flow rate and exhaust velocity should remain constant for the moving aircraft. In the CERC data, this product is slightly higher than the product of the engine rating and the thrust percentage selected for the take-off, leading to a slightly higher diameter than that obtained as described above. The above approach, therefore, will lead to slightly lower buoyancy flux and thence slightly higher ground-level concentrations, but the differences are small compared to the other uncertainties in the approach described.

4.1.8 For four-engine aircraft, ADMS-Airport simplifies the representation to two plumes, combining the plumes from the two engines on a given wing into a single plume (with the same V_p and T_p), based on sensitivity tests carried out as part of the PSDH work. An effective initial plume diameter is assigned to preserve total mass flow rate.

4.2 Modelling Categories (MCATs)

Overall Approach

4.2.1 The heat and momentum flux associated with jet aircraft exhaust gases for a given mode of operation (e.g. taxiing or take-off) varies from one aircraft engine to another. If the impact of these fluxes on pollutant dispersion is to be taken into account, it is not enough therefore to know only the spatial (and temporal) distribution of the total emissions but also how the emissions are distributed amongst engines with different efflux parameters. It is impracticable to treat every aircraft/engine combination at Heathrow separately, so there is a need to sub-divide the total range of combinations into a number of modelling categories (MCATs) based on the sensitivity of model results to variation in the efflux parameters.

4.2.2 In this context, the results of a programme of test runs carried out earlier were utilised, and these are summarised briefly below. In that work, an aircraft exhaust plume for a simplified source configuration, with unit emission rate, was modelled in ADMS-Airport with constant meteorology, corresponding either to a steady head wind or a steady cross wind.

4.2.3 Model runs were carried out for a range of engine efflux parameters, and the variation in concentrations was recorded. For this purpose, two concentration metrics were used – the maximum ground level concentration and the average ground-level concentration over a 1 km x 1 km area surrounding the source, in both cases only including receptors greater than 200 m from the source. Clearly it is difficult to capture the complexities of the variation in the ground-level concentration field with efflux parameters using a few scalar quantities, but the metrics chosen were judged adequate for determining MCAT boundaries.

4.2.4 The tests were carried out separately for engines at take-off thrust and engines at idling thrust, on the grounds that the required number of MCATs may differ in these two situations.

For take-off, the source corresponded to the initial part of the roll when the aircraft was moving at low velocity, on the grounds that the impact of the exhaust heat flux is less when the aircraft is moving faster.

4.2.5 In the programme of work to determine the MCAT boundaries, it proved useful to represent the plume-rise potential of the exhaust gases in terms of the initial buoyancy flux (*B*) – a standard parameter in plume rise modelling – defined as

$$B = \frac{g(T_p - T_a)V_p D_p^2}{4T_p} \tag{4}$$

where *g* is the acceleration due to gravity. *B* has units m^4s^{-3}.

4.2.6 From general principles, it is expected that the impact of efflux conditions on ground-level concentrations (in given atmospheric conditions) will depend on both *B* and on the initial (horizontal) 'momentum flux' (*M*), another conventional parameter in plume modelling, defined as

$$M = \frac{\rho_p V_p^2 D_p^2}{4\rho_a} \tag{5}$$

where ρ_p is the density of the plume and ρ_a is the density of the ambient air. The inclusion of ρ_a in the denominator is conventional in this context, but gives *M* the units m^4s^{-2} rather than the units of a momentum flux. $\pi\rho_a M$ can be identified as $\dot{m}V_p$, where $\dot{m}$ is the mass flow rate of the engine defined earlier, so $\pi\rho_a M$ can also be identified as the thrust of the engine if the momentum of the incoming air can be ignored (which is the case for a stationary engine).

4.2.7 Given that the plume composition is principally air, Equation (5) is approximately equivalent to

$$M = \frac{T_a V_p^2 D_p^2}{4T_p} \tag{6}$$

4.2.8 In practice, *B* is strongly correlated with *M* for aircraft engines, with high thrust engines tending to have high values of *B*, and the tests demonstrated that it is adequate to characterise the plume-rise potential of aircraft engine exhaust plumes in terms of *B* alone. Thus, the partitioning of aircraft/engine combinations into MCATs from a plume-rise perspective for any particular fleet can be carried out in terms of the range of *B* values encompassed by the fleet.

Take-Off

4.2.9 In the take-off tests described in Appendix 2, *B* ranged from around 190 m^4s^{-3} to 900 m^4s^{-3}, which spans the range for the principal commercial jets at Heathrow airport at take-off thrust.

4.2.10 If a criterion is set that the defined concentration metric should not vary over an MCAT by more than ±5% from its value at the mid-point, the results suggest that 1/*B* should not change by more than about 25% from the bottom to the top of its range for the MCAT, indicating a range of *B* of around 100 m^4s^{-3} for a typical mid-range value of 400 m^4s^{-3}. In practice, not every sub-range of 1/*B* may contain sufficient emissions to warrant it being modelled separately, in which case an *ad hoc* decision may be taken to extend neighbouring MCATs to encompass the aircraft/engine types accounting for this small fraction of the emissions. For the 2008/9 Heathrow fleet, this line of reasoning suggested that around 7 MCATs would be sufficient for take-off roll emissions.

4.2.11 Based on the above criteria, generally speaking a major aircraft type (e.g. B737, A320, B747 etc) can be allocated to a singe MCAT despite the range of sub-series and engine fits associated with the type. Thus, for presentational convenience, category boundaries were chosen so that major aircraft types were not split across categories, wherever possible, accepting that this leads to some non-uniformity in the range of *B* per category. In the case of the B777, the range of *B* was too wide to be encompassed in a single MCAT (with the B777-200ER, for example, having significantly lower values of 1/*B* than the B777-200), so two categories were used.

4.2.12 In the context of the Project for the Sustainable Development of Heathrow, CERC also carried out a number of sensitivity tests using the pre-release version of ADMS-Airport[17], which similarly concluded, broadly speaking, that separate categories are required for the major aircraft types for take-off NO_x emissions whereas the variation from engine to engine within these main types is generally not large enough to warrant separate categories.

4.2.13 Having defined the MCAT boundaries, a single set of efflux parameters is used to model the emissions in a given MCAT, with the values chosen to correspond to a specific aircraft type/engine combination within the category. An element of judgement is involved in selecting the representative aircraft/engine, with the broad aims that the chosen representative should itself account for a significant fraction of the emissions in the category and that the representative should not be too close to the edge of the range, to avoid unnecessary bias (unless the emissions associated with the other aircraft/engine combinations in the MCAT are a small fraction of the MCAT total). Usually, an obvious candidate for the category representative suggests itself.

4.2.14 Take-off thrust is a variable that typically ranges between 85% and 100%. However, the sensitivity investigations by CERC[17] indicated that it was adequate to use a single representative take-off thrust when working out efflux parameters for take-off. In terms of the earlier discussion, the range of initial buoyancy flux for a typical range of variation of take-off thrust is small compared to the range encompassed by an MCAT. In the current work, efflux parameters for take-off were worked out at 85% thrust, which is more likely to slightly overestimate than underestimate ground-level concentrations.

4.2.15 The resulting MCATs used for modelling the 2008/9 Heathrow aircraft emissions from take-off roll are shown in Table 4.2, which gives the efflux parameters for the representative engine and the approximate range of initial buoyancy flux, *B*, associated with each category.

4.2.16 For receptors beyond the immediate vicinity of the airport, it may be possible to demonstrate that a smaller set of high-thrust MCATs would suffice, but for convenience the full set of MCATs was used in calculating concentrations throughout the study area.

Climb

4.2.17 Initial climb (from wheels off to throttle-back, typically at 1000-1500 ft height) is typically at a thrust setting of 80-85% of rating. As noted above, the efflux parameters for take-off were worked out at the 85% setting so, bearing in mind the earlier comments on sensitivity to thrust setting, the set of MCATs and efflux parameters developed for take-off were also used for initial climb (Table 4.2).

4.2.18 Emissions from the climb-out phase (typically above 1000-1500 ft) have an insignificant impact on ground-level concentrations, so were omitted from the modelling.

Low-Thrust Flight Phases (Taxiing, Hold and Landing Roll)

4.2.19 The sensitivity tests indicated that there is not a strong variation in concentrations per unit emission with *B* at taxiing thrust, such that all aircraft type/engine combinations can be assigned to a single MCAT at this thrust setting. On the other hand, tests indicated that it would be overly conservative to treat the emissions as having zero buoyancy. Thus a representative aircraft type/engine was chosen for the MCAT (A319-100 fitted with the IAE V2522 engine), as shown in Table 4.2. This has a *B* value close to the low end of the range of *B* values for 7% thrust, which will lead to a slight tendency to overestimate ground-level concentrations from the fleet as a whole. The corresponding efflux parameters at 7% thrust are given in Table 4.2.

Approach

4.2.20 As discussed in the inventory report, approach emissions have been defined for two segments, an upper segment (down to 2000 ft) and a final approach segment (from 2000 ft to ground). Thrust during final approach is typically 30% of engine rating. Given the lower thrust and the elevated nature of the emissions, a single MCAT was judged sufficient for this flight phase; efflux parameters for the representative engine (taken to be the same as for the low-thrust MCAT) were worked out at 30% thrust. Emissions from the upper approach segment have an insignificant impact on ground-level concentrations, so were omitted from the modelling. The efflux parameters at 30% thrust are given in Table 4.2.

4.3 Spatial Representation of Aircraft Emissions

4.3.1 The principal features of the spatial representation of emissions on the horizontal plane have been discussed in the 2008/9 inventory report[1], but additional spatial considerations arise from the dispersion modelling methodology.

Take-Off Roll

4.3.2 The moving jet/plume model in ADMS-Airport works with a given aircraft speed, whereas during take-off roll the speed changes continuously as the aircraft accelerates. In addition, the emission rate changes along the roll as a consequence of engine spool-up and forward-speed effects. This is handled within ADMS-Airport by splitting the total roll into discrete length segments, treating all the emissions in a segment as arising at a representative point and having a representative value of aircraft speed. The number of length segments is under user control, and should be made large enough to avoid significant inaccuracies at the receptors of interest arising from the discretisation process. A maximum spacing of 200 m is suggested for the take-off roll in the ADMS-Airport User Guide; sensitivity tests carried out in earlier work suggested that 100 m upper limit was appropriate when the runway is fairly close to residential areas, so this was the spacing chosen for the present work.

4.3.3 The 2008/9 inventory report takes the discussion of the spatial distribution of roll emissions to the point of identifying that for a given start of roll point the distribution along the runway is governed by *VR* (speed at lift off) and *tR* (roll time), which in principal vary on a flight-by-flight basis. For dispersion modelling purposes, however, a measure of simplification is introduced. First, it is adequate to assign a representative value of *VR* to each MCAT based on the relatively small range of *VR* values; the values are shown in Table 4.2. Secondly, each flight was assigned to one of a set of roll-time categories of five-second range. Thus, the total number of different spatial distributions along a particular runway is given by the number of start-of-roll points, the number of MCATs and the number of *tR* categories needed to accommodate the emissions associated with an MCAT[*].

Taxiing and Landing Roll

4.3.4 As described in the inventory report, taxiing emissions were calculated separately for each link of the taxiway network. As noted above, a single MCAT was used for dispersion modelling purposes, but the jet/plume modelling in ADMS-Airport requires the direction of travel of the aircraft on the taxiway to be identified, so the emissions for each direction of travel on a given link were modelled separately. The ADMS-Airport User Guide suggests a maximum spacing of 400 m between taxiway sources, but the spacing used will depend on distance between taxiways and nearest sensitive receptors. Earlier sensitivity tests suggested that 100 m spacing was appropriate for all ground level sources, and the results presented here are for this spatial resolution.

[*] Where only a small fraction of the emissions is assigned to a *tR* category at the edge of the principal range, the emissions may be lumped with the adjacent category. On the other hand, the roll time associated with a given *tR* category was not taken simply as the mid point but as the emissions-weighted average of the individual times assigned to the category.

4.3.5 The emission inventory takes into account that for some aircraft types a fraction of arriving aircraft use reverse thrust (at above idle thrust setting). The emissions from that portion of the landing roll over which reverse thrust is used have been calculated separately from the remaining landing roll emissions. The exhaust plumes emitted during reverse thrust deployment have complex exit conditions, and it would be optimistic to assume that the ADMS-Airport jet/plume model would apply in its standard form. Thus the emission calculated for reverse thrust were treated in the modelling as simple volume sources with a vertical extent of 15 m from the ground upwards and a mean height of 7.5 m. Given the uncertainty in the time after touchdown at which reverse thrust operation commences, the emissions were assumed to be distributed uniformly between touchdown and exit. Other landing-roll emissions not associated with reverse thrust were treated as taxiing emissions, again distributed between touchdown point and runway exit.

Initial Climb and Final Approach

4.3.6 As described in the inventory report, initial-climb emissions associated with a given end-of-roll location were distributed along a straight line (aligned with the runway) inclined to the horizontal at an angle dependent on aircraft type category and cut-back height. Sensitivity tests on the separation of the discrete plumes used by ADMS-Airport suggested that 200 m was an appropriate resolution for initial-climb sources.

4.3.7 Uniform acceleration between lift-off speed and cut-back speed is assumed within ADMS-Airport in order to assign a speed to each of the representative plumes along the trajectory. A minor simplification introduced for initial climb was to assume constant emission rate along the trajectory (i.e. ignoring the impact of aircraft speed changes on exhaust emission rates)[*]. Emissions above 1000 ft have an insignificant impact on ground-level concentrations, and have not been included in the dispersion modelling.

4.3.8 Final approach (from 2000 ft to ground) was modelled as a straight-line segment ending at touch-down, inclined at 3° to the horizontal. During final approach, the speed is assumed to decrease at uniform deceleration to a landing speed that is aircraft category dependent (see the 2008/9 inventory report). As with initial climb, for the purposes of modelling the emission rate was assumed constant along the trajectory. Sensitivity tests indicated that a spacing of 200 m for the representative jet sources was adequate for final approach.

Other Aircraft Emissions

4.3.9 In the 2008/9 inventory, APU emissions have been calculated on a flight-by-flight basis, and assigned to the particular stand used by the flight. Each stand is modelled in ADMS airport as a separate source of horizontal size 50 m x 50 m.

4.3.10 There are no data available on the efflux parameters associated with the exhaust gases from APUs, and the PSDH work was unable to give any guidance on the impact of buoyancy on the dispersion of these emissions. Thus, the emissions were modelled as a simple volume source of depth 12 m and mid-height 6 m (the default values in ADMS-Airport), which is likely to overstate the contribution of APUs to ground-level concentrations close to the apron areas.

4.3.11 PM emissions from aircraft brake and tyre wear wre treated as a volume source of depth 15 m and mid-height 7.5 m.

4.3.12 Engine testing represents a minor source of aircraft emissions, and the complexities of jet/plume modelling were ignored for this source. The emissions were treated as volume sources of depth 15 m, with a mid-height of 7.5 m.

[*] Changes in emission rate due to forward-speed effects are taken into account in calculating the total initial-climb emissions, but not when distributing these emissions along the initial-climb line segment.

5 Representation of Non-Aircraft Emissions in ADMS-Airport

5.1 Road-Vehicle Emissions

5.1.1 For road-vehicle emissions arising on a road network, ADMS-Airport (in common with ADMS-Roads and ADMS-Urban) has the facility to take traffic data (flows, speeds and traffic composition) directly as input, using the data both to quantify the pollutant emissions on each link of the network and to derive parameters defining the traffic-induced turbulence that affects the near-field dispersion of the emissions. For the emissions calculations, ADMS-Airport uses emission factors taken from currently approved national sources.

5.1.2 When entering traffic data directly into ADMS-Airport, the available vehicle categories are restricted to LDV (Light Duty Vehicles – cars and vans) and HDV (Heavy Duty Vehicles – HGV and buses). For more flexibility, emissions for the pollutants of interest can be calculated externally and input to ADMS-Airport on a link-by-link basis. This option was preferred for the 2008/9 study because the traffic data supplied for the inventory retained four vehicle categories (cars, LGVs, HGVs and buses). In addition, this option allowed greater flexibility in calculating emissions using the latest emission factor and fleet fraction data set (described in detail in the inventory report), for which there is the need to supplement the published data with additional judgements and choices governed by the specific circumstances of the study. The choices made for the 2008/9 inventory are described in the inventory report[1].

5.1.3 One potential difficulty with calculating the emissions externally is that ADMS-Airport needs to know the traffic flows and speeds anyway in order to calculate the parameters associated with traffic-induced turbulence. A way around this problem was found by first inputting the traffic data (to enable ADMS-Airport to calculate turbulence parameters) then intervening in the set-up process to replace the internally-calculated emissions based on this traffic data set with externally-calculated emissions.

5.1.4 A subsidiary problem associated with calculating emission externally relates to temporal profiles. ADMS-Airport allows a single hour-of-year profile to be associated with each emission source, but there are two temporal profiles associated with externally-calculated road-vehicle emissions: the temporal profile of emissions (for each pollutant separately) and the temporal profile of the traffic data (which determines the temporal profile of the traffic-induced turbulence parameters). These profiles may be quite different if the traffic has more than one vehicle category, each with a different temporal flow profile*. For example, HGVs may constitute a relatively small fraction of the total flow, but a large fraction of the total emissions, and they tend to have a rather different diurnal profile to that for cars. One approximate way around this problem is to carry out ADMS model runs for each vehicle category separately in the expectation that the emissions profile for an individual vehicle category will mirror the traffic flow profile. (This will not be exactly true if speed also varies throughout the day, but the approximation may be adequate.)

5.1.5 An alternative approach was adopted in the present work, based on the nature of the traffic data made available for the 2008/9 inventory. This provided flow data (for each of a number of vehicle categories) and speed data for each hour of a representative weekday and for each hour of the weekend (i.e. separate data for each of 72 hours, termed the ‘traffic’ hours). Thus emissions were calculated separately for each of the 72 traffic hours, and separate dispersion model runs were done for each of these representative hours, using only the appropriate subset of the full set of hours of the meteorological data. Thus, for example, for the 10 am weekday traffic hour, the model was run for the set of 10 am weekday hours in the

* A separate issue is that each road link in principle has its own temporal profile of total flow if there are several vehicle categories. However, ADMS-Airport has provision for up to 500 separate temporal profiles in a given model run. Also, the traffic profiles may not be very different from one link to another, so it may be possible to use a few representative profiles, which was the approach adopted by CERC in the PSDH work. The variation in emission profiles may be wider.

met data for the twelve-month period; for the 10 am Saturday traffic hour, the model was run for the set of 10 am Saturday hours in the twelve-month period. The results from the 72 runs were then combined externally, with appropriate weighting between weekday and weekend hours. Splitting the total hours in the year amongst 72 runs does not lead to a significant increase in overall run time (although there is some per-run overhead), and does give some computational advantages, in that the overall task can be run on several machines and the potential losses from set-up errors or computer failure are reduced.

5.1.6 One potential problem with running for subsets of the meteorological data is that the output of the met pre-processor for ADMS carries a memory from hour-to-hour in relation to boundary-layer depth in convective condition, in that it takes account of the build-up of the convective layer during the day as heat flux from the ground (in response to incoming solar radiation) 'burns off' the early morning inversion and pumps heat into the growing convective layer. The solution adopted was to carry out an initial run of the meteorological pre-processor separately, outputting the hourly processed parameters such as boundary-layer depth, which can then be fed back as input to the dispersion model run.

5.1.7 In terms of near-field dispersion for road vehicles, ADMS-Airport internally assigns an initial vertical depth of 1 m and a mid-height of 1 m to the emissions on each road link but, as discussed above, also includes an additional turbulence component that adds to the near-field dispersion of the emissions.

5.2 Other Airport-Related Emissions

5.2.1 Airside-vehicle/plant emissions and surface car park emissions were treated as volume sources with a depth of 3 m and a mid-height of 1.5 m. Multi-storey car parks were assigned the same parameters, which is a conservative assumption (i.e. tending to overestimate concentrations) given the likely vertical distribution of the emissions and the potential impact of building wakes. However, these car parks are generally far from off-airport receptors and the impact of the approximation is insignificant.

5.2.2 For heating plant emissions, the five largest sources (Cargo CHP, 448, T4, T5 and BA Maintenance) were treated as stack sources, taking account of nearby buildings, using the 'building-effects' module of ADMS-Airport. Initially, the stack efflux parameters were carried over from the PSDH work[18] (albeit ignoring differences between summer and winter modes of operation for 448 and T4), as shown in Table 5.1. In some instances, the efflux temperature and/or speed was adjusted downwards to ensure that the heat up the stack was no more than 20% of the total fuel energy input, to avoid the potential for overestimating plume rise (values shown in parentheses), given that only approximate stack efflux characterisation was possible in some cases. The emissions from smaller plant were assumed to be released into the wake of the associated building. The total contribution from heating plant emissions to period-mean NO_x concentrations at off-airport receptors is typically around 1 $\mu g/m^3$, so uncertainties in stack modelling have little impact on total off-airport concentrations.

5.3 LAEI Emissions

5.3.1 At the time of this assessment, the latest published version of the LAEI was for the year 2006[19], with projections to 2010. Emissions for 2008/9 were obtained by interpolation between 2006 and 2010 values, except for road vehicle emissions.

5.3.2 For source categories other than road vehicles, emissions are expected to vary slowly from year to year, so interpolation errors are expected to be small. However, for road vehicles there has been an enhanced evolution of the vehicle fleet in the London area in recent years, in response to initiatives such as the congestion charging scheme (CCS) and the London LEZ (low emission zone), which have phased developments. The LAEI 2010 forecasts are characterised as including the effects of the Western Extension of the CCS, an increase in the CCS fee from £5 to £8 and the inclusion of Scenario 2 of Phase 5 of the LEZ modelling. Thus, it was judged optimistic (tending to underestimate) to interpolate road vehicle emissions between 2006 and 2010, so 2006 values were used for 2008/9. This assumption ignores the influence of greater penetration of higher Euro-standard vehicles into the fleet by 2008/9, but the potential overestimation is accepted*.

5.3.3 It should be noted that the road-vehicle emissions in the LAEI 2006 inventory (and 2010 projections) were not calculated with the final version of the new emission factors and fleet projections (described in the 2008/9 Heathrow inventory report), which had not been released when the LAEI 2006 inventory was compiled.

5.3.4 The sources included in the LAEI are categorised as follows

- point sources
  - Part A processes
  - Part B processes
  - boiler plant
- mobile sources
  - road transport
  - rail
  - ship
  - airport/aircraft
    - Heathrow airport
    - smaller airports
- area sources
  - gas
  - coal
  - oil
  - agriculture-nature
  - sewage
  - solvents

5.3.5 However, for the purpose of calculating the concentration contribution around Heathrow from sources in the LAEI area, only three categories of source were treated separately:

(a) large point sources;
(b) the section of the Great Western railway line passing through the near-Heathrow area; and
(c) all other sources

The treatment of large point sources is discussed in Section 2.

5.3.6 The section of the Great Western railway line within the 11 km square near-Heathrow area was singled out for more detailed attention on the grounds that it is a source of relatively high emission density within the study area and it passes close to residential areas that also receive a significant contribution from road vehicle emissions. The emissions have been modelled as a ‘line’ source of 20 m width and 10 m depth. This is a simplified representation of near-field influences on the dispersion of the emissions - such as the impact of vehicle-induced turbulence and effect of the topography close to the railway line (cuttings and embankments) - so concentrations within about 100 m of the line are subject to uncertainty. The total emissions on this stretch of line within the 11 km area, interpolated from the LAEI 2006 inventory and 2010 projections, are given in Table 5.2.

5.3.7 To avoid double-counting, emissions from Heathrow airport in the LAEI were omitted from the modelled LAEI sources; similarly, road-vehicle emissions on major roads in the 11 km x 11 km road network area were also omitted, but emissions from minor roads were retained. The LAEI also contains non-road, non-airport emissions in the 1 km squares within the interior of the airport, which derive from the spatial disaggregation of emissions in categories such as off-road vehicle emissions and industrial combustion. These emissions were also omitted from the modelling of LAEI sources, having been already included in the airport

* Recent evidence suggests that the reduction in traffic-related NO_x concentrations due to penetration of lower-emission vehicles into the fleet has been lower than expected in the last few years.

inventory. The relevant 1 km squares are shown on Fig 5.1.

5.3.8 Sources in category (c) were treated as area sources at a 1 km spatial resolution. 'Mobile' sources held within the LAEI as line sources were 'lumped' in with area sources but, as noted above, road-vehicle emissions on major roads within, and close to, the study area are not taken from the LAEI but based on traffic modelling (and treated as line sources). Thus (major road) road-vehicle emissions taken from the LAEI are at least 1 km – and typically many km - from any receptor in the study area. The breakdown by source category of 2008/9 emissions in the LAEI area treated as 1 km area sources is shown in Table 5.3.

5.3.9 The spatial density (emissions per km^2 per year) of the LAEI area sources included in the modelling is shown at 1 km spatial resolution in Fig 5.1. It should be borne in mind that the emission density drops significantly within the 11 km square road network area because LAEI road vehicle emissions are omitted from this area, to be replaced by emissions based on Heathrow-specific traffic modelling (see 2008/9 inventory report).

5.3.10 The area sources within the 11 km square road-network area were assigned an initial vertical extent of 10 m. Other area sources from the LAEI, principally to the east of the road-network area, were assigned an initial vertical spread of 30 m, representing the larger average urban canopy depth in central London. However, sources outside the road-network area are more than 1 km from any receptor within the 9 km square study area where concentrations are calculated, so their contribution within this area is not sensitive to the precise value of initial depth chosen nor to the spatial smearing implicit in treatment at 1 km resolution.

5.3.11 The dispersion modelling also requires a temporal profile to be assigned to each source category. These profiles can generally be expressed in terms of an hour-of-day profile (considered constant over the year in relative terms) and a month-of-year profile, although more detailed hour-of-year profiles have been used for airport sources (see earlier). Past investigations have demonstrated that annual-mean concentrations are not sensitive to the fine details of temporal profiles provided broad features are represented (such as day/night differences). Of course the details of the profiles are more important if higher percentiles of the hourly distribution of concentrations are modelled directly..

5.3.12 For all LAEI sources, the month-of-year profile was taken to be flat. For hour-of-day variation, a profile was devised for the LAEI road traffic emissions based on traffic flow profiles given in the LAEI methodology report[20]. Typical profiles for cars and HGV were given equal weight in devising an emissions profile, given that both categories contribute appreciably to overall road-traffic emissions, and the resulting profile was simplified as in Fig 5.2. All transport emissions were assigned this simplified profile. All other emissions were assigned a flat hour-of-day profile.

5.3.13 For road vehicles, the LAEI gives emissions of NO_x, PM_{10} and $PM_{2.5}$, but for other source categories $PM_{2.5}$ emissions are not given. This gap was filled using ratios of UK $PM_{2.5}/PM_{10}$ emissions by source category, as given in the 2007 NAEI inventory[21], making a reasonable association between categories in the LAEI and those in the NAEI. The resulting $PM_{2.5}/PM_{10}$ ratios used for the LAEI source categories are shown in Table 5.4.

5.4 NAEI Emissions

5.4.1 The starting point for estimating the contribution from 2008/9 emissions in the 'NAEI area' (see Fig 2.1) was the 2007 NAEI inventory[21], the latest version of the inventory published at the time of this assessment*. It should be noted that road vehicle emissions for the 2007 inventory were quantified by the NAEI team using an interim set of emission factors, since the details of the revised set of factors and fleet composition projections were still being worked out at the time of its compilation. These factors were closer to the final released version (discussed in the 2008/9 Heathrow inventory report) than to the previous set of

* The 2008 inventory was published during the course of this assessment but too late to be used directly. However the reported UK total NO_x for 2008 was only 1% higher than the value for 2008/9 interpolated from 2007 and 2010 values.

factors, but a few subsequent revisions were incorporated into the final set.

5.4.2 Consideration was given to using information from the local authority inventory prepared for the borough of Slough, which lies close to the western edge of the study area; in principal, this may incorporate more local information than used in the NAEI. The latest available version of the Slough inventory at the time of the assessment was for the year 2005[22]. Although data in that inventory relating to commercial/residential combustion (and some minor source categories) came directly from the NAEI, emissions for industrial combustion and transport were calculated from Slough-specific information. However, the road traffic emissions were calculated using the older set of emission factors, and the traffic data (derived from a traffic model) are now several years out of date, so road-vehicle emissions in the 2007 NAEI were preferred. Of course, the road-vehicle emissions in the Slough inventory are distributed on the road network whereas the NAEI emissions are available at a 1 km spatial resolution, but for receptors in the Heathrow study area the additional spatial resolution in Slough is not critical.

5.4.3 For the large industrial combustion sources, the NAEI updates the emissions for individual major plant annually, so the 2007 NAEI has more recent information than in the Slough inventory. In conclusion, emissions from the Slough 2005 inventory were not substituted for those in the 2007 NAEI for any source category.

5.4.4 NO_x emissions for 2008/9 were obtained by linear interpolation between published 2007 NAEI values and projections for 2010. Projected 2010 UK NO_x totals have been published as part of the UK contribution to the National Emissions Ceiling Directive (NECD) status report[23]. This showed a 15.8% reduction in total UK NO_x emissions between 2007 and 2010. Assuming a constant rate of decrease, this was equivalent to a 6.6% drop between 2007 and the 2008/9 period of interest. An indicative sectoral breakdown of this reduction for major source categories (such as combustion in energy, industrial combustion, transport, other stationary sources) was derived from ancillary published information[24]. For a given source sector, the spatial distribution of the emissions at the 1 km level in 2008/9 was assumed the same as in the 2007 inventory.

5.4.5 For PM, no recently published national projections are available, but recent national inventories and previous forecasts indicate a much slower rate of decrease per year than for NO_x. Thus PM_{10} (and $PM_{2.5}$) emissions were taken to be the same in 2008/9 as in 2007. The spatial disaggregation at the 1 km level is published for PM_{10} only, so sectoral $PM_{2.5}/PM_{10}$ ratios are applied to generate a disaggregated $PM_{2.5}$ inventory.

5.4.6 From a modelling perspective, only two categories of NAEI source were distinguished: (a) large point sources and (b) all other sources. The criteria for choosing the point sources and the approach to modelling them has been discussed in Section 2. All other sources were treated as area sources at 1 km spatial resolution, including road vehicle sources. However, it should be borne in mind that road-vehicle emissions within the 11 km square road network area, as discussed above, were not taken from the NAEI but based on traffic modelling (and treated as line sources), so road-vehicle emissions from the NAEI are at least 1 km – and typically many km distant - from any receptor in the study area. The area sources in the NAEI sub-area were assigned an initial depth of 10 m.

5.4.7 The breakdown of 2008/9 emissions by source category for the NAEI sub-area marked on Fig 2.1 is shown in Table 5.5, and the spatial density (emissions per km^2 per year) of the total emissions at 1 km spatial resolution in shown in Fig 5.3. It is worth noting that the emissions per km on the sections of the Great Western line outside the 11 km square inner area are much lower in the NAEI than those from the LAEI in the 11 km square inner area (by around a factor of three). This is consistent with the discrepancy for rail emissions that was found previously in a comparison of the 2004 LAEI and NAEI inventories carried out by the NAEI team[25] and is the subject of ongoing investigation.

5.4.8 As with LAEI sources, the monthly profile of emissions was assumed uniform for all NAEI sources. The hour-of-day profile for transport sources was taken to be the same as for LAEI transport sources, and was assumed uniform for other sources.

6 Background Contribution

6.1 The contribution from all sources not modelled explicitly is taken from measurements at rural monitoring sites, using the AURN (Automatic Urban and Rural Network) sites Harwell (OS 446869,186004) for westerly wind directions (as given by Heathrow met data) and Rochester Stoke (OS 583155,176313) for easterly wind directions, as described in Section 2. Although in principle this provides a means of estimating the background contribution at an hourly time resolution, the methodology outlined above requires only the contribution to period-mean concentrations, which is less sensitive to differences in the wind field between the rural sites and Heathrow. The model evaluation[2] does make use of concentrations on an hourly basis, but only in the form of concentration differences between two sites that are close enough that the background contribution can be taken to be the same at the two sites.

6.2 Although both Harwell and Rochester Stoke are in rural environments, it is necessary to ensure that they are not significantly affected by major point sources in the region. Didcot power station is close to Harwell (7 km), but is NE of the site, so does not contribute there in westerly winds. Similarly, Kingsnorth power station is close to Rochester Stoke (4 km), but is SW of the site so does not contribute there in easterlies. Section 2 gives further information in relation to large point sources.

6.3 One potential limitation to using Rochester Stoke measurements to give the background contribution at Heathrow in easterlies is that there was a major outage of the NO_x instrument there from 15/01/09 to 19/03/09. It is recommended practice to fill such gaps with data from other suitable sites where possible, and data from the AURN site at Lullington Heath (OS 553826,101616) were used for this purpose. However, the annual mean NO_x concentration in easterlies at Lullington Heath is appreciably lower than at Rochester Stoke, so an adjustment was made: the average concentration in easterlies during the 'gap' period derived from monitoring data at Lullington Heath was scaled up by the ratio of the average concentration in easterlies at Rochester Stoke for the whole 2008/9 period (excluding the gap) to the equivalent concentration for Lullington Heath (a ratio of 1.63).

6.4 The total annual mean NO_x background concentration contribution at Heathrow for the 2008/9 period worked out by this methodology was 14.3 $\mu g/m^3$, also shown in Table 6.1.

6.5 Similarly, the PM_{10} and $PM_{2.5}$ background contributions at Heathrow were derived from measured concentrations at Harwell (for westerly winds) and Rochester Stoke (for easterlies). Data capture at the two sites was good for both pollutants, so there was no need for any gap-filling procedure. The instruments at both sites are of the TEOM (Tapered Element Oscillating Microbalance) type, and the PM_{10} concentrations in the national air quality archive[26] are reported as gravimetric equivalent, using a scaling factor of 1.3. However, it is now recommended that TEOM PM_{10} concentrations are corrected using the Volatile Correction Model[27] where possible, so this correction method was applied to the PM_{10} concentrations at Harwell and Rochester Stoke. Table 6.1 shows the uncorrected (without the factor of 1.3) and VCM-corrected contributions to the annual-mean background.

6.6 There is no recommended correction factor for TEOM $PM_{2.5}$ measurements; the uncorrected[*] background contribution derived from Harwell and Rochester Stoke measurements is given in Table 6.1. Equivalence with the EU reference method for $PM_{2.5}$ has not been shown for the standard TEOM instrument. It was considered preferable, therefore, to derive the $PM_{2.5}$ background contribution on the VCM-corrected PM_{10} contribution, using typical $PM_{2.5}/PM_{10}$ ratios for 'background' (i.e. non-roadside) sites derived from gravimetric measurements, which are not highly variable from one site to another. The AQEG report on particles[28] quotes linear regression relationships between annual mean $PM_{2.5}$ and PM_{10} concentrations for four (urban) background sites, and the average of the four concentrations derived from applying each relationship to the VCM-corrected background PM_{10} concentrations at Heathrow was taken as the $PM_{2.5}$ background. By coincidence, the value derived by this

[*] The instruments are conventionally set up with an (US) EPA default adjustment protocol (TEOM reading*1.03 + 3 $\mu g/m^3$).

procedure is very close to that given by $PM_{2.5}$ TEOM measurements.

7 NO_x to NO_2 Relationships

7.1 Introduction

7.1.1 The oxides of nitrogen emitted from combustion sources are principally in the form of NO, with a relatively small percentage of NO_2 (termed 'direct' or 'primary' NO_2) for most sources, whereas the key pollutant of interest from the viewpoint of human health is NO_2. After release, further NO_2 is formed in the atmosphere by transformation of NO, principally as a result of the reaction with ambient ozone. In the reaction with ozone, the total (molecular) quantity of NO_x is preserved, so it is convenient to address the question of what fraction of NO_x is in the form of NO_2 separately from the question of how much NO_x is released. Thus, the 2008/9 emissions inventory[1] gives NO_x emissions (with the convention that molecular concentrations are converted to mass units as if all the NO_x were NO_2), whereas the fraction of NO_x released directly as NO_2 is considered in the following section.

7.1.2 The modelling process described above directly yields annual mean NO_x concentrations, whereas, as noted above, the key air quality metric of interest from a human health viewpoint is annual mean NO_2 concentration. It has become common practice to derive annual mean NO_2 concentrations from annual mean NO_x concentrations using non-linear empirical or semi-empirical relationships based on UK national monitoring data. This technique avoids having to include directly in the modelling the non-linear gas-phase chemistry representing inter-conversion between NO and NO_2. On the other hand, there is some scatter about the fitted empirical relationships, which translates into an uncertainty in the derived concentrations at a particular location.

7.1.3 One possible approach is to use a purely empirical relationship derived from UK monitoring data, as described in the AQEG (Air Quality Expert Group) report on NO_2[29]: this was the approach used in the original 2002 modelling study for Heathrow[30]. However, being based on historical monitoring data, this does not have the flexibility to allow investigations of the potential future changes in NO_2/NO_x ratios in response to potential changes in background ozone (O_3) levels and/or primary NO_2 fractions*.

7.1.4 An alternative approach, also described in the AQEG report, is based on the work of Clapp and Jenkin[31] and further developed by Jenkin[32],[33], which explicitly recognises the chemical coupling between NO, NO_2 and O_3 in the atmosphere, and does allow moderate changes in background ozone level and primary NO_2 fraction to be taken into account. This type of approach to the NO_2-to-NO_x relationship has been adopted in the national PCM modelling in recent years.

7.1.5 Under the majority of atmospheric conditions, the dominant pathway by which NO is converted to NO_2 is via the reaction with O_3, i.e.

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{1}$$

During daylight hours, NO_2 is converted back to NO as a result of photolysis, which also leads to the regeneration of O_3:

$$\begin{aligned} NO_2 + sunlight &\rightarrow NO + O \\ O + O_2(+M) &\rightarrow O_3(+M) \end{aligned} \tag{2}$$

where *M* is a third body, most commonly N_2. It is because NO and NO_2 are highly coupled in this way that it is convenient to refer to them collectively as NO_x.

* Primary NO_2 fraction is the fraction of NO_x that is emitted as NO_2 rather than NO. Traditionally this has been set at around 5% for combustion sources, but there is now clear evidence that much higher values are appropriate to some sources, such as modern diesel road cars, vehicles fitted with certain types of exhaust after-treatment and taxiing aircraft.

7.1.6 The approach (termed the ‘Jenkin approach’ below for convenience) is centred around two relationships, first the relationship between total oxidant concentration [OX] (which is the sum of O_3 and NO_2 concentrations) and the NO_x concentration and, secondly, the relationship between the fraction of [OX] that is NO_2 and the NO_x concentration. Based on these two relationships, NO_2/NO_x ratios can be derived.

7.1.7 The approach will be summarised below. (All concentrations referred to in this section are annual mean values in ppb.)

7.1.8 It should be noted that the Jenkin approach is an alternative to using the ‘chemistry’ module within ADMS-Airport, which was the approach used in the PSDH work. The Jenkin approach is a post-processing step after total annual mean NO_x (and primary NO_2) concentrations have been calculated, so brings computational flexibility to the overall calculation, whereas the use of the chemistry module requires all NO_x sources to be included in the same ADMS-Airport run. The accuracy of the approach adopted here is discussed in the 2008/9 model evaluation report.

7.2 Summary of Approach

Total Oxidant

7.2.1 The first relationship is expressed as

$$[OX] = A\,[NO_x] + B \tag{3}$$

where $[OX]$ is the total oxidant concentration (i.e. $[NO_2]+[O_3]$), $[NO_x]$ is the NO_x concentration, and A and B are constants. B is identified as the regional background oxidant* level and A as the contribution to oxidant generated by sources of NO_x, considered to be principally the primary NO_2 fraction of the NO_x emissions†.

7.2.2 The parameter A varies from site to site as the nature of the dominant sources varies, and can be derived for an individual site if simultaneous measurements of O_3, NO and NO_2 concentrations are available.

7.2.3 Assuming that the (oxidant-preserving) reactions (1) and (2) are dominant, the effective value of A at any given receptor can be obtained as a weighted average of primary NO_2 fractions for the various source types contributing to total NO_x concentrations at the receptor, with the weighting factor given by the relative contribution to total NO_x concentration. Thus, the effective value of A at a particular point p is given by:

$$A(p) = \frac{\sum_i (fNO_2)_i \;([NO_x](p))_i}{[NO_x](p)} \tag{4}$$

where $(fNO_2)_i$ is the primary NO_2 fraction for source i and $([NO_x](p))_i$ is the contribution from source i to the total NO_x concentration $[NO_x](p)$. The values of $(fNO_2)_i$ used for the Heathrow 2008/9 modelling study are discussed later. $A(p)[NO_x](p)$ can be identified as the total concentration of primary NO_2 at p, treated as if it were a conserved pollutant.

Oxidant Partitioning

7.2.4 The second key relationship of the approach gives the fraction of total oxidant that is in the form of NO_2, as a function of NO_x concentration, i.e.

* Also, it can be viewed as the regional ozone concentration in the limit of insignificant NO_x concentration.
† Although Jenkin terms this the ‘local’ contribution to oxidant, it should be noted that the *total* NO_x concentration appears, which includes a contribution from distant sources.

$$[NO_2]/[OX] = f([NO_x]) \quad (5)$$

in which case,

$$[NO_2] = g([NO_x]) \text{ where } g([NO_x]) = (A[NO_x] + B) f([NO_x]) \quad (6)$$

7.2.5 In the original version of the Jenkin approach, two forms of $f(NO_x)$ were given, one for near-road receptors and one for background receptors, with the forms derived from monitoring data at a large number of UK sites. In shape, the curves echo the theoretical relationship between $[NO_2]/[OX]$ and $[NO_x]$ for the photo-stationary state in average daylight conditions, i.e. the relationship resulting from equilibrium in the reactions (1) and (2). However, the idealised relationship does not apply for the following reasons:

(a) Even if equilibrium is established in a particular set of weather conditions, the idealised form of the relationship will not apply to the annual mean concentration because the relationship is non-linear and concentrations vary from hour to hour.
(b) For receptors close to major sources, equilibrium may not be reached in the time it takes pollutant to reach the receptor. The relevant time constant depends on the instantaneous concentrations of NO, NO_2 and O_3 and on the light intensity.

7.2.6 In the more recent work[33], Jenkin attributes the departure from the idealised relationship principally to the variability in hourly concentrations of NO_x. Thus sites are categorised according to the inter-quartile ratio for the distribution of hourly NO_x values in the year (i.e. the ratio of the 75th percentile of hourly concentrations to the 25th percentile of hourly concentrations). Sites with higher value of the ratio (i.e. showing greater variability) give lower values of the $[NO_2]/[OX]$ ratio for a given $[NO_x]$ concentration (where all concentrations are annual mean values). Empirical curves of $[NO_2]/[OX]$ versus $[NO_x]$ for each site category are then derived from national monitoring data (75 urban and 13 rural sites) collected over a number of years up to 2006, with the relationships expressed as a 6th order polynomial. The category boundaries and the coefficients of the polynomials are given in Table 7.1.

7.2.7 In this refinement of the methodology, roadside sites are not separated out explicitly – as they were in the original version – but are assigned to categories purely on the basis of their inter-quartile ratio. Generally, sites close to major sources tend to yield larger inter-quartile ratios, but in fact each of the categories contains a mixture of site types.

7.2.8 This revision of the methodology has now been assimilated into the national Pollution Climate Mapping work by making an association between receptor location and Jenkin inter-quartile category.

7.2.9 The inter-quartile ratios (IQRs) for the continuous NO_x/NO_2 sites operating close to the airport in the 2008/9 period are shown in Table 7.2*. The sites are marked on Fig 7.1, which also gives the shortened form of the site name used in the 2008/9 model-evaluation report. Generally, the IQR ratios are in the range 2.5 to 3.5, which would put them in Category II, the category containing the majority of sites (both near road and background) in Jenkin's analysis. Oaks Rd has the largest IQR (4.8), even though it is not close to a busy road, which can be attributed to its proximity to the airport boundary: the site receives a significant contribution from on-airport sources in northerly winds but not in southerly winds. A similar effect can be observed at Hatton Cross which, according to the modelling, has a significant contribution from on-airport sources in westerly winds (although in this case there is also a modest contribution from the A30). Although their IQR values would put them in Jenkin Category III (>3.5), indicating a lower NO_2/NO_x ratio than for Category II, it is not clear that this reduction would apply when the variability arises from an airport contribution rather than from a nearby road: some of the reduction in NO_2/NO_x ratios observed in the set of data used by Jenkin may have resulted from the limited amount of time between source and receptor for near-road sites, whereas Heathrow Oaks Rd is many hundreds of metres away from the dominant on-airport sources. Thus measured NO_2/NO_x ratios at Oaks Rd and

* A more detailed characterisation of the NO_x and NO_2 data sets is given in the 2008/9 model evaluation report.

Hatton Cross will be compared with calculated values based on both Jenkin Category II and Category III relationships.

7.2.10 The Hayes and Oxford Avenue sites have IQR values within the Category II range despite having a significant contribution from the nearest road, and the value for the Hillingdon site (3.63) is only just above the range. This is consistent with the implementation of the Jenkin formulation within the national PCM modelling, which assigns a Jenkin category to near-road sites on the basis of land area type (see Table 7.3). For the London Borough of Hillingdon, the assignment would be Category II. In the context of generating annual mean NO_2 concentrations from modelled annual-mean NO_x concentrations over a grid of receptors, the data suggest that at distances from major roads where exceedences might arise (and at greater distances) it is appropriate to use the Category II relationship in the Heathrow area. The polynomial functions giving the $[NO_2]/[OX]$ ratio for Category II and Category III are shown in Fig 7.2.

7.2.11 The Colnbrook site looks anomalous in terms of its IQR value (4.6), given that the site does not receive a major NO_x contribution from either the airport or nearby roads according to the modelling (as confirmed by the measured total period-mean NO_x concentration at the site). This is taken as a manifestation of components of variability in IQR ratios not captured by the Jenkin analysis, and the Category II relationship is still judged to be appropriate. Nevertheless, calculated NO_2/NO_x ratios using both Category II and Category III relationships are compared with the measured ratio in the 2008/9 model evaluation report.

Variation in *A* and *B*

7.2.12 The Jenkin approach offers - via the coefficients *A* and *B* in (3) - the possibility of examining the influence on the NO_2/NO_x relationship of potential future increases in regional background oxidant levels and in primary NO_2 fractions. It should be noted, however, that this use of the method relies on an assumption that the $[NO_2]/[OX]$ versus $[NO_x]$ curves themselves do not vary with *A* or *B*, whereas in fact a degree of 'buffering' is expected, with a change in $[NO_2]/[OX]$ versus $[NO_x]$ curve partly offsetting the impact of an increase in *B* or *A*. Jenkin[34] recognised this potential for buffering, but judged that ignoring would be an acceptable approximation provided *A* and *B* were not taken too far beyond the range spanned by the original data set, suggesting a limit on *A* of about 0.25 and a limit on *B* of around 40 ppb.

7.2.13 Early implementations of the approach in an airport air quality context (e.g. for the Stansted G1 project[35]) used the original estimates of *B* extracted by Jenkin from analysis of monitoring data up to 2001[32], which were given separately for four regions of the country, taking account of observed trends in background ozone levels to forecast NO_2/NO_x ratios for future years. Recently Jenkin has analysed data from 2001 to 2006[33] from Harwell, Lullington Heath and Rochester Stoke to give an indication of the recent inter-annual variability in the extracted value of *B* and to investigate recent trends. This analysis shows that the year-to-year variability in *B* is larger than any observable trend. The analysis also identifies a gradient in the value of B across the country, as the balance between photochemical generation and surface deposition of oxidant varies from region to region.

7.2.14 The insights gained from this type of analysis have been Jenkin to develop a methodology for generating annual maps of *B* for the UK at 100 km scale*, for use in the annual Pollution Climate Mapping exercise that generates national maps of background (and roadside) NO_2 concentration (as described, for example, for the 2007 version[11]). The map for 2008 is awaiting publication, but advance information[36] indicates that an appropriate value for Heathrow (which sits near the junction of three 100 km region) based on the map is around 34.8 ppb. A subsequent evaluation[36] of the methodology used to generate the maps, by comparison with monitoring data, suggests that the 2008 map may be overestimating in the region around Heathrow on average by around 1.3 ppb.

7.2.15 Thus, the value of *B* adopted for the 2008/9 assessment was 33.5 ppb, accepting the approximation of using 2008 values for the 2008/9 period. A local test of the methodology for

* Soon to become 10 km scale (Jenkin, personal communication)

predicting total oxidant concentrations is included in the 2008/9 model evaluation report.

Testing of the Jenkin Approach

7.2.16 Versions of the semi-empirical Jenkin approach have been tested in earlier airport studies using continuous monitoring data from sites close to Heathrow Airport[12]. The approach was found to give a similar level of agreement in NO_2/NO_x ratios to that of previous purely empirical approaches, whilst offering the added flexibility to account (approximately) for potential future increases in background ozone levels and primary NO_2 fractions. In addition, a local test of the model has been carried out as part of the Heathrow 2008/9 model evaluation exercise.

7.3 Primary NO_2 Ratios

7.3.1 As noted above, an effective value of *A* at a given location can be estimated from information on the primary NO_2 fraction for each source contributing to the total NO_x concentration at the location. The following section summarises the information available for the principal sources contributing to NO_x concentrations around Heathrow.

Aircraft

7.3.2 For the PSDH, a team at Sheffield University carried out detailed modelling of the gas-phase kinetics occurring within representative aircraft engines spanning the range of overall pressure ratios (OPRs) found in modern aircraft fleets. This work yielded ranges of values for the primary NO_2 fraction for each of the ICAO reference modes, as shown in Table 7.4. For implementation, a mean value was selected by the PSDH, also shown in the table. The modelled fractions at low thrust are significantly larger than the fractions at higher thrust, partly because of the role of hydrocarbons from the incomplete combustion of the fuel in generating NO_2 from NO in the exhaust stream. The low-thrust values are also considerably higher than the conventional assumption of around 5% primary NO_2 from combustion processes.

7.3.3 In the Sheffield modelling, the value of fNO_2 varied with engine OPR (Overall Pressure Ratio) – with higher values at lower OPR - and the ranges given in Table 7.4 reflected the range of values found for the range of OPR in a typical modern fleet. Nevertheless, recognising the uncertainty in the modelling, the PSDH chose the mid-point of the fNO_2 range as a typical or representative value for the fleet rather than as a rigorous weighted-average over the OPR distribution in the LHR fleet. The OPR values in the current fleet at Heathrow span much the same range as in the PSDH work, so it is appropriate to apply the same representative values.

7.3.4 The value given for the ‘idle’ mode is associated with the 7% ICAO reference thrust. However, the same chapter of the PSDH report advocates using taxiing flow rates lower than those at 7%, recognising that aircraft generally taxi at a thrust setting lower than 7%. In principal, the lower thrust setting could influence the value of fNO_2 (more likely to increase it than decrease it) but the relevant information is not available. Given that the PSDH did not advocate any modification of the representative ‘idle’ value to account for lower taxiing thrust, no adjustment to fNO_2 was made for the present study.

7.3.5 Each LTO flight phase recognised in the emissions calculation in Section 2 was assigned an fNO_2 value based on Table 7.4. Take-off and initial climb at reduced thrust were assigned the ‘85% thrust’ value from the table. Although, there is a range of thrust settings used in practice, a more detailed calculation is judged unnecessary, in view of the uncertainties noted above. The lower segment of approach was assigned the ‘30% thrust’ value. Taxiing, hold and landing emissions were assigned the ‘7% thrust’ value, as discussed earlier.

7.3.6 There are no data on primary NO_2 fractions for APUs nor does the PSDH make any specific recommendations. Given that the increase in fNO_2 for main engines at low thrust is associated with the increase in hydrocarbons generated by incomplete combustion, an appropriate value of fNO_2 for APUs was judged from a comparison of the typical cycle-average HC emission index for APUs and that for main engines at various thrust settings. Although there is much variability, typically APU HC emission indices are closer to main engine indices for the 30% thrust setting, so the '30% thrust' value of fNO_2 from Table 7.4 was applied (fNO_2=15%).

7.3.7 For engine testing, a significant fraction of the emissions is expected to derive from low-thrust operation. Thus, the '7% thrust' value in Table 7.4 was applied to all the NO_x emissions. Engine testing emissions are a minor source of NO_x so the potential overestimation in using this value is insignificant.

Landside Road Vehicles

7.3.8 There is evidence from many continuous NO/NO_2 monitors in urban areas, particularly in London, that the average value of fNO_2 associated with road traffic emissions has been increasing significantly over the last few years. This is consistent with vehicle emission measurements, which indicate that fNO_2 for some recent vehicle categories (such as Euro III diesel cars) is significantly higher than for older categories (and considerably higher than the traditional 5% value that used to be applied to combustion processes).

7.3.9 This issue was investigated by AQEG[37], leading to estimates of fNO_2 for individual vehicle categories. The latest national set of emission factors released by the DfT in 2009 and labelled TRL2009 in the 2008/9 emission inventory report, includes estimates of fNO_2 as a function of vehicle type and Euro standard. This set of values has been extended by the NAEI team[38] include a few additional categories that are recognised separately in the national fleet projections but not included in the TRL2009 data (such as Euro 3 and Euro 4 diesel cars with diesel particulate filters). The full set of values is shown in Table 7.5

7.3.10 Traffic flows used in the emissions inventory were provided separately for cars, LGVs, HGVs and buses/coaches. To enable composite fNO_2 values to be derived for the main vehicle categories, the vehicle-km breakdown by sub-category (including Euro standard) within each category was taken from national statistics, using published fleet composition projections from the NAEI, as discussed in the 2008/9 emission inventory report.

Airside Vehicles

7.3.11 The authors of the NAEI review of primary NO_2 emission[39] factors for various sources were not able to find any specific information on fNO_2 for off-road vehicles and mobile plant. Since these sources operate with compression ignition internal combustion engines running on diesel fuel, usually without any advanced exhaust after-treatment systems fitted, it was assumed that values of fNO_2 for such sources are similar to those for older pre-Euro III diesel engines on HGVs and buses. Thus, it was recommended that fNO_2 be taken as 0.15. Accordingly, for the 2008/9 assessment, this value was applied to all the specialist-vehicles categories in the airside-vehicle methodology described in Section 2.

7.3.12 For road vehicles, the fNO_2 factors discussed in the previous section were applied, given that identification of vehicle category, fuel type and Euro standard is intrinsic to the emissions methodology described in Section 2. There is additional uncertainty relating to the fraction of the vehicles retrofitted with exhaust after-treatment but, in the absence of specific information, the forecast national averages provided by the NAEI were applied.

Other

7.3.13 For heating plant, the default value for fNO_2 of 5% was retained.

7.3.14 For car parking sources, the values discussed above for road vehicles were applied, assuming that the vehicle-km breakdown by Euro standard is the same as in the national fleet. The additional distance travelled within car parks is at low speed, but the values in Table 7.5 are appropriate for typical urban speeds, so are reasonably appropriate. It is not clear what is an appropriate value of fNO_2 for cold-start NO_x emissions. Clearly, some types of exhaust after-treatment may be working inefficiently when cold, but in some instances this may lower the value of fNO_2. On the other hand, poor combustion will increase the concentration of hydrocarbons in the exhaust which may increase fNO_2. In the absence of any specific information, the values in Table 7.5 were applied, but the uncertainties are noted. Additional car parking emissions, however, are a small contributor to total ground-level NO_x emissions.

7.3.15 The LAEI includes an inventory of primary NO_2 for road vehicles on an equal footing with that for other pollutants, with the effective fNO_2 varying from 1 km square to another as the traffic composition varies. On average, the fNO_2 value over the LAEI area was 18.5%. For other airports in the area, the average fNO_2 value for ground-level aircraft emissions from the 2008/9 Heathrow emission inventory (21%) was applied. For rail and shipping sources, a value of 15% was applied, based on factors used in the NAEI[39]. For other LAEI sources (point sources and area sources), a value of 5% was used, as in the NAEI.

7.3.16 The NAEI provides an average fNO_2 value for road-vehicle emissions worked out for a national fleet composition, using vehicle-specific fNO_2 factors as discussed above for emissions on the near-Heathrow road network. The value for 2008 (17.2%) was used for the 2008/9 modelling. For rail and shipping, the NAEI uses a value of 15%, as noted earlier, and for other sources a value of 5%.

7.3.17 An appropriate value for the NO_x contribution from 'distant' sources is more difficult to assign, given the mix of sources involved. In Jenkin's work, the regional background oxidant level was estimated from the least polluted site in the region by assuming that 10% of the NO_x at that site was primary NO_2. Correspondingly, for the current study it was assumed that an fNO_2 value of this order was associated with the contribution to NO_x concentrations from distant sources. However, given that the 10% figure tallied with measurements made up to 2001, it was assumed that the value would grow by 0.5% per year, based on the predicted growth in the effective fNO_2 from traffic sources given in the AQEG report and bearing in mind that many of the distant sources excluding point sources are traffic-related. Thus, for 2008/9 the 10% value was increased to 14%.

7.3.18 Table 7.7 summarises the fNO_2 values used for the Heathrow 2008/9 modelling study.

8 Short-Period Concentrations

Hourly-Mean NO_2

8.1 As noted in Appendix 1, there is an AQS objective (and EU equivalent limit) that the hourly-average NO_2 concentrations should not exceed 200 $\mu g/m^3$ on more than 18 occasions in a calendar year. For receptor locations at which both the annual-mean and short-period objectives apply, the former is usually more onerous. However, the short-period objective applies at more location types, including locations where people are regularly exposed for short but not long periods.

8.2 Given that dispersion models are less reliable at predicting short-term peaks than annual means, the technical guidance for local authority air quality review and assessment[15] suggests an approach that specifies an annual mean NO_2 concentration below which the probability of more than 18 hourly exceedences of 200 $\mu g/m^3$ is acceptably low. The surrogate annual mean value is currently set at 60 $\mu g/m^3$ on the basis of monitoring data from the UK national networks. This approach has been adopted in the present work for locations in the study area, if any, where a comparison against the short-period objective is considered appropriate. A local test of the approach is described in the 2008/9 model evaluation report.

24-Hour Mean PM_{10}

8.3 The AQS objective (and EU limit) on the number of times in a year that the 24-hour mean concentration exceeds 50 $\mu g/m^3$ (not more than 35, see Appendix 1) is generally more stringent than the objective/limit on the annual mean. Dispersion models are inherently less accurate at predicting the number of exceedences of the 24-hour mean PM_{10} objective than the annual mean concentration, so the technical guidance for local authority air quality review and assessment[15] suggests the following relationship between the number of occasions in a year that the 24-hour mean concentration exceeds 50 $\mu g/m^3$ and the annual mean concentration.

$$\text{No. 24-hour mean exceedences} = -18.5 + 0.00145 \times \text{annual mean}^3 + (206/\text{annual mean})$$

Although this relationship was based on monitoring data obtained from TEOM instruments (using the interim adjustment factor of 1.3), it is assumed that it is also adequate when using a reference-equivalent measurement technique. The 2008/9 model-evaluation report includes a local test of the relationship using VCM-corrected data. For 35 exceedences, the equivalent annual mean is 31.5 $\mu g/m^3$.

8.4 This relationship has been used in the present work to estimate the number of 24-hour mean exceedences from the annual mean PM_{10} concentrations calculated using the methodology detailed in this report.

9 References

[1] Underwood B Y, Walker C T and Peirce M J (2010) Heathrow Airport emission inventory 2008/9. AEAT/ENV/R/2906 Issue 1.

[2] Underwood B Y, Walker C T and Peirce M J (2010) Heathrow Airport air quality modelling for 2008/9: results and model evaluation. AEAT/ENV/R/2948 Issue 1.

[3] GLA (2009) 'Clearing the Air': The Mayor's draft Air Quality Strategy for consultation with the London Assembly and functional bodies. ISBN 978 1 84781 297 1.

[4] DfT (2003) The Future of Air Transport. Cm 6046. The air quality condition is stated in para 11.62.

[5] DfT (2007) Adding Capacity at Heathrow. Consultation Document.

[6] DfT (2009) Britain's Transport Infrastructure. Adding Capacity at Heathrow: Decisions Following Consultation.

[7] DfT (2006) Project for the Sustainable Development of Heathrow: Report of the Airport Air Quality Technical Panels.

[8] CERC (2008) ADMS-Airport User Guide. An outline description of the code is given on the CERC website www.cerc.co.uk.

[9] Defra (2007) The Air Quality Strategy for England, Scotland, Wales and Northern Ireland. Cm 7169 NIA 61/06-07.

[10] HMSO (2007) The Air Quality Standards Regulations 2007, Statutory Instrument 2007 No. 64.

[11] Grice S et al (2009) UK air quality modelling for annual reporting 2007 on ambient air quality assessment under Council Directives 96/62/EC, 1999/30/EC and 2000/69/EC. AEAT/ENV/R/2656 Issue 1

[12] Underwood B Y, Walker C T and Peirce M J (2005) Stansted air quality modelling beyond 25 mppa: modelling test. AEAT/ENV/R/1879/Issue 1. CD/189

[13] www.environment-agency.gov.uk

[14] Carruthers D, Blair J and Johnson K (2003) Validation and sensitivity study of ADMS-Urban for London. FM489/R5/03.

[15] Defra (2009) Part IV of the Environment Act 1995.Local air quality management. Technical guidance. LAQM.TG(09)

[16] ICAO Engine Exhaust Data Bank, Issue 16 (5th Feb 2009), available on the CAA website (www.caa.co.uk).

[17] McHugh C, Williams M, Price C and Lad C (2007) Air quality studies for Heathrow: base case, segregated mode, mixed mode and third runway scenarios modelled using ADMS-Airport. FM699/R23_Final/07.

[18] Underwood B Y (2007) Emissions methodology for future LHR scenarios. AEAT/ENV/R/2323 Final. Available as one of the technical documents supporting the 'Adding Capacity at Heathrow' consultation.

[19] LAEI (2006) London Atmospheric Emissions Inventory 2006. Compiled by AEA on behalf of the Greater London Authority.

[20] GLC (2009) London Atmospheric Emissions Inventory 2006: Emissions Estimation Methodology Manual. Supplied by the LAEI Project Team (AEA).

[21] Murrells *et al.* (2009), UK Emissions of Air Pollutants 1970-2007. AEA, Harwell, Oxfordshire.

[22] Davison E, Lelland A and Peace H (2007) Slough emissions inventory 2005 update. AEAT/ENV/R/48579.

[23] EEA (2009) NEC Directive status report 2008. European Environment Agency Technical Report 11/2009

[24] Wagner A and Watterson J (2009) Overview of the air quality and non-CO_2 projections. NAEI Stakeholder Day Presentations 2009. www.airquality.co.uk.

[25] Tony Bush (NAEI) personal communication.

[26] www.airquality.co.uk

[27] www.volatile-correction-model.info

[28] AQEG(2005) Particulate matter in the United Kingdom. www.defra.gov.uk/environment/quality/air/airquality/publications/particulate-matter

[29] AQEG (2005) Nitrogen dioxide in the United Kingdom. (A report prepared for **defra**)

[30] Underwood B Y, Walker C T and Peirce M J (2004) Air quality modelling for Heathrow Airport 2002. AEAT/ENV/R/1694/Issue 1.

[31] Clapp L J and Jenkin M E (2001) Analysis of the relationship between ambient levels of O_3, NO_2 and NO as a function of NO_x in the UK. Atmospheric Environment 35, 6391-6405.

[32] Jenkin M E (2004) Analysis of sources and partitioning of oxidant in the UK – Part 1: the NO_x-dependence of annual mean concentrations of nitrogen dioxide and ozone.

[33] Murrells T et al. (2008) Modelling of tropospheric ozone. First annual report. AEAT/ENV/R/2567.

[34] Jenkin M E (2005) Personal communication.

[35] Underwood B Y, Walker C T and Peirce M J (2006) Stansted Air Quality Beyond 25mppa: Methodology. AEAT/ENV/R/2055/Issue 1.

[36] Jenkin (2009) Personal communication.

[37] AQEG (2006) Trends in primary nitrogen dioxide in the UK. http://www.defra.gov.uk/environment/airquality

[38] Murrells T (2010) Personal communication.

[39] Murrells T, Passant N, Brophy N and Watterson J (2007) Emissions of nitrogen dioxide and nitrous acid from road transport and other sources. AEAT/ENV/R/2434 Issue 1.

Table 3.1 Characteristics of the Heathrow met data for the 2008/9 period

Parameter	Value
Data capture	97%
No. calm hours	11
Mean wind speed	4.08 m/s
Mean temperature	10.9°C

Table 4.1 Coefficients in the relationships between exhaust velocity or temperature and BPR (taken from ADMS-Airport User Guide[8])

Aircraft mode	Thrust setting	m_V	c_V	m_T	c_T
Take-off	100%	-25.27	485	-8.86	141
Initial climb	85%	-22.65	446	-8.17	133
Landing	30%	-12.44	260	-4.98	95
Taxiing	7%	-5.52	117	-4.1	77

Table 4.2 MCATs used for ADMS-Airport representation of Heathrow 2008/9 aircraft emissions

MCAT	Principal aircraft types	B range (m^4s^{-3})	$\%NO_x$[a]	Representative Aircraft type	Representative Engine	V_p (m/s)	T_p (°C)	D_p (m)	B (m^4s^{-3})	VR (m/s)
High thrust[b]										
1	A319, other[c]	<180	5.6	A319-100	IAE V2522-A5	335.5	93.1	1.01	179.9	77.2
2	B737, A320, A321	180-270	16.5	A320	IAE V2527-A5	258.9	78.3	1.34	204.6	77.2
3	B757	270-350	4.5	B757-200	RR RB211-535E4	353.1	99.5	1.27	317.1	77.2
4	B767, A300, A310, A340-300, A380	350-520	16.7	B767-300	RR RB211-524H	350.4	94.3	1.56	450.1	77.2
5	B777-200	520-630	8.3	B777-200	GE GE90-85B	255.7	64.4	2.50	574.3	77.2
6	B777-200(ER); B777-300	630-740	18.9	B777-200(ER)	RR Trent 895	316.9	86.4	2.13	700.6	77.2
7	B747, A340-600	>740	29.6	B747-400	RR RB211-524G	350.4	94.3	2.13[d]	861.3	79.7
Approach	All	All	-	A319-100	IAE V2522-A5	199.3	70.7	0.98	76.2	-
Low thrust[e]	All	All	-	A319-100	IAE V2522-A5	90.1	57.0	1.03	29.7	-

[a] Fraction of NO_x in the MCAT, shown only for take-off
[b] Used for take-off and initial climb
[c] ‘Other’ includes small aircraft types and types not readily categorised but accounting for a small fraction of the emissions
[d] Effective diameter taking into account that plumes from 4 engines are merged into 2 in the ADMS-Airport modelling
[e] Used for taxiing, hold and landing roll

Table 5.1 Stack efflux parameters

Plant	Stack height (m)	Stack diameter (m)	Efflux velocity[a] (m/s)	Efflux temperature[a] (°C)
Cargo CHP	30.3	2.40	31.2 (15.0)	280 (200)
448	29.0	2.57	6.4 (3.0)	210
T4	30.5	1.30	4.6 (2.0)	191
T5	25.0	0.50	5.1	80
BA Maintenance	19.8	0.50	48.0	181

[a] Adjusted values shown in brackets

Table 5.2 Emissions for 2008/9 on the section of the Great Western railway line passing through the 11 km square near-Heathrow area

Pollutant	Emissions (t/year)
NO_x	621
PM_{10}	18
$PM_{2.5}$	14

Table 5.3 2008/9 emissions within the LAEI inventory area treated as 1 km area sources in the 2008/9 dispersion modelling study

LAEI source category		Emissions (t/year)		
		NO_x	PM_{10}	$PM_{2.5}$
Point [a]		3,152	302	201
Mobile	Major roads[b]	32,245	1,957	1,457
	Minor roads	2,248	216	151
	Cold starts	388	123	110
	Ship and rail[c]	2,181	60	46
	Airports[d]	124	6	5
Area[e]		19,171	338	162
Total		59,509	3,003	2,133

[a] Excludes 'large' point sources modelled individually
[b] Excludes emissions in 11 km near-Heathrow road network area
[c] Excludes emissions on section of Great Western rail line passing through 11 km area
[d] Excludes Heathrow
[e] This is the 'area' source category as defined in the LAEI, which includes emissions from gas, coal, oil, agriculture-nature, sewage and solvent

Table 5.4 $PM_{2.5}$/PM_{10} ratios for (non-road) LAEI sources

Category	$PM_{2.5}$/PM_{10} ratio
Area sources (weighted average)	0.48
Point sources	0.67
Other transport	0.76

Table 5.5 2008/9 emissions within the selected NAEI area treated as 1 km area sources in the 2008/9 dispersion modelling study

Source category	Emissions (t/year)		
	NO_x	PM_{10}	$PM_{2.5}$
Energy Production and Transformation	47	1	1
Commercial, Institutional and Residential Combustion	2,562	183	122
Industrial Combustion	1,215	56	38
Industrial Processes	0	77	37
Production and Distribution of Fossil Fuels	0	0	0
Solvent Use	0	93	62
Road Transport[a]	7,124	513	443
Other Transport	2,146	154	117
Waste Treatment and Disposal	19	117	88
Agriculture	0	20	3
Nature	7	55	8
Point sources[b]	359	47	31
Total	13,479	1,316	950

[a] Excludes emissions on the (small) part of the major road network that intersects the selected NAEI area
[b] Excludes the large point sources modelled explicitly

Table 6.1 Rural background concentrations

Pollutant	Period-mean concentration (µg/m^3)	
	Raw	Adjusted
NO_x	14.3	-
PM_{10}	14.6[a]	17.2[b]
$PM_{2.5}$	9.6[c]	9.6[d]

[a] TEOM (without 1.3 factor)
[b] VCM corrected
[c] TEOM with default set-up
[d] derived from VCM-corrected PM_{10}

Table 7.1 Polynomial expressions for the relationship between $[NO_2]/[OX]$ versus $[NO_x]$ for various categories of the inter-quartile ratio of hourly NO_x concentrations, based on national monitoring data up to 2006[33]

Cat	Range[b]	Coefficients of 6th order polynomial[a]					
		$[NO^x]^6$	$[NO_x]^5$	$[NO_x]^4$	$[NO_x]^3$	$[NO_x]^2$	$[NO_x]$
I	< 2.5	4.856E-14	-3.290E-13	-9.371E-09	2.824E-06	-3.684E-04	2.582E-02
II	2.5 – 3.5	-1.673E-13	1.195E-10	-3.469E-08	5.305E-06	-4.692E-04	2.595E-02
III	> 3.5	-2.881E-13	1.857E-10	-4.843E-08	6.620E-06	-5.211E-04	2.591E-02
IIIa	around 3.5[c]	-2.423E-13	1.607E-10	-4.329E-08	6.132E-06	-5.020E-04	2.593E-02

[a] $[NO_x]$ in ppb; expressions valid for 0-160 ppb
[b] This is the range of the inter-quartile ratio
[c] This additional category was introduced specifically in the context of the PCM modelling

Table 7.2 Inter-quartile ratio (IQR) for the monitoring sites around Heathrow, based on 2008/9 data[a] (see 2008/9 model evaluation report for further discussion of monitoring data)

Site Name	Short name	25th %ile of hourly averages ($\mu g/m^3$)	75th %ile of hourly averages ($\mu g/m^3$)	IQR[c]
Heathrow LHR2	LHR2	48.0	160.0	3.33
Heathrow Oaks Road	Oaks Rd	17.0	82.0	4.82
Heathrow Green Gates	Green Gates	29.0	88.0	3.03
Slough Colnbrook	Colnbrook	15.0	69.0	4.60
London Hillingdon Harmondsworth	Harmondsworth	23.0	74.0	3.22
London Hillingdon	Hillingdon	40.0	145.0	3.63
Hillingdon Sipson	Sipson	27.0	82.0	3.04
London Harlington	Harlington	25.0	74.0	2.96
London Hillingdon 3 Oxford Avenue	Oxford Ave	36.1	106.6	2.95
Hillingdon Hayes	Hayes	53.0	157.0	2.96
Hounslow 2 - Cranford	Cranford	25.0	74.7	2.99
Hounslow Hatton Cross	Hatton Cross	21.6	85.7	3.97

[a] A fuller discussion of the 2008/9 monitoring data is given in the 2008/9 model evaluation report

Table 7.3 Categorisation (see Table 7.1) used for near-road receptors in the national mapping

Area Type	Description	Population	Category
1	Central London		II
2	Inner London		II
3	Outer London		II
4	Inner Conurbation		II
5	Outer Conurbation		II
6	Urban Big	> 250,000	IIIa
7	Urban Large	>100,000	IIIa
8	Urban Medium	> 25,000	IIIa
9	Urban Small	> 10,000	IIIa
10	Rural		III

Table 7.4 Primary NO_2 fractions for aircraft exhaust emissions

ICAO LTO operating condition (% F_{00})[1]	Primary NO_2 fraction	
	Range (%)	Mean (%)
Take-off (100)	1 – 8	4.5
Climb-out (85)	2 – 8.5	5.3
Approach (30)	10 – 20	15.0
Idle (7)	25 – 50	37.5

[1] F_{00} is the engine rating, i.e. maximum sea level thrust

Table 7.5 Primary NO_2 fraction (*fNO_2*) by vehicle category

Vehicle category	Standard	fNO_2 (%)
Petrol LDV	Pre-Euro 1	4
	Euro 1	4
	Euro 2	4
	Euro 3	3
	Euro 4	3
	Euro 5	3
Diesel LDV	Pre-Euro 1	11
	Euro 1	11
	Euro 2	11
	Euro 3	25
	Euro 3 with DPF	35
	Euro 4	55
	Euro 4 with DPF	55
	Euro 5	50
HDV	Pre-Euro I	11
	Euro I	11
	Euro II	11
	Euro III	14
	Euro IV	14
	Euro V	10

Table 7.6 Summary of primary NO_2 fractions used in the 2008/9 modelling

	Source category	*fNO_2* (%)
Airport	Aircraft	See Table 7.4
	Airside vehicles – specialist	15.0
	Airside vehicles – road vehicles	See Table 7.5
	Heating plant	5.0
	Car parking	See Table 7.5
Road Network	Road vehicles	See Table 7.5
LAEI	Road vehicles	18.5
	Airports (excluding Heathrow)	21.0
	Rail and shipping	15.0
	Other	5.0
NAEI	Road vehicles	17.2
	Rail and shipping	15.0
	Other	5.0
Background		14.0

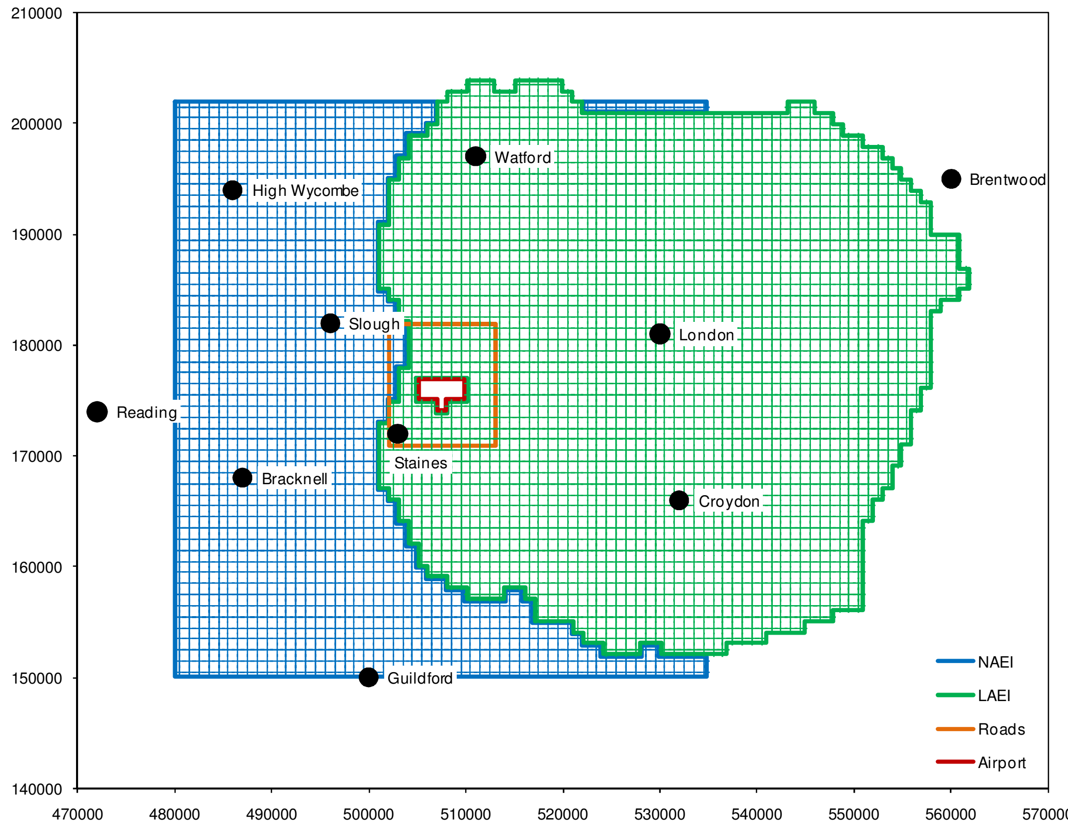


Fig 2.1 Inventory areas used in the 2008/9 air quality modelling

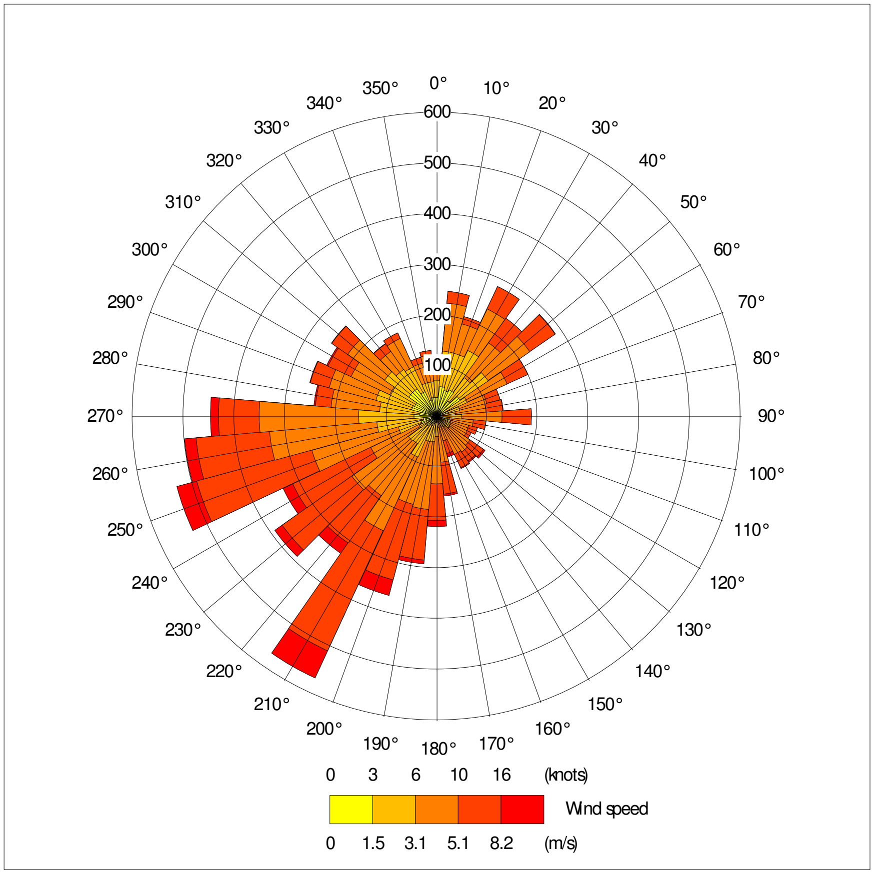


Fig 3.1 Frequency distribution of wind direction and speed at Heathrow for the 2008/9 period

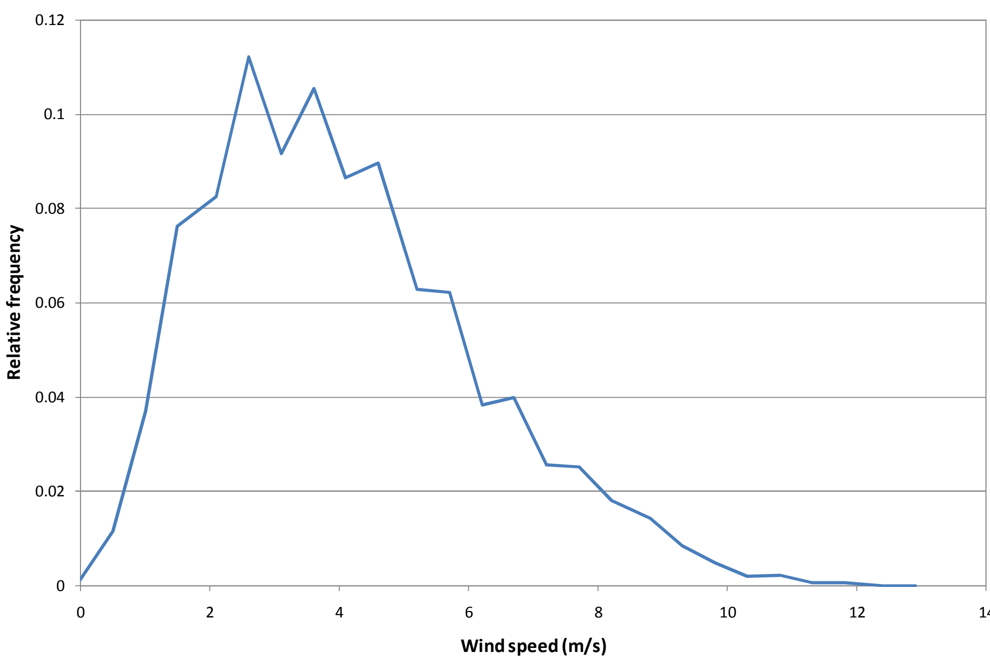


Fig 3.2 Frequency distribution of wind speed (irrespective of angle) at Heathrow for the 2008/9 period

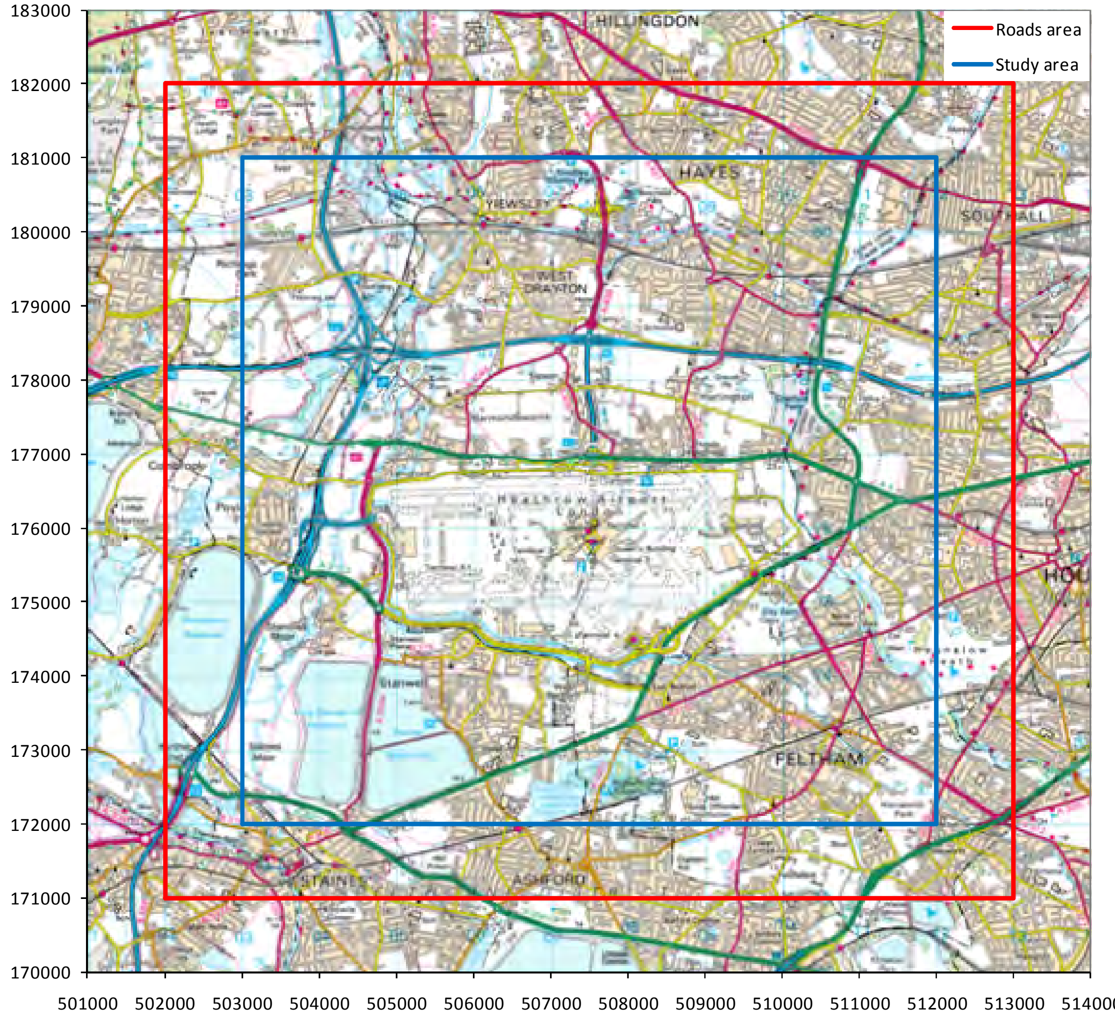


Fig 3.3 Road network area and study area

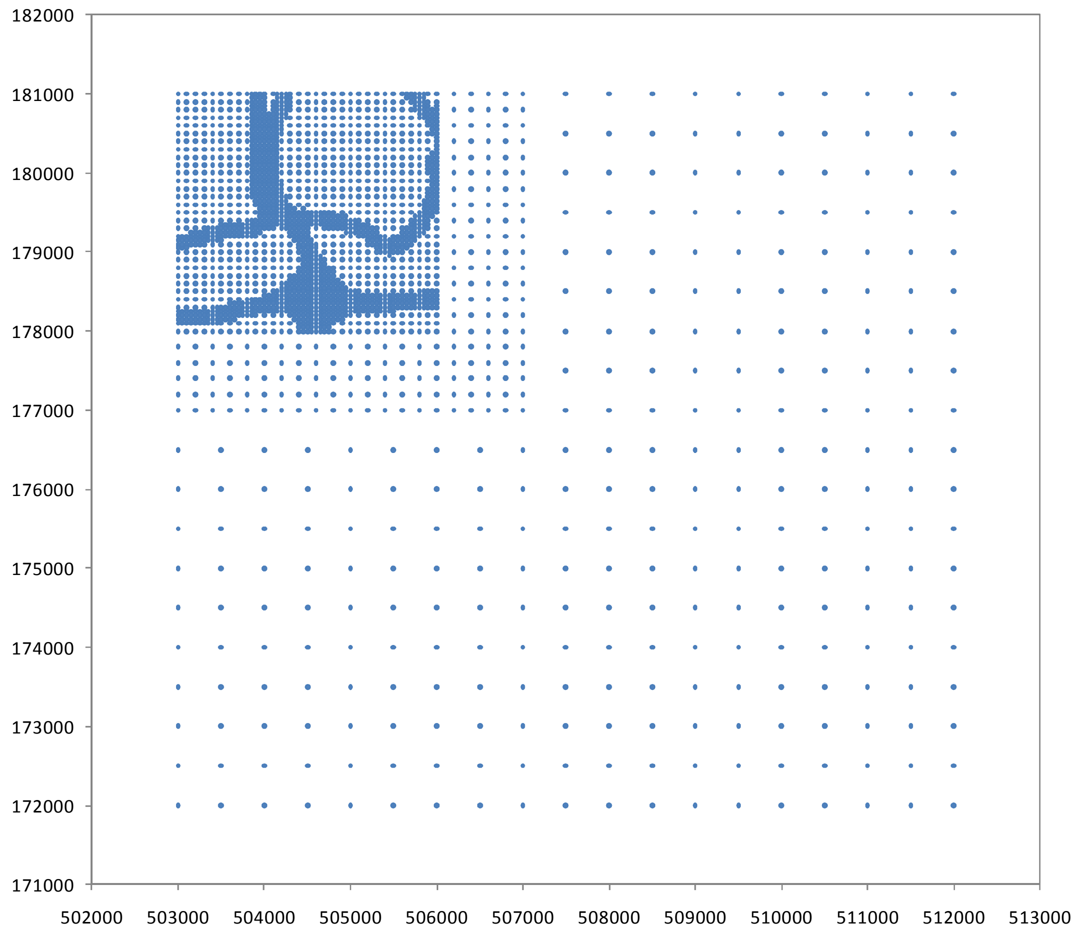


Fig 3.4 Example of receptor points associated with one of the nine road-network segments. (The individual 'intelligent gridding' points around the road links are too closely spaced to be resolved at this scale.)

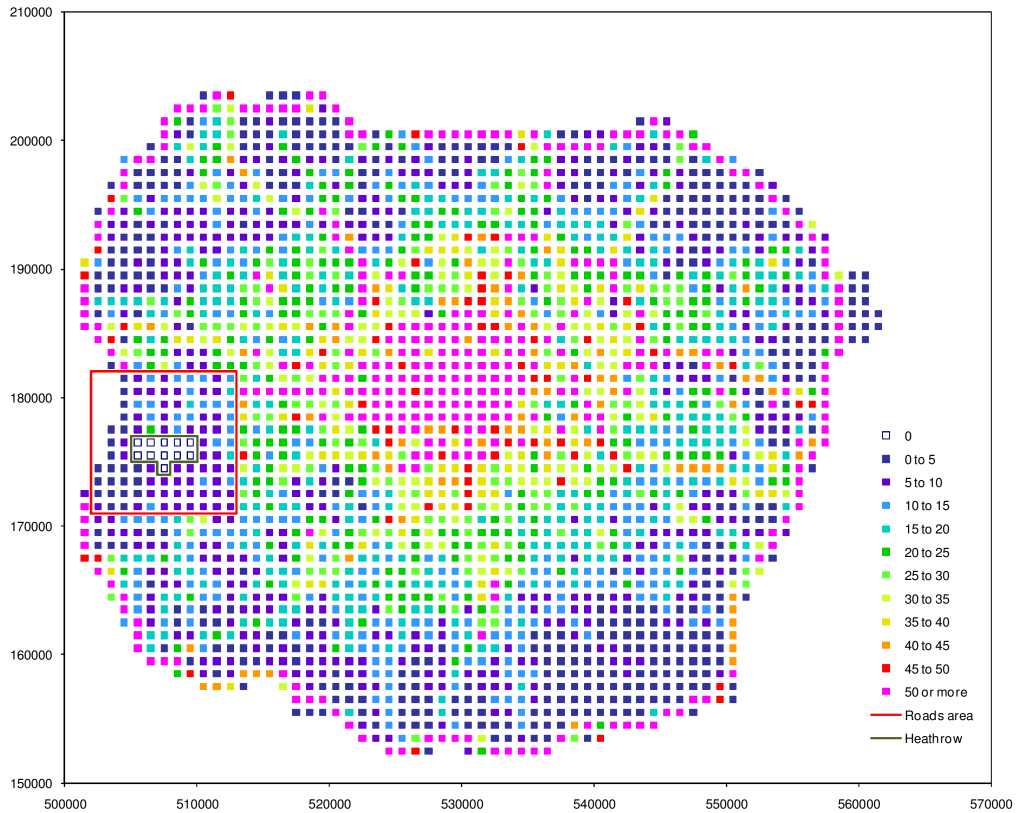


Fig 5.1 (a) Spatial density of emissions (tonne/km^2/year) for LAEI area sources: NO_x

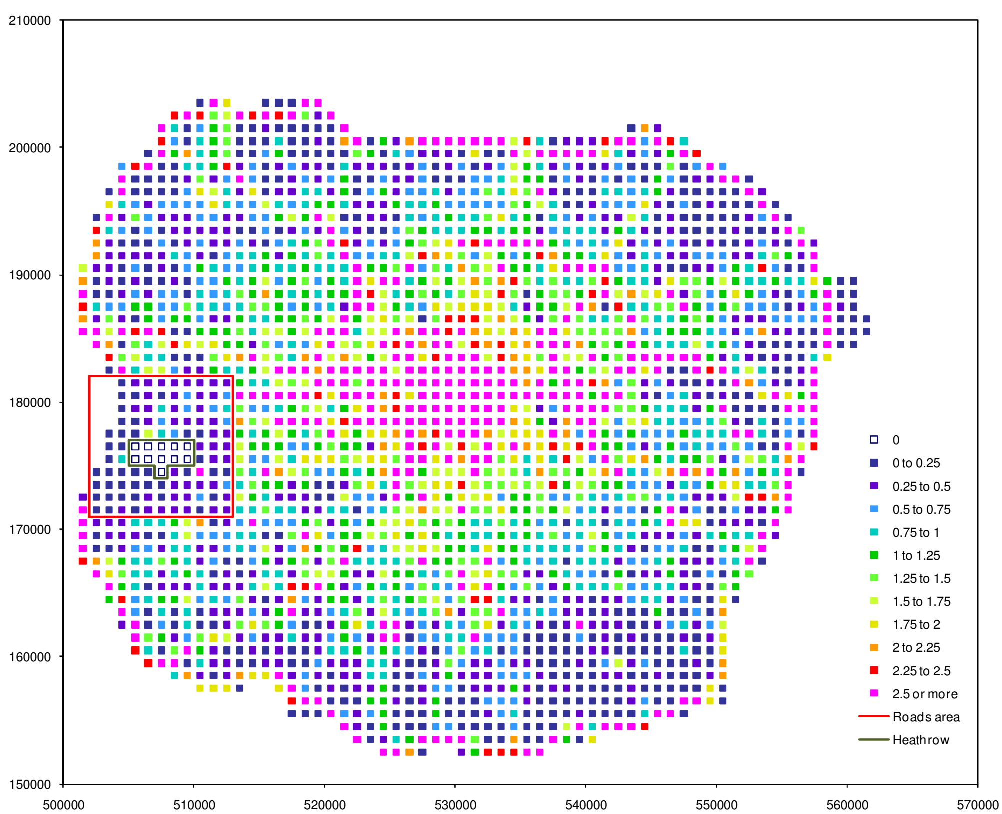


Fig 5.1 (b) Spatial density of emissions (tonne/km^2/year) for LAEI area sources: PM_{10}

Fig 5.1 (c) Spatial density of emissions (tonne/km^2/year) for LAEI area sources: $PM_{2.5}$

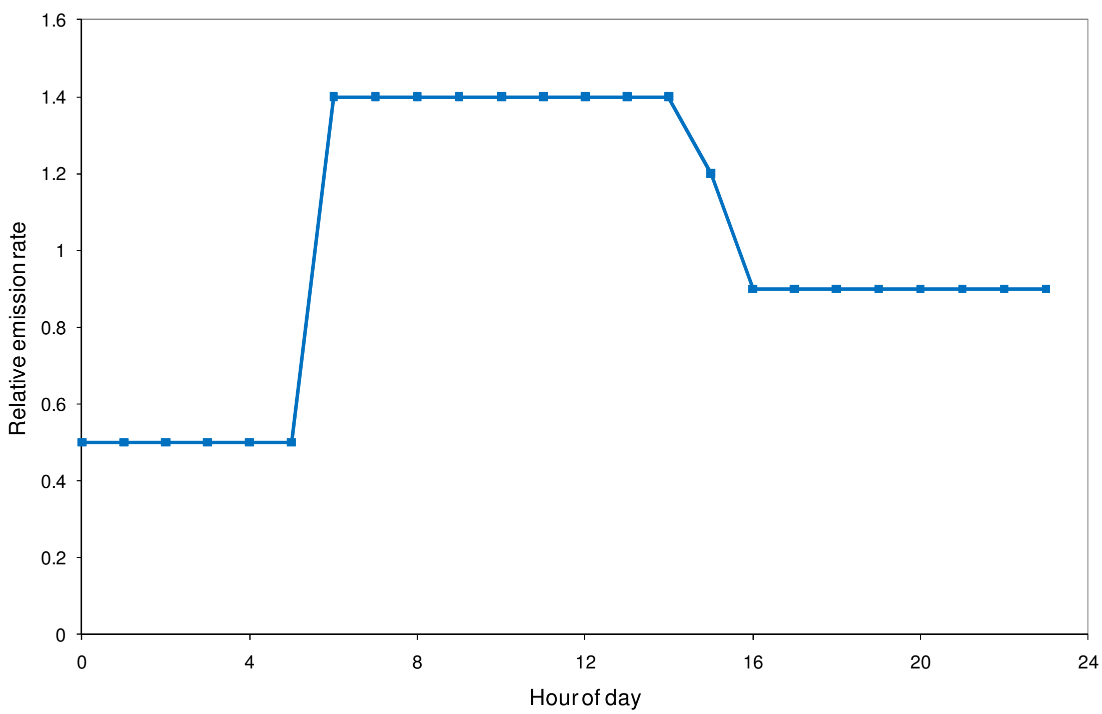


Fig 5.2 Diurnal profile of emissions for LAEI sources

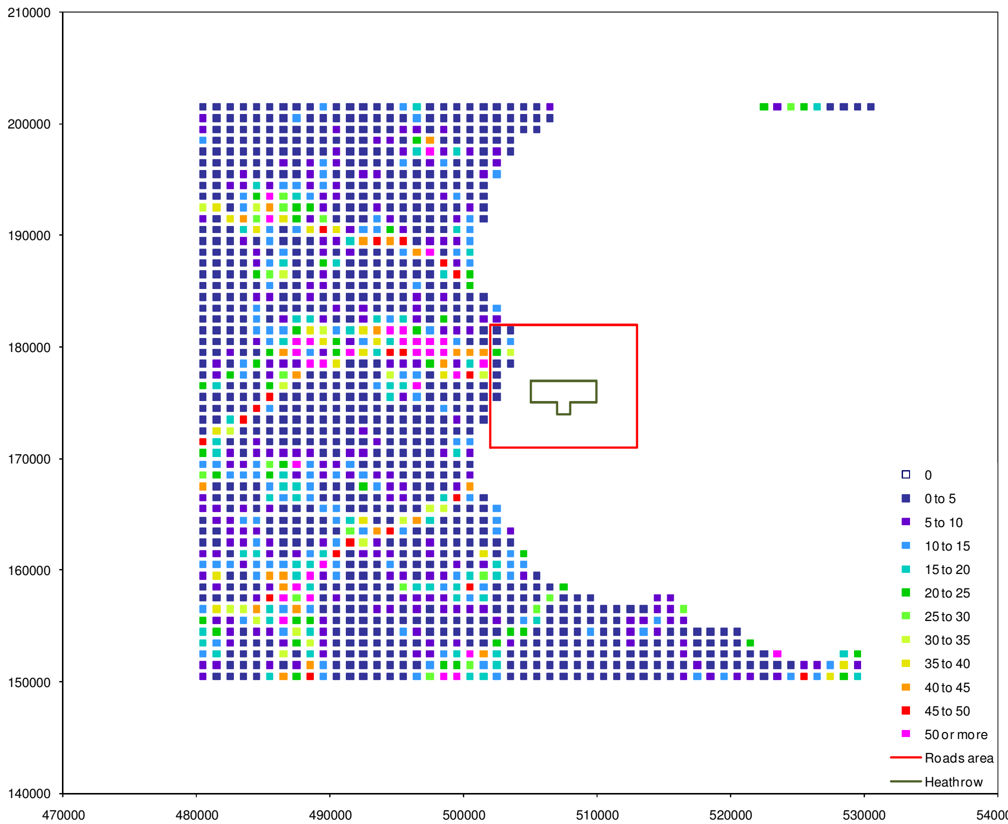


Fig 5.3 (a) Spatial density of emissions (tonne/km^2/year) for NAEI area sources: NO_x

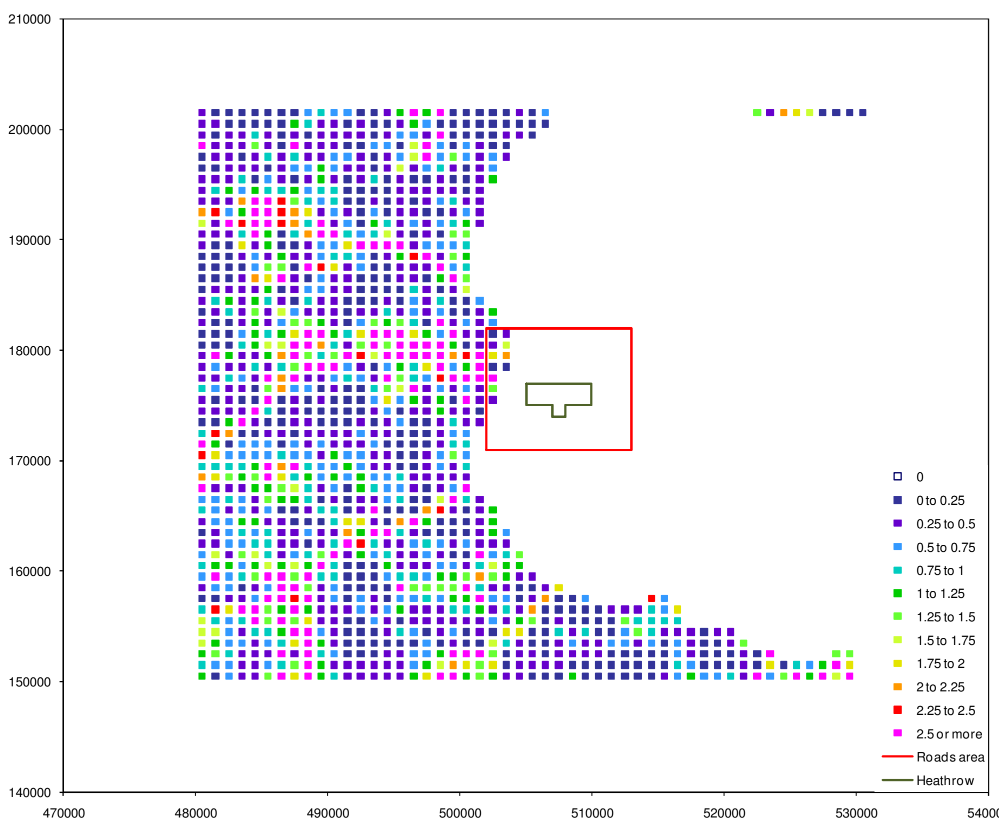


Fig 5.3 (b) Spatial density of emissions (tonne/km^2/year) for NAEI area sources: PM_{10}

Fig 5.3 (c) Spatial density of emissions (tonne/km^2/year) for NAEI area sources: $PM_{2.5}$

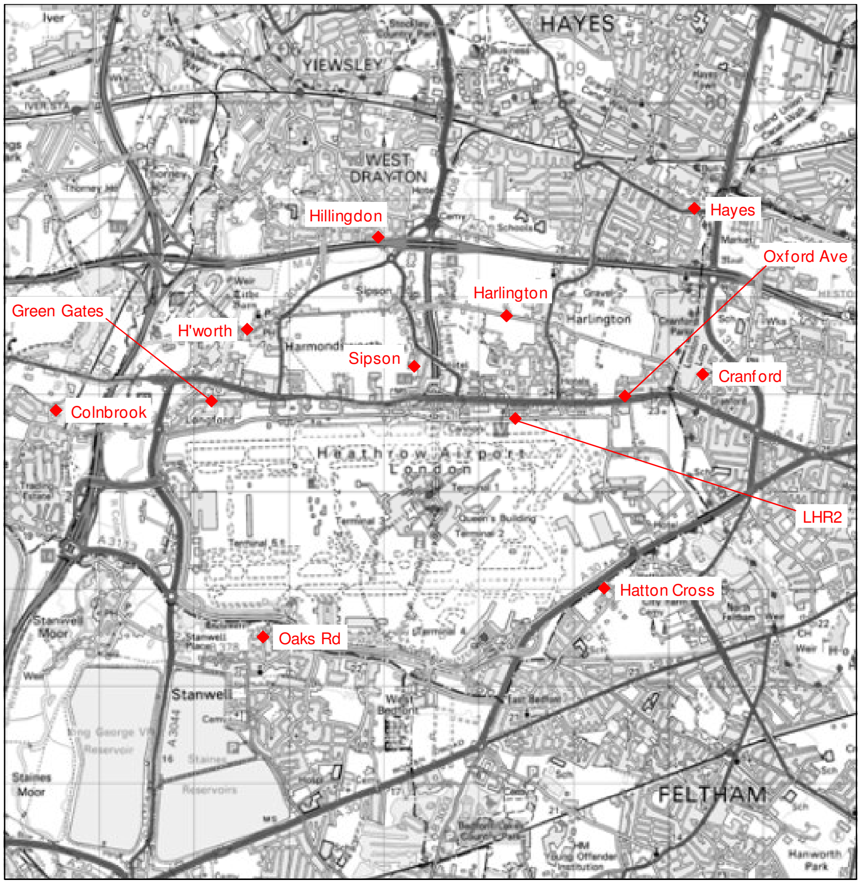


Fig 7.1 Location of monitoring sites used in the 2008/9 modelling study

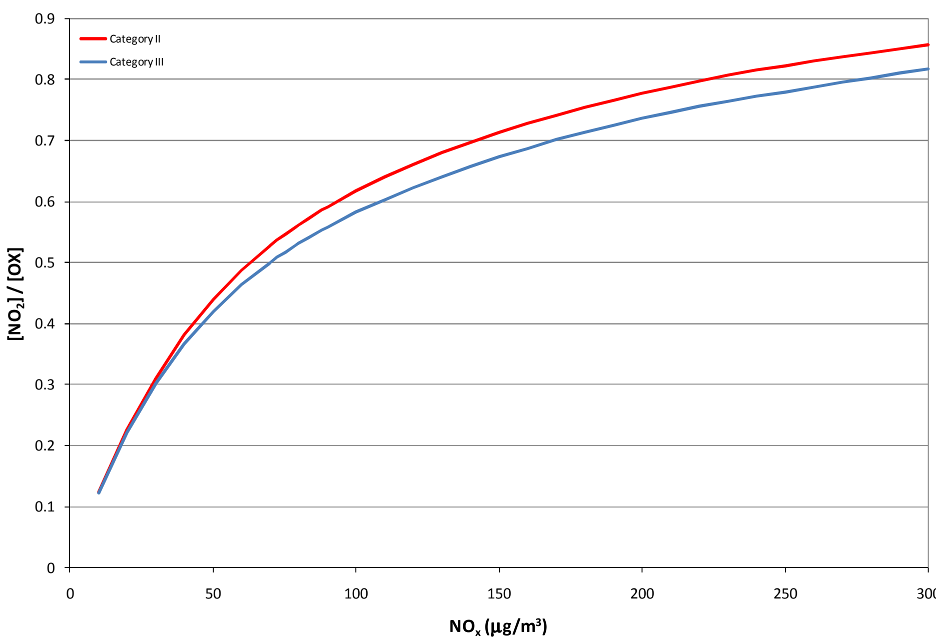


Fig 7.2 The polynomial fits to the f_{II} (red) and f_{IIIa} (blue) curves in the revised Jenkin methodology

Appendices

Appendix 1: Relevant Air Quality Strategy Objectives and EU Limit Values for Selected Pollutants

Appendix 2: Sensitivity to Efflux Parameters

Appendix 1

Relevant Air Quality Strategy Objectives and EU Limit Values for Selected Pollutants

Pollutant	Objective	Metric[a]	Date[b]	European obligations	Date[b]
Nitrogen dioxide (NO_2)	200 µg/m^3 not to be exceeded more than 18 times per year	1 hour mean	31.12.2005	200 µg/m^3 not to be exceeded more than 18 times per year	1.1.2010
	40 µg/m^3	annual mean	31.12.2005	40 µg/m^3	1.1.2010
Particles[c] (PM_{10})	50 µg/m^3 not to be exceeded more than 35 times a year	24 hour mean	31.12.2004	50 µg/m^3 not to be exceeded more than 35 times a year	1.1.2005
	40 µg/m^3	annual mean	31.12.2004	40 µg/m^3	1.1.2005
Particles[d] ($PM_{2.5}$)	25 µg/m^3	annual mean	2020	Limit value 25 µg/m^3	1.1.2015
		annual mean		Stage 2 indicative limit value of 20 µg/m^3	1.1.2020[e]
				Exposure concentration obligation of 20 µg/m^3	1.1.2015[e]
	Target of 15% reduction in concentrations at urban background	annual mean	between 2010 and 2020	Exposure reduction target relative to the 2010 AEI[f] (0% to 20% reduction)	2020

[a] Averaging period
[b] Date to be achieved by and maintained thereafter
[c] The objectives given here for PM_{10} do not apply in Scotland.
[d] AQS objectives for $PM_{2.5}$ have not been included in Regulations for the purpose of Local Air Quality Management. (The limit value given here for $PM_{2.5}$ does not apply in Scotland.)
[e] Will be reviewed by the European Commission by 2013
[f] The three-year running annual mean or AEI is calculated from the $PM_{2.5}$ concentration averaged across all urban background locations in the UK (i.e. the AEI for 2010 is the mean concentration measured over 2008, 2009 and 2010).

Appendix 2

Sensitivity to Efflux Parameters

A2.1 As described briefly in Section 3, tests were carried out to determine the sensitivity of ground-level concentrations to the efflux parameters characterising the exhaust plumes from aircraft on the ground in various phases of the LTO cycle. The principal aim of the tests was to determine a suitable basis for partitioning the full range of aircraft/engine combinations in the fleet at a large airport such as Heathrow into categories for dispersion modelling purposes (MCATs). A subsidiary aim of the tests was to check if the initial buoyancy flux parameter, *B*, calculated from engine efflux parameters as in Section 3, serves as an adequate determinant of the impact of exhaust heat and momentum on ground-level concentrations, such that it can be used to partition the aircraft/engine combinations in a given fleet into MCATs.

A2.2 For the tests, a simple source was set up in ADMS-Airport representing the early part of a take-off roll, where the aircraft is moving at relatively low speed, given that plume rise has less effect at higher speeds. The source, with unit emission rate, was represented as a pair of horizontal straight-line elements of 10 m length, set at engine mid-height, representing two engines[*], with an aircraft speed of 15 knots. ADMS-Airport was run separately for two fixed meteorological conditions: constant wind of 2 m/s blowing against the direction of motion of the aircraft and a constant wind of 2 m/s blowing perpendicular to the direction of motion of the aircraft. Other meteorological parameters were representative of neutral atmospheric stability. Concentrations were calculated on a grid of receptors, with a mesh spacing of 10 m and extending over an area of 1 km x 1 km centred on the source.

A2.3 A range of aircraft/engine combinations were chosen to span the range of efflux conditions expected in the fleet at a large airport such as Heathrow, both now and in the next 20 years. Aircraft/engine combinations for future aircraft types were taken from the table of defaults given in the ADMS-Airport User Guide[8]. Engine heights and spacing were appropriate to the particular aircraft type. Efflux parameters were obtained as described in Section 3.

A2.4 Two concentration metrics were used - the maximum ground level concentration and the average ground-level concentration, in both cases including only receptors at greater than 200 m from the source. Clearly it is difficult to capture the complexities of the variation in the ground-level concentration field with efflux parameters using a few scalar quantities, but the metrics chosen were judged adequate for determining MCAT boundaries. The lower limit on distance from source to receptor was set to reflect that receptors of interest are unlikely to be closer than this to the runway and to avoid artefacts due to the finite receptor mesh size.

A2.5 The calculations were carried out separately for take-off thrust and idling thrust.

Take-Off Thrust

A2.6 For take-off, the efflux parameters were calculated for 85% thrust were used; the resulting parameters are shown in Table A2.1.

A2.7 For illustration, Fig A2.1 shows the shape of the concentration contours for a low and high buoyancy aircraft/engine combination at take-off thrust, for both the headwind and crosswind cases. In the crosswind case, the figure shows that the plume travels a greater distance before turning into the wind as a consequence of the higher momentum flux. Near-field concentrations are higher in the low-buoyancy case.

[*] Four-engined aircraft were also represented by two engines, as suggested by the ADMS-Airport User Guide, following sensitivity studies carried out by CERC. Of course, appropriate adjustments have been made to the effective diameter to account for the merging of aircraft plumes.

A2.8 Table A2.2 gives the two concentration metrics defined earlier, for each of the 16 selected aircraft/engine combinations. It was found by inspection that a fairly linear relationship can be obtained by plotting concentration metric versus 1/*B*: Figs A2.2(a) and (b) show the resulting fitted regression lines for the along-wind and cross-wind cases respectively.

A2.9 Thus, these results indicate that the partitioning of aircraft/engine combinations into MCATs from a plume-rise perspective for any particular fleet (for a given flight phase such as take-off) can be carried out in terms of the range of *B* values encompassed by the fleet. Over the whole range of efflux parameters tested, the ratio of highest to lower value for maximum concentration (at >200 m from the source) is about a factor of 2 (headwind) to 3 (crosswind) for a range of 1/*B* of about a factor of 5; the corresponding ratio for the average concentration (at >200 m from the source) is around 1.7 (headwind) to 2.0 (crosswind)[*]. If a criterion is set that the defined concentration metrics should not vary over an MCAT by more than ±5% from its value at the mid-point, the results suggest that 1/*B* should not fall by more than about 25% from the top to the bottom of its range for the MCAT.

Taxiing

A2.10 Efflux parameters for taxiing were worked out at a thrust of 7% of engine rating. The values of the parameters and the corresponding values of *B* buoyancy for the chosen engines are shown in Table A2.3. The values of B are much lower than for take-off thrust, as expected, and even for the highest-thrust engine is below the take-off value of *B* for the lowest-thrust engine.

A2.11 Table A2.4 gives the concentration metrics at this thrust setting. The concentrations are lower than would be expected for an equivalent value of *B* at take-off thrust, showing that although *B* may be an adequate parameter on its own to characterise engines for a given phase of the LTO cycle separate consideration needs to be given to phases with very different thrust settings[†].

A2.12 Figs A2.3 (a) and (b) show that there is little systematic variation of maximum concentration (at distances greater than 200 m) with 1/*B*, and only a slight trend for the average concentration. Bearing in mind that taxiing accounts for a much smaller fraction of ground-level aircraft NO_x emissions than does take off and that taxiing emissions are more widely distributed spatially, it is unwarranted to use more than a single MCAT for taxiing emissions.

[*] Of course, it may be possible to find individual locations where the dynamic range of the concentrations is larger than for these two metrics
[†] At least some of the discontinuity between high and low thrust settings may be due to the use of a cut-off distance of 200 m.

Table A2.1 Efflux parameters at take-off for representative engines used in the test runs for take-off thrust

Aircraft	Engine	V_p (m/s)	T_p (°C)	D_p (m)	B (m^4 s^{-3})
New 120*	CFM56-X	185.2	53.4	1.87	187.0
New 150*	CFM56-X	223.7	56.1	1.61	178.5
New 180*	CFM56-X	254.8	68.6	1.54	232.5
B737	CFM56-7B27	332.8	92.2	1.11	211.9
A320	CFM56-5B4/P	312.4	84.8	1.16	202.0
A321	V2533-A5	345.0	96.6	1.16	250.1
B757	RB211-535E4	353.1	99.5	1.28	321.2
B767	CF6-80C2B7F	330.5	91.3	1.65	464.1
A300	CF6-80C2A5	330.5	91.3	1.65	464.7
B787*	GENx	212.3	54.2	2.52	394.3
A330	PW4168A	330.5	91.3	1.76	525.7
A350*	T500	256.1	56.0	2.20	379.4
A340	CFM56-5C4	296.5	79.1	1.93	491.9
B777	GE90-92B	257.3	64.9	2.59	623.3
B747	CF6-80C2B1F	330.5	91.3	2.28	883.9
New 450*	CFM56-7B27	266.1	57.4	2.92	715.3

* Denotes that aircraft/engine combinations taken from ADMS-Airport default list

Table A2.2 Concentration metrics for the representative engines at take-off thrust

Aircraft	Engine	1/B 10^{-3} (m^{-4} s^3)	Concentration (μg/m^3) Head wind Max*	Head wind Ave*	Cross wind Max	Cross wind Ave
New 120*	CFM56-X	5.35	156.5	3.12	254.0	2.87
New 150*	CFM56-X	5.60	157.6	3.37	252.1	3.13
New 180*	CFM56-X	4.30	144.7	2.93	228.4	2.78
B737	CFM56-7B27	4.72	153.4	2.88	270.4	2.97
A320	CFM56-5B4/P	4.95	155.6	2.97	273.2	3.02
A321	V2533-A5	4.00	143.9	2.71	243.4	2.77
B757	RB211-535E4	3.11	129.7	2.49	201.2	2.44
B767	CF6-80C2B7F	2.15	108.4	2.27	143.7	2.03
A300	CF6-80C2A5	2.15	108.3	2.27	143.5	2.03
B787*	GENx	2.54	107.5	2.64	136.0	2.25
A330	PW4168A	1.90	102.0	2.19	127.8	1.91
A350*	T500	2.64	104.2	2.85	125.3	2.42
A340	CFM56-5C4	2.03	102.8	2.31	127.2	2.00
B777	GE90-92B	1.60	87.0	2.26	99.3	1.81
B747	CF6-80C2B1F	1.13	78.3	1.88	85.5	1.47
New 450*	CFM56-7B27	1.40	73.9	2.34	75.7	1.80

* For receptors > 200 m from the source

Table A2.3 Efflux parameters at take-off for representative engines used in the test runs for taxiing thrust

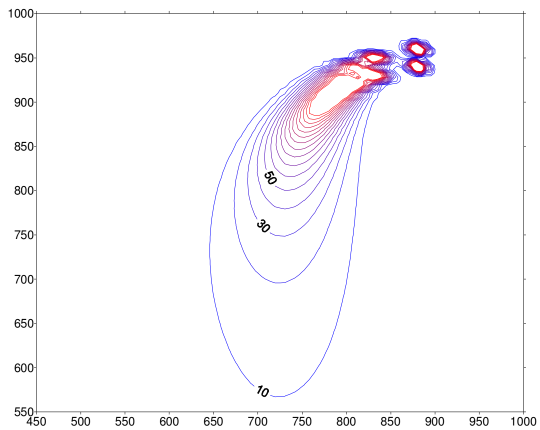
Aircraft	Engine	V_p (m/s)	T_p (°C)	D_p (m)	B (m^4 s^{-3})
New 120*	CFM56-X	50.9	39.3	1.91	35.5
New 150*	CFM56-X	63.6	40.3	1.59	31.8
New 180*	CFM56-X	70.5	42.0	1.53	34.8
B737	CFM56-7B27	89.4	56.5	1.12	34.9
A320	CFM56-5B4/P	84.4	52.8	1.18	33.3
A321	V2533-A5	92.4	58.7	1.17	41.2
B757	RB211-535E4	94.4	60.2	1.30	52.9
B767	CF6-80C2B7F	88.8	56.1	1.68	76.5
A300	CF6-80C2A5	88.8	56.1	1.68	76.6
B787*	GENx	59.6	35.9	2.50	61.8
A330	PW4168A	88.8	56.1	1.79	86.7
A350*	T500	71.3	37.3	2.20	61.1
A340	CFM56-5C4	80.6	49.9	1.95	81.3
B777	GE90-92B	71.0	42.8	2.60	103.7
B747	CF6-80C2B1F	88.8	56.1	2.31	145.8
New 450*	CFM56-7B27	73.1	37.7	2.96	114.6

* Denotes that aircraft/engine combinations taken from ADMS-Airport default list

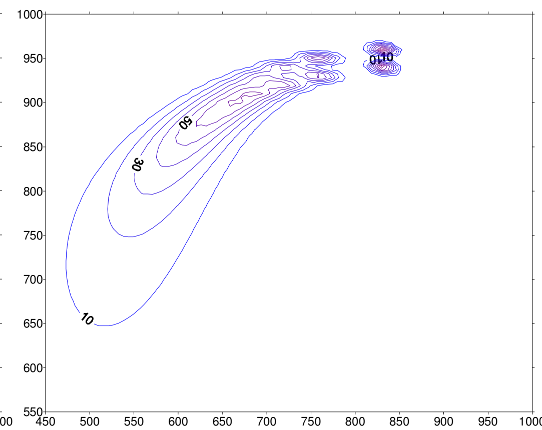
Table A2.4 Concentration metrics for the representative engines at taxiing thrust

Aircraft	Engine	*1/B*	Concentration (µg/m^3)			
			Head wind		Cross wind	
		10^{-3} (m^{-4} s^3)	Max*	Ave*	Max	Ave
New 120*	CFM56-X	28.15	120.07	3.40	92.9	2.46
New 150*	CFM56-X	31.41	144.09	3.80	106.6	2.77
New 180*	CFM56-X	28.71	148.64	3.76	110.2	2.77
B737	CFM56-7B27	28.62	129.31	3.57	102.7	2.66
A320	CFM56-5B4/P	30.00	133.50	3.66	102.6	2.70
A321	V2533-A5	24.26	124.29	3.34	97.6	2.50
B757	RB211-535E4	18.89	118.43	3.02	96.7	2.29
B767	CF6-80C2B7F	13.07	116.06	2.62	101.6	2.03
A300	CF6-80C2A5	13.05	116.04	2.62	101.6	2.03
B787*	GENx	16.19	148.00	3.15	123.0	2.39
A330	PW4168A	11.53	114.42	2.49	103.6	1.94
A350*	T500	16.37	165.71	3.38	145.1	2.60
A340	CFM56-5C4	12.30	122.06	2.62	108.2	2.03
B777	GE90-92B	9.64	129.72	2.49	124.2	1.96
B747	CF6-80C2B1F	6.86	109.03	1.98	118.3	1.60
New 450*	CFM56-7B27	8.73	154.02	2.75	198.4	2.24

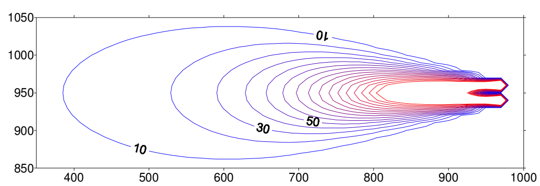
* For receptors > 200 m from the source



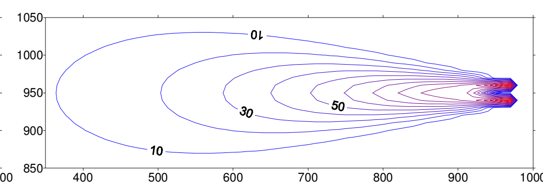
New120 CFM56-X, crosswind



New450 GE90-130B, crosswind



New120 CFM56-X, headwind



New450 GE90-130B, headwind

Fig A2.1 Concentration contours for aircraft/engine combinations at the low and high ends of the range of B (initial buoyancy flux parameter) used in the tests.

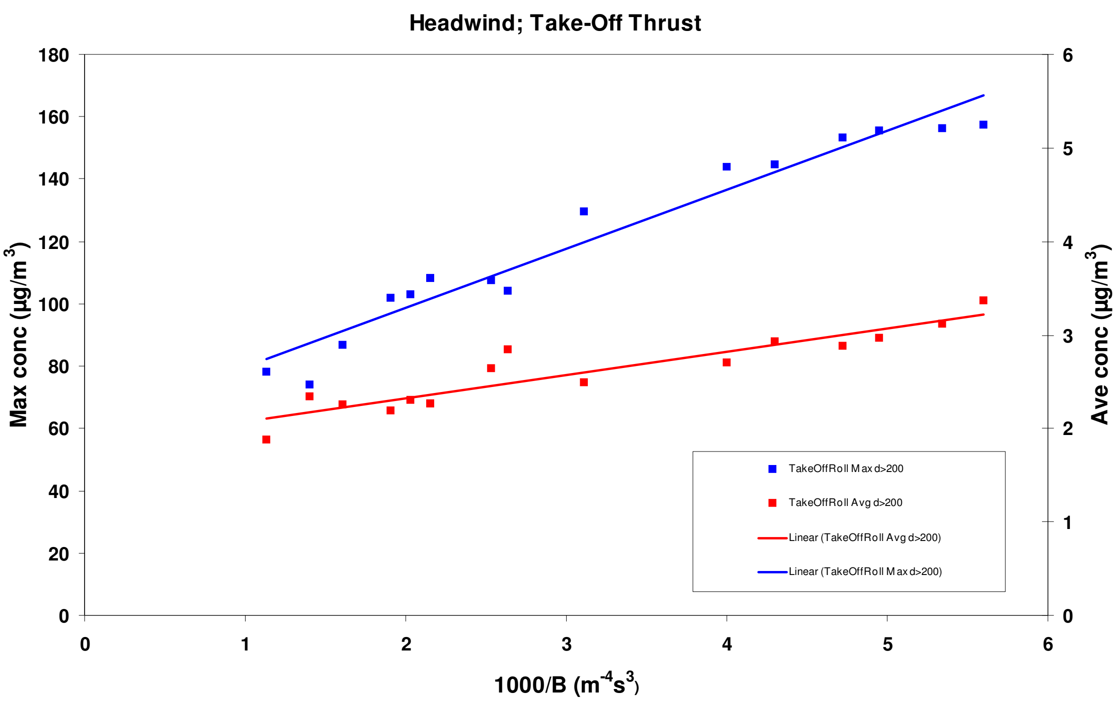


Fig A2.2 (a) Maximum and average concentration (for distances > 200 m from the runway) as a function of the inverse of the initial buoyancy flux parameter: take-off thrust. headwind

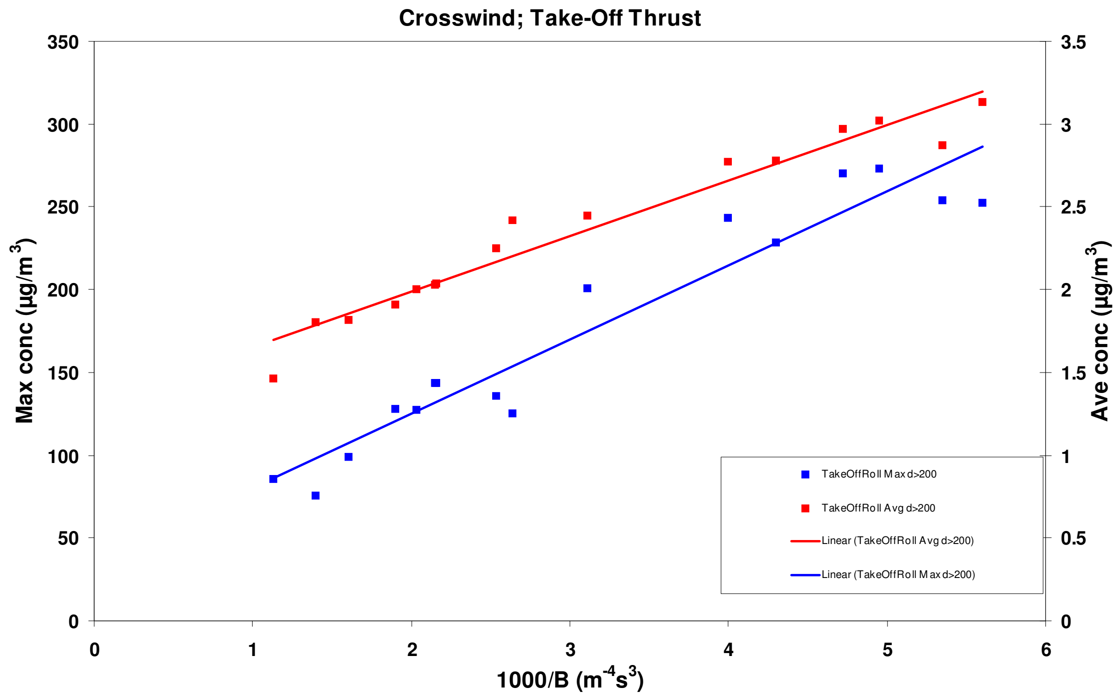


Fig A2.2 (b) Maximum and average concentration (for distances > 200 m from the runway) as a function of the inverse of the initial buoyancy flux parameter: take-off thrust, crosswind

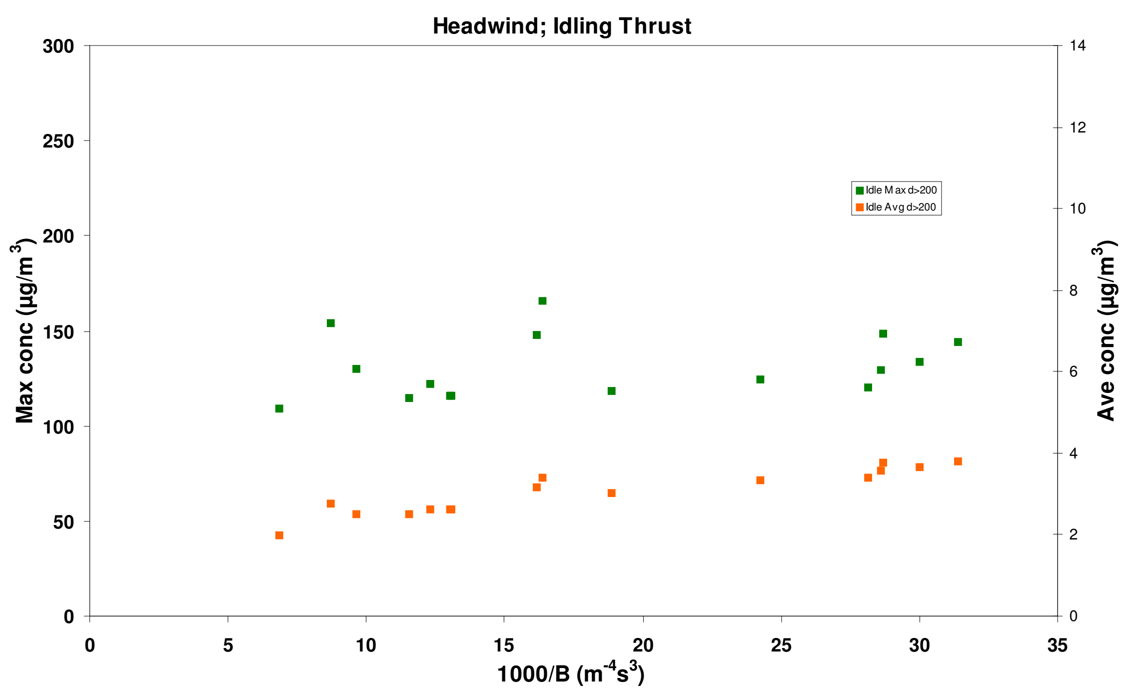


Fig A2.3 (a) Maximum and average concentration (for distances > 200 m from the runway) as a function of the inverse of the initial buoyancy flux parameter: idling thrust. headwind

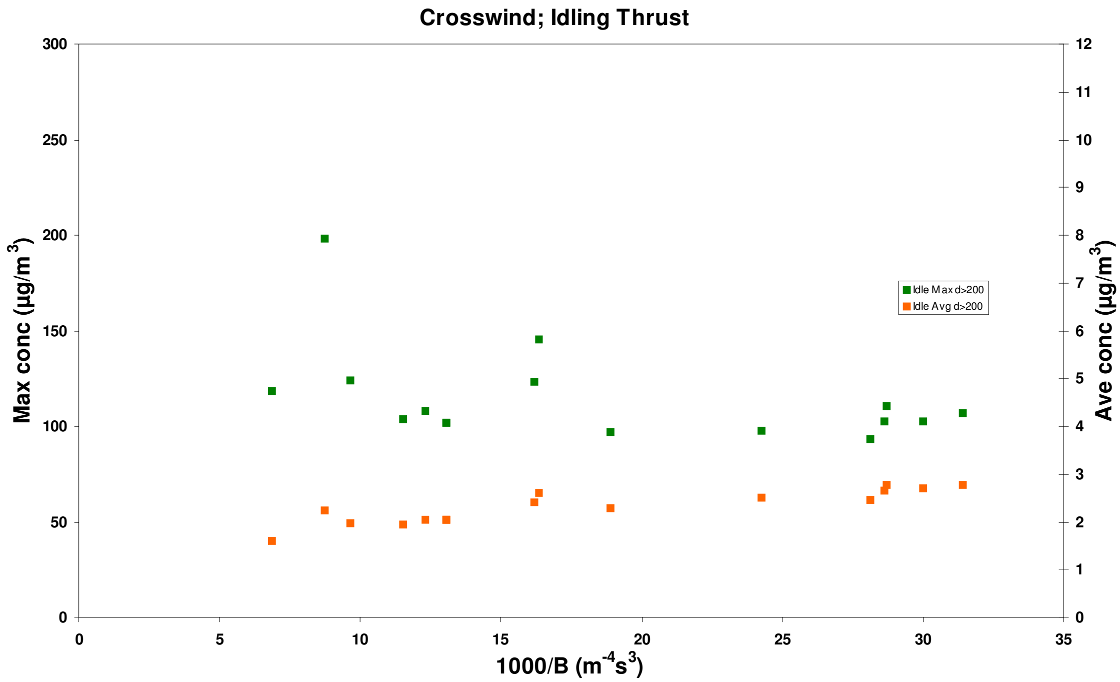


Fig A2.3 (b) Maximum and average concentration (for distances > 200 m from the runway) as a function of the inverse of the initial buoyancy flux parameter: idling thrust. crosswind

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